Introduction to Hadron Collider Physics

Part 3. Tools for hadron collider physics

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Heavily drawing from lectures written in collaboration with Peter Christiansen & Alice Ohlson - Lund University

Note on references: all the images from experiments are taken from the experiment websites unless otherwise noted

Outline of these introductory lectures

- **Part 1: Introduction**
  - Fundamental components of matter
  - Drawing particles and interactions: Feynman diagrams

10' Q&A + break

- **Part 2: Standard Model forces and interactions**
  - Electromagnetism
  - Weak interactions
  - Quantum Chromodynamics

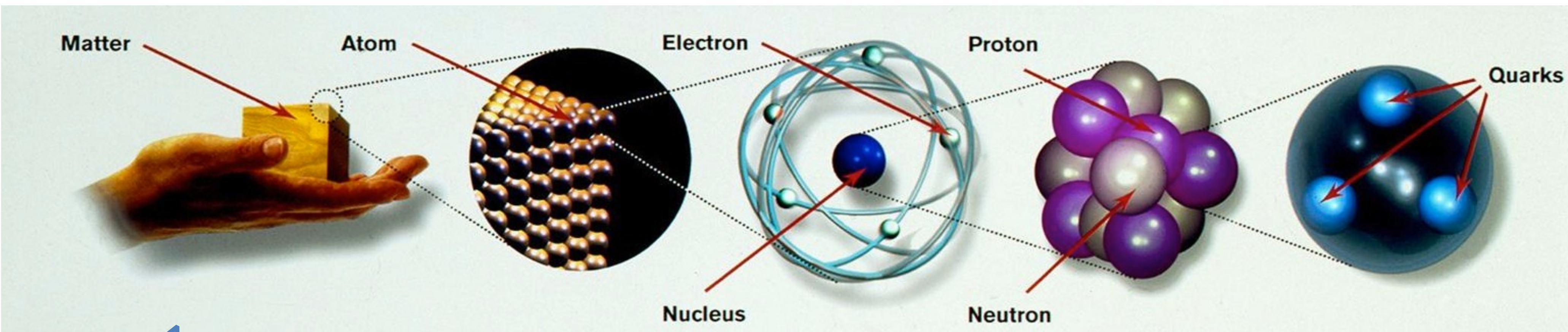
- **Part 3: Tools**
  - Particle accelerators: the LHC
  - Detectors for particle physics
  - CERN and particle physics collaborations

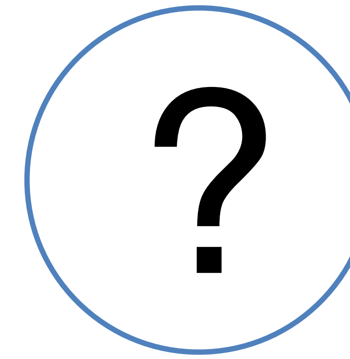
10' Q&A + break

- **Part 4: Beyond the Standard Model**
  - The Higgs discovery
  - Problems of the Standard Model
  - Solutions beyond the Standard Model
  - Dark Matter

10' Q&A + break

What are we made of?





Physical dimensions

Larger

Smaller

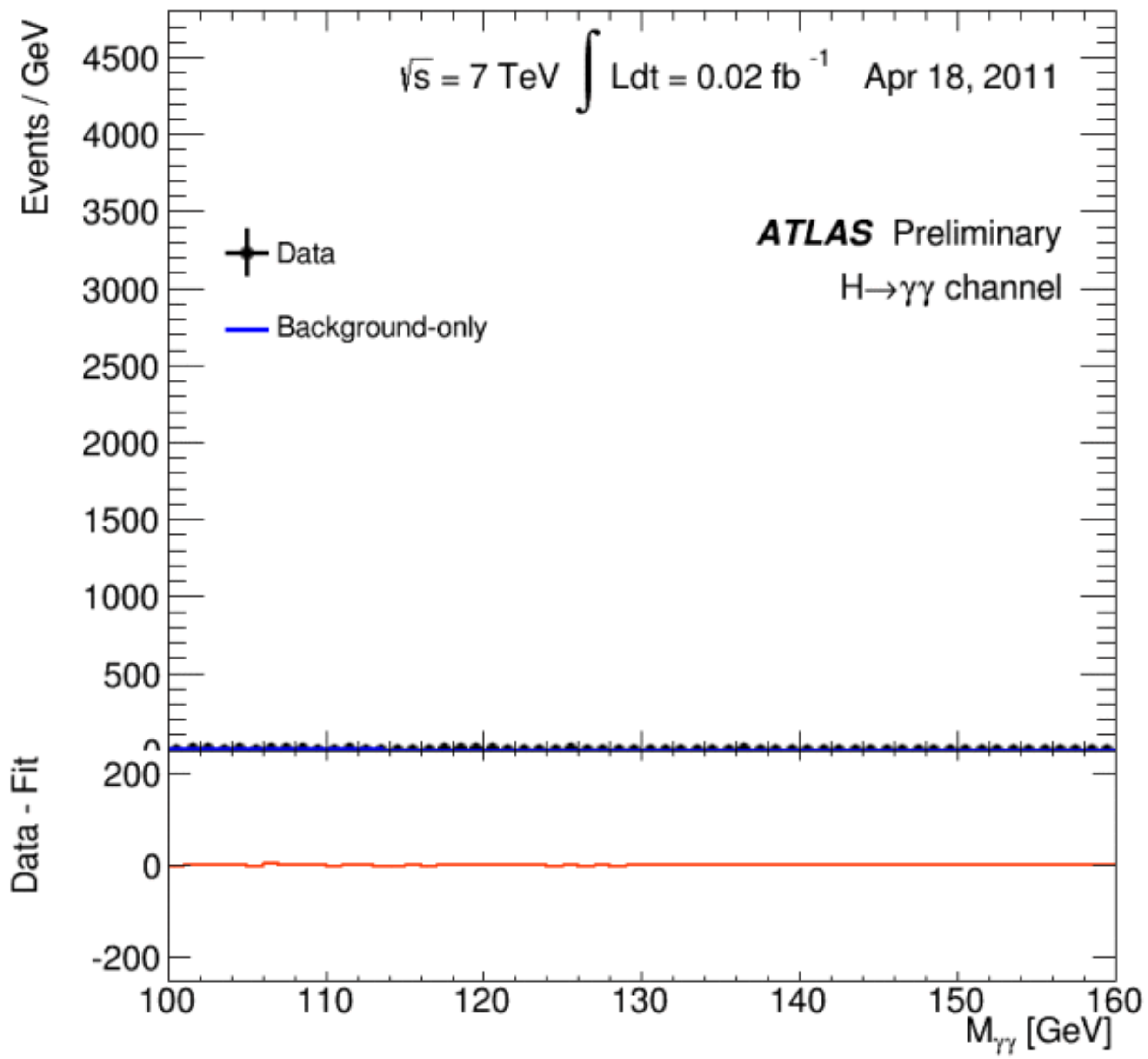
Energy necessary to create and study the smallest components of matter

Smaller

Larger

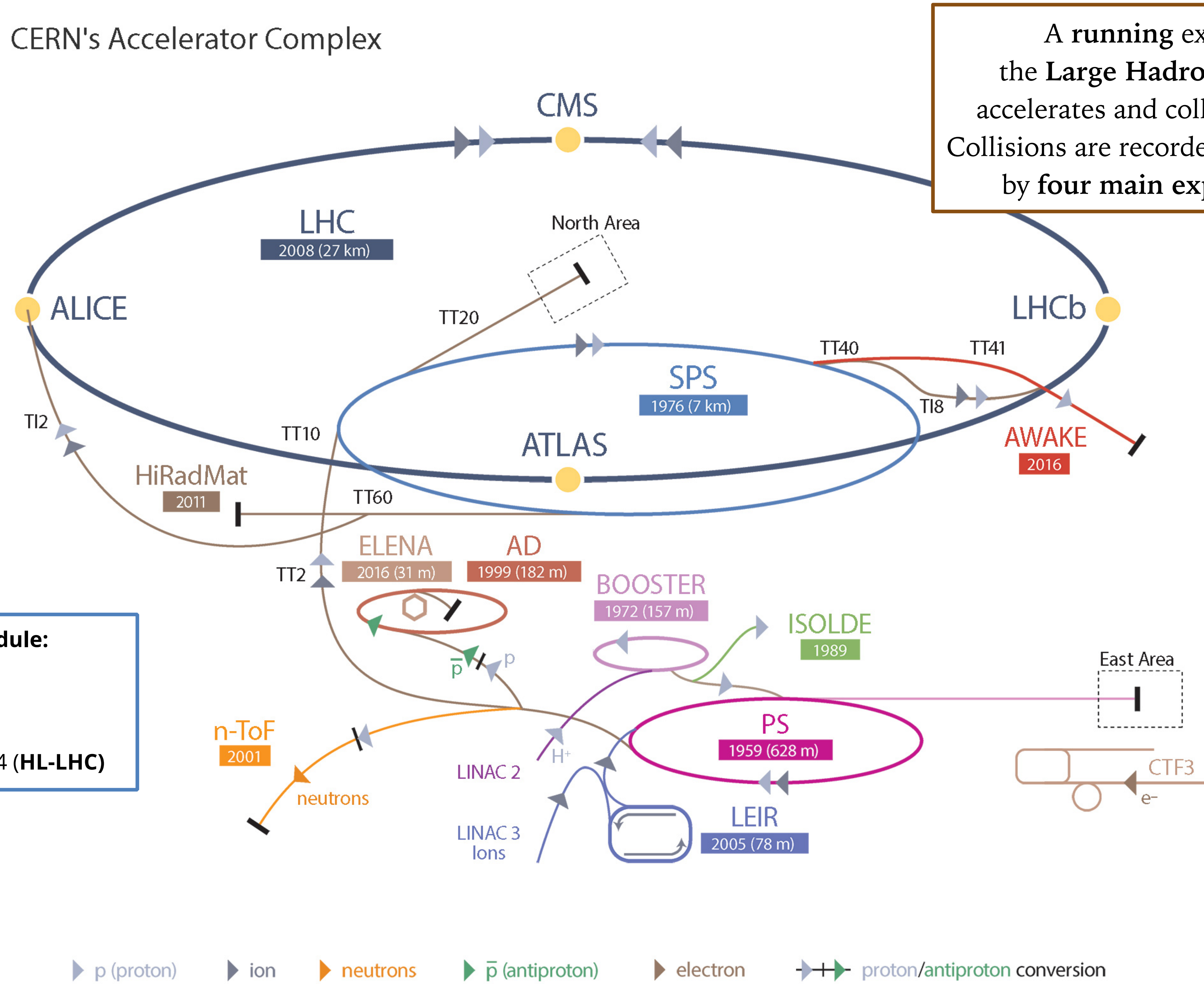
Where do we find this energy?

What does it take for a high energy physics discovery?



- A particle **collider** (LHC)
  - Many collisions/second
  - Only one in 10^{13} may contain an interesting event (e.g. Higgs boson)
- **Detectors** able to select and precisely measure particles (photons)
  - ATLAS, CMS (LHCb, ALICE)
  - Millions of read-out channels
- Many **teams** that:
  - Operate the detector
  - Reconstruct and calibrate particles
  - Do the data analysis

What does it take for a discovery? A (large) collider

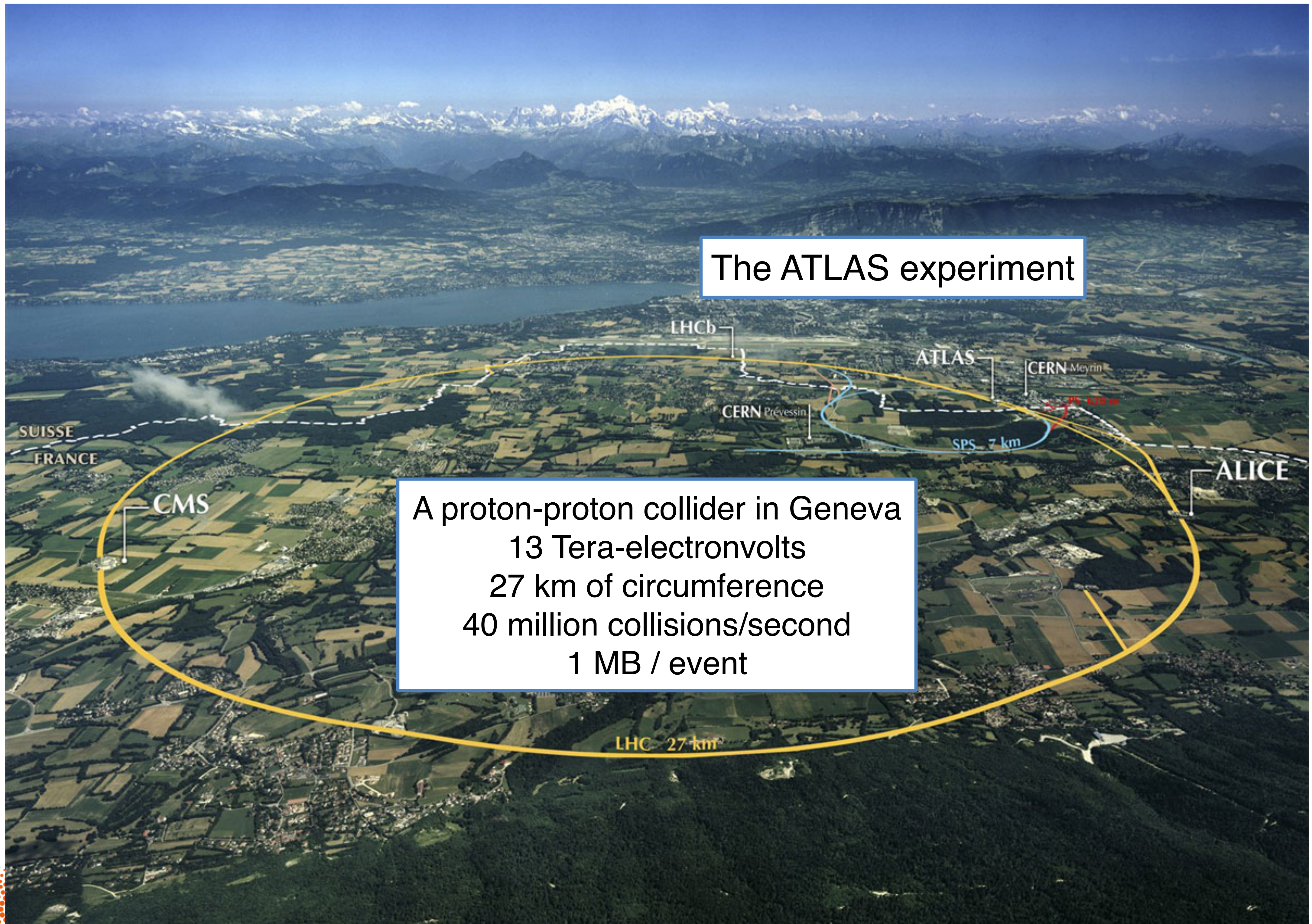


A **running** example:
the **Large Hadron Collider**
accelerates and collides protons
Collisions are recorded and analyzed
by **four main experiments**

LHC collisions schedule:
- 2010-2012: Run-1
- 2015-2018: Run-2
- 2022: beginning of Run-3
- ~2027: beginning of Run-4 (**HL-LHC**)

LHC: the biggest human-made discovery machine

(Q: what else provides us with highly energetic particles?)



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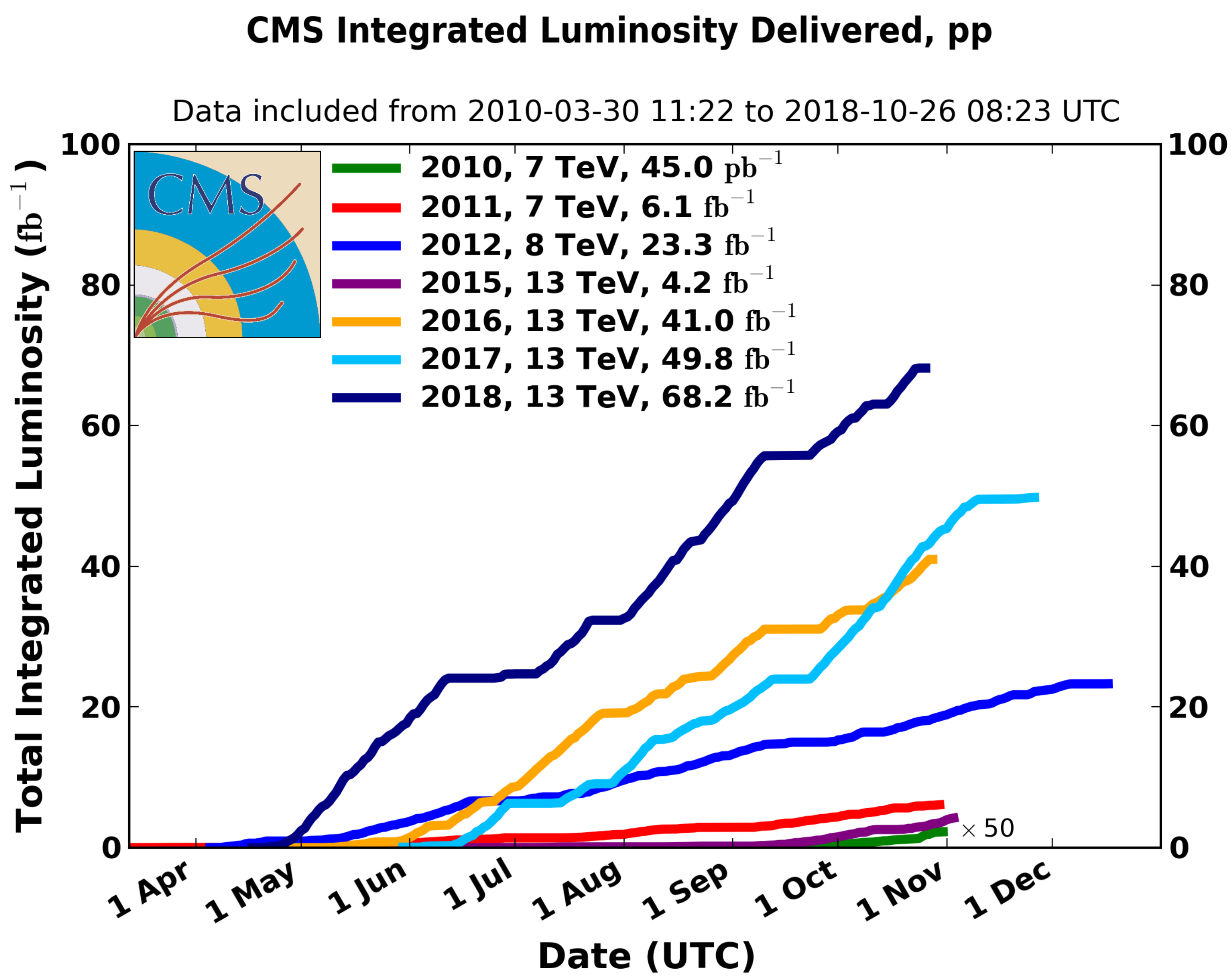
The Large Hadron Collider

Lecture 3

The future is even bigger: Future Circular Colliders!

What does it take for a high energy physics discovery?



√s = Centre of mass energy

More energy ⇔ can discover more massive particles ($E=mc^2$)

Luminosity = how much data is collected (proportional to # of collisions)

More data ⇔ more chances to see rare processes

Tera electron volt (TeV)?

1 Macina: 51 calories
1 calorie: 26000000 TeV

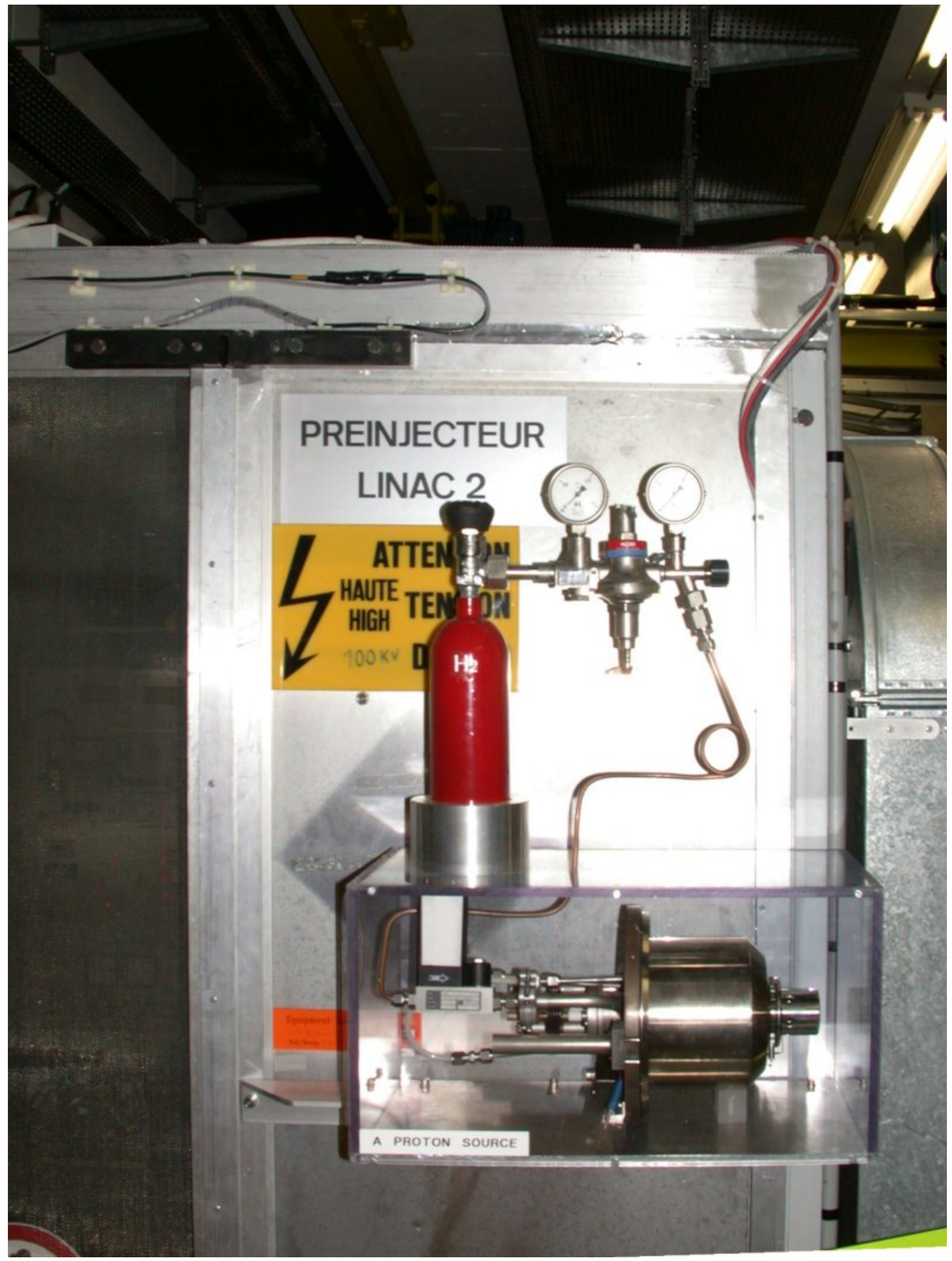
> LHC?

A single **proton**'s energy is 13 TeV

There are 10^9 protons in a *bunch* colliding at the LHC, concentrated in less than the diameter of a human hair!

[Powering up the LHC takes the equivalent of 300k homes]

Where do all the protons come



Some LHC parameters

Quantity	number
Circumference	26 659 m
Dipole operating temperature	1.9 K (-271.3°C)
Number of magnets	9593
Number of main dipoles	1232
Number of main quadrupoles	392
Number of RF cavities	8 per beam
Nominal energy, protons	7 TeV
Nominal energy, ions	2.76 TeV/u (*)
Peak magnetic dipole field	8.33 T
Min. distance between bunches	~7 m
Design luminosity	10^{34} cm^{-2} s^{-1}
No. of bunches per proton beam	2808
No. of protons per bunch (at start)	1.1 x 10^{11}
Number of turns per second	11 245
Number of collisions per second	600 million

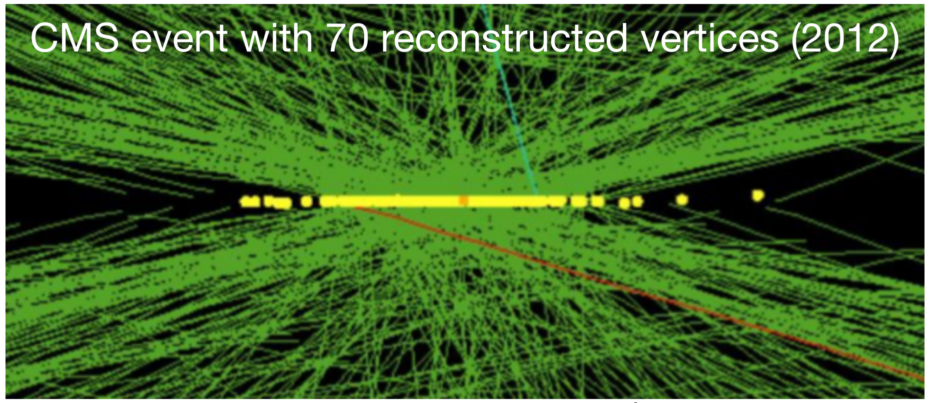
(*) Energy per nucleon

This means: *a lot* of LHC data

- Bunch crossing frequency: up to 30 MHz
  - A collision of bunches **every 25 nanoseconds**
- **Consequences:** Detectors need fast electronics, good “buffering”

- Up to 2808 bunches of protons per proton beam
  - Each of them with up to 10^{11} protons
    - Try it at home: it is easier to collider many grains of rice than 2 grains of rice, and protons are much smaller than rice…
  - Leading to **~1 billion proton-proton collisions per second**

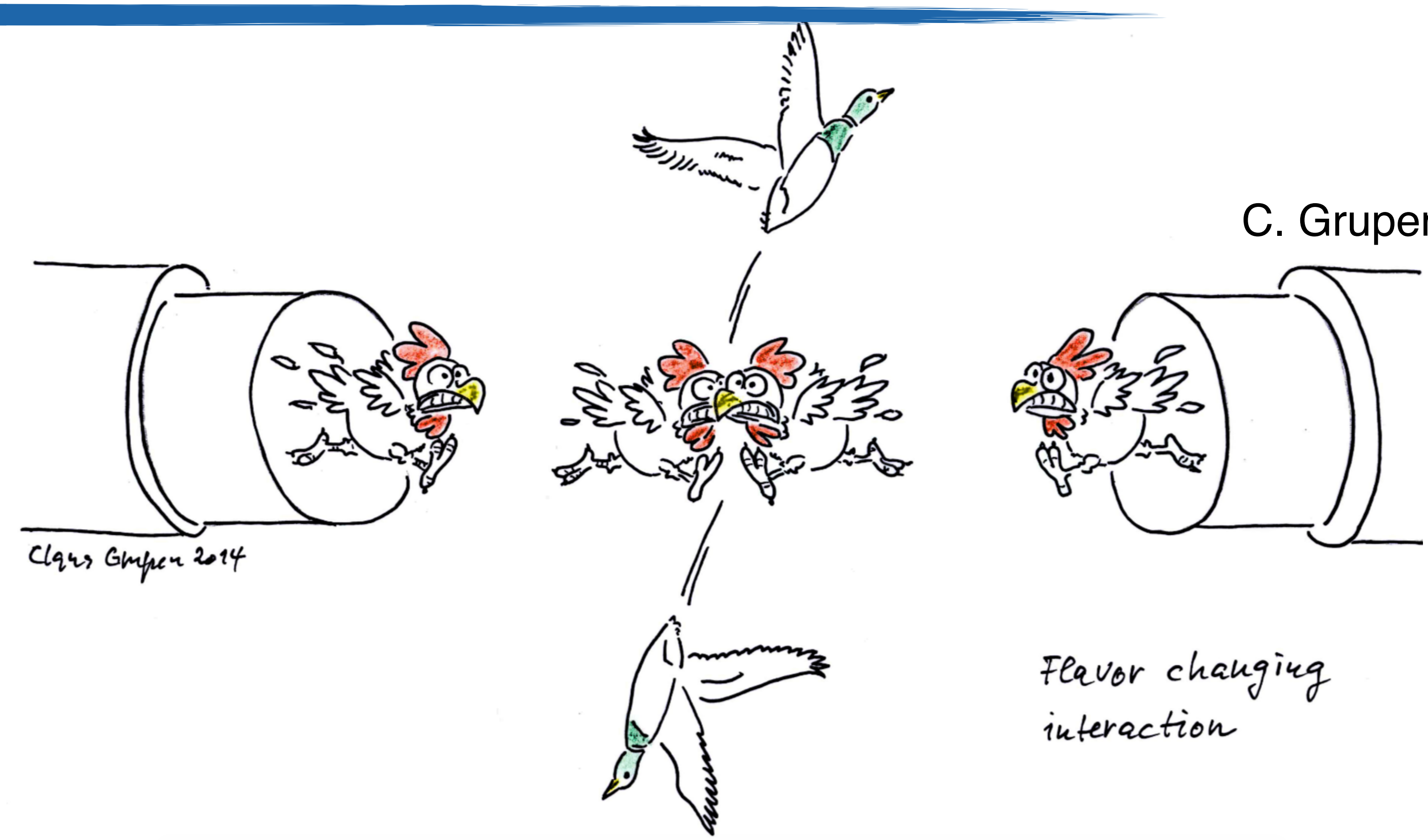
    ➔ many simultaneous collisions (pile-up): up to 70 now, will be up to 200 at HL-LHC
- **Consequences:** Detectors need to be radiation-hard, and we need ways to disentangle which physics process occurs in which individual collision



Large Hadron Collider, Collisions

Elastic collisions

C. Grupen

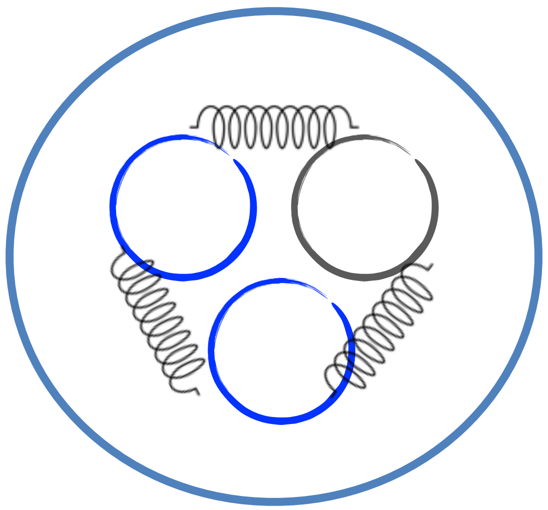


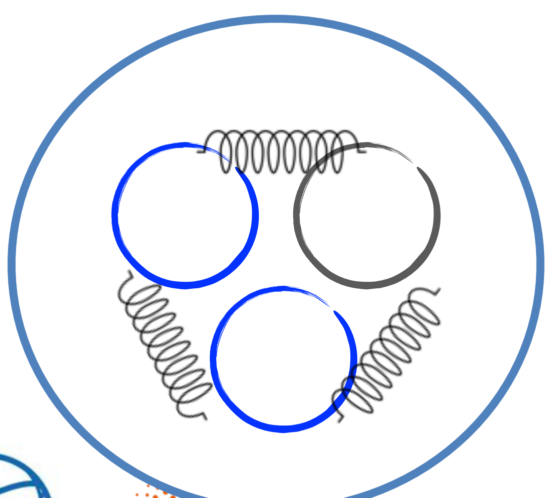
Inelastic collisions: the most interesting

Using $E=mc^2$ we can create new particles

Proton-proton collisions at the LHC

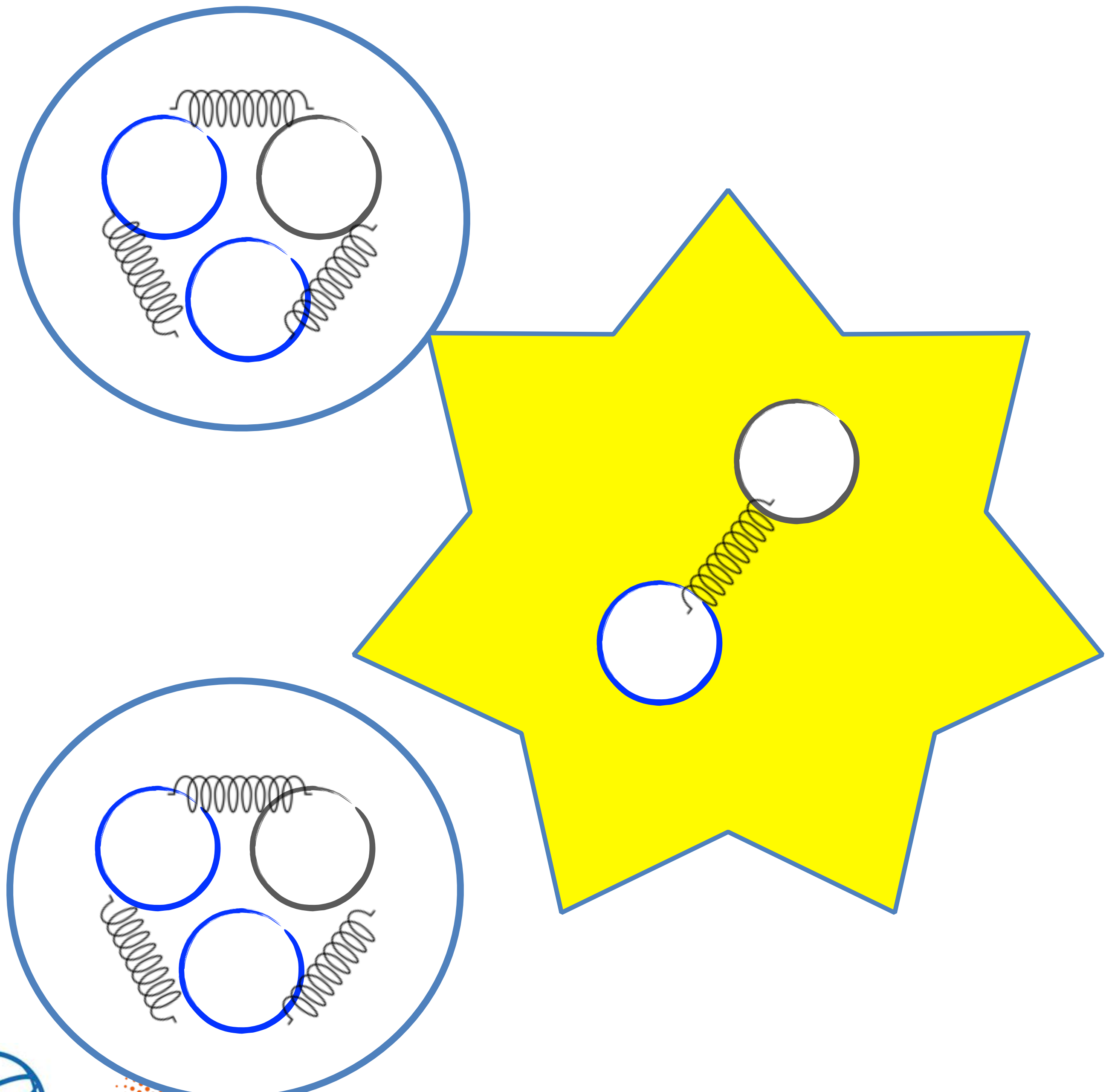
Protons are made of quarks and gluons





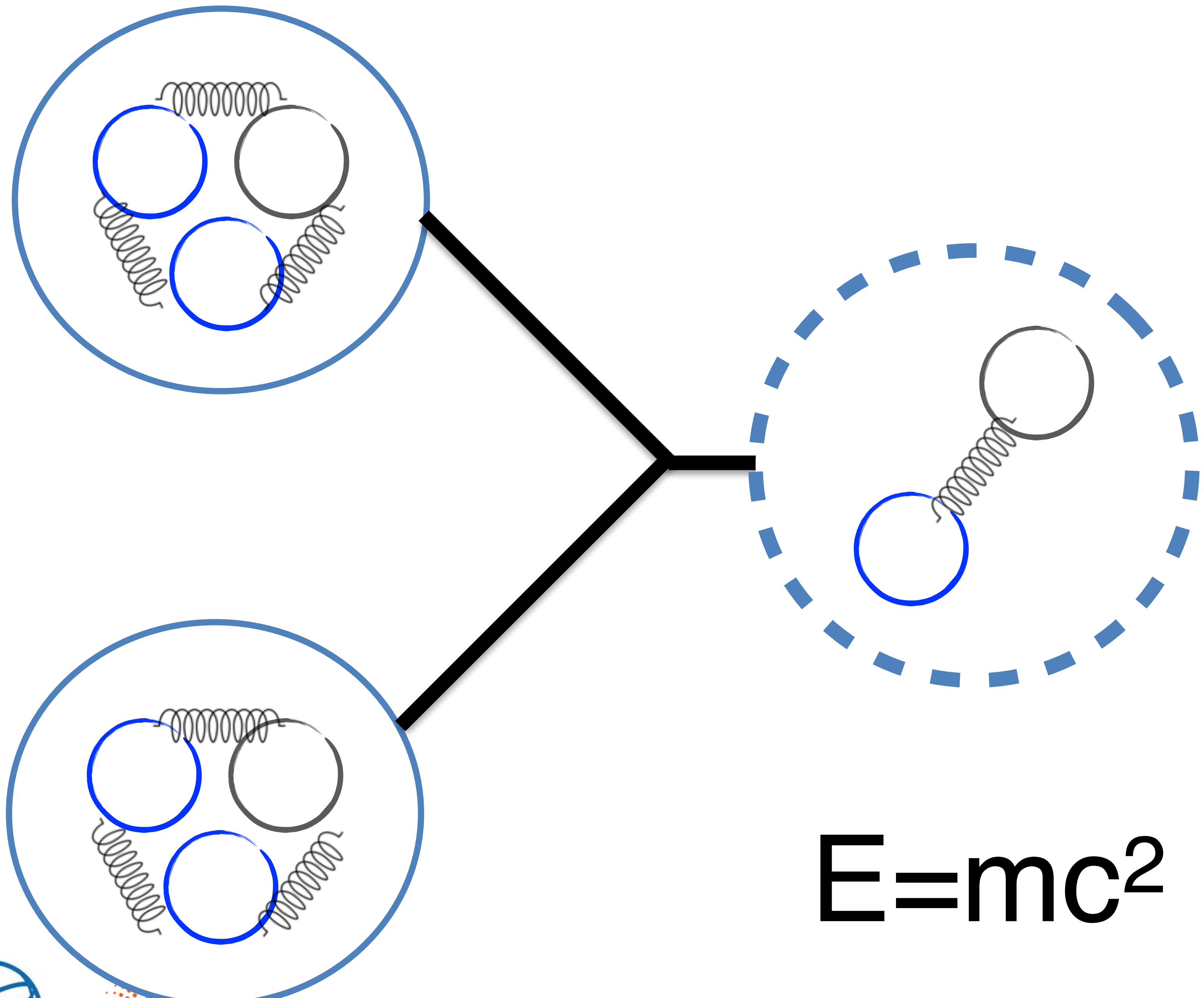
Proton-proton collisions at the LHC

…it is quarks and gluons colliding at the LHC…



Proton-proton collisions at the LHC

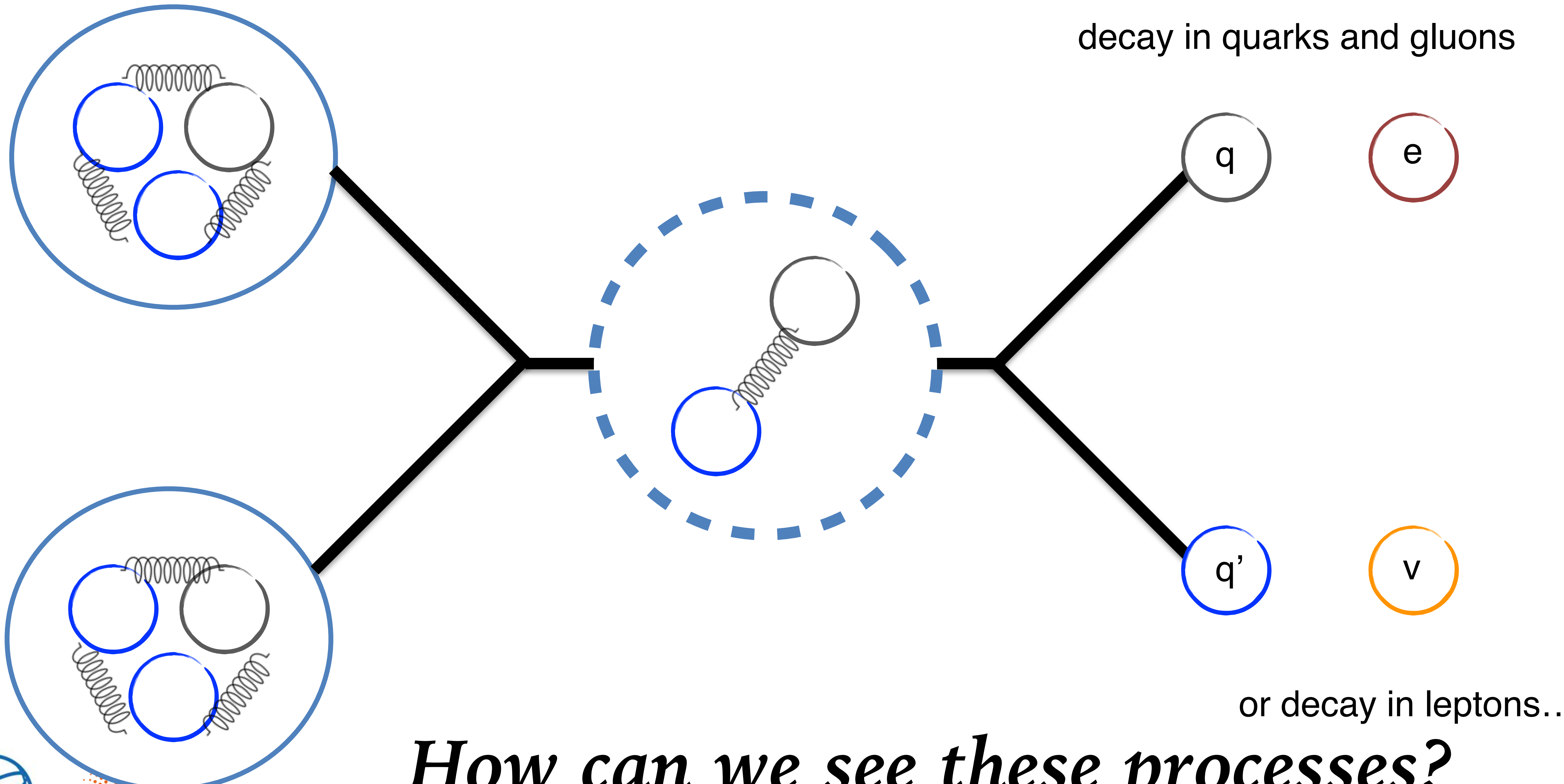
...and can create new particles...



$E=mc^2$

Proton-proton collisions at the LHC

…these particles are not stable and in a short time they decay!



How can we see these processes?

What do we want to measure?

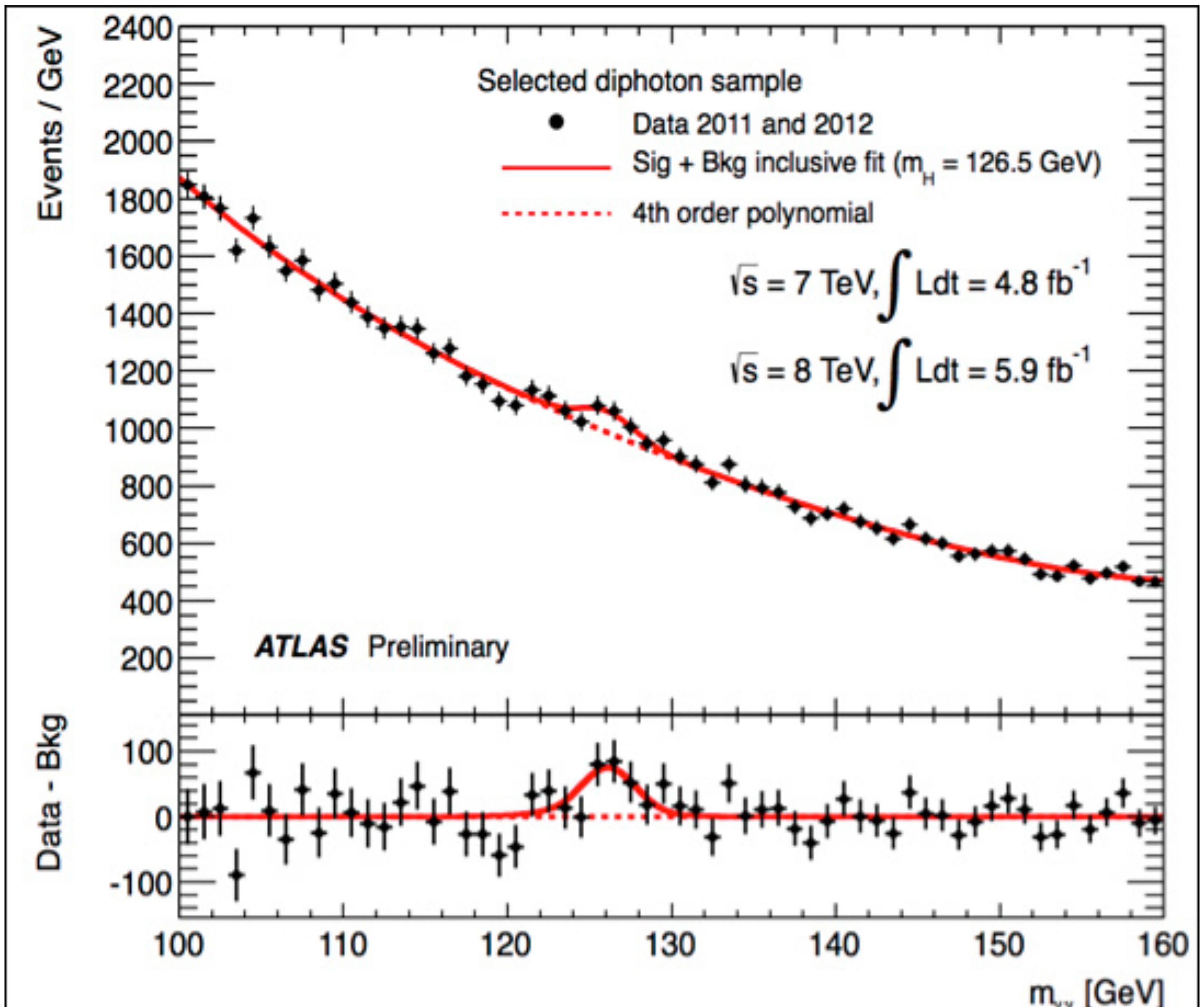
This already existed on the internet

At least:

- **Particle type**
  - Charge
  - Mass
- **Particle properties**
  - Position
  - Energy

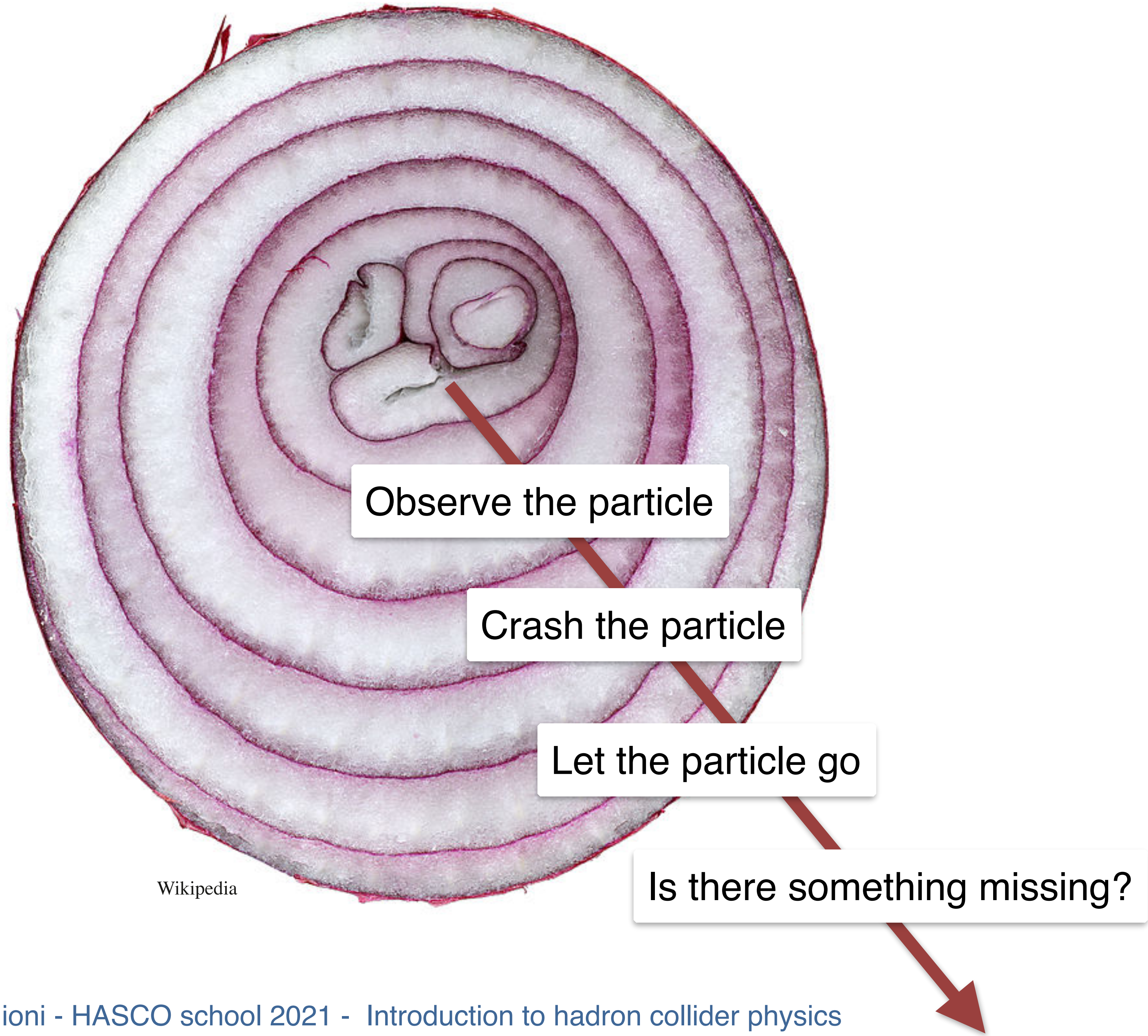
An example: the Higgs boson

What does it take to discover the Higgs decay in two photons?



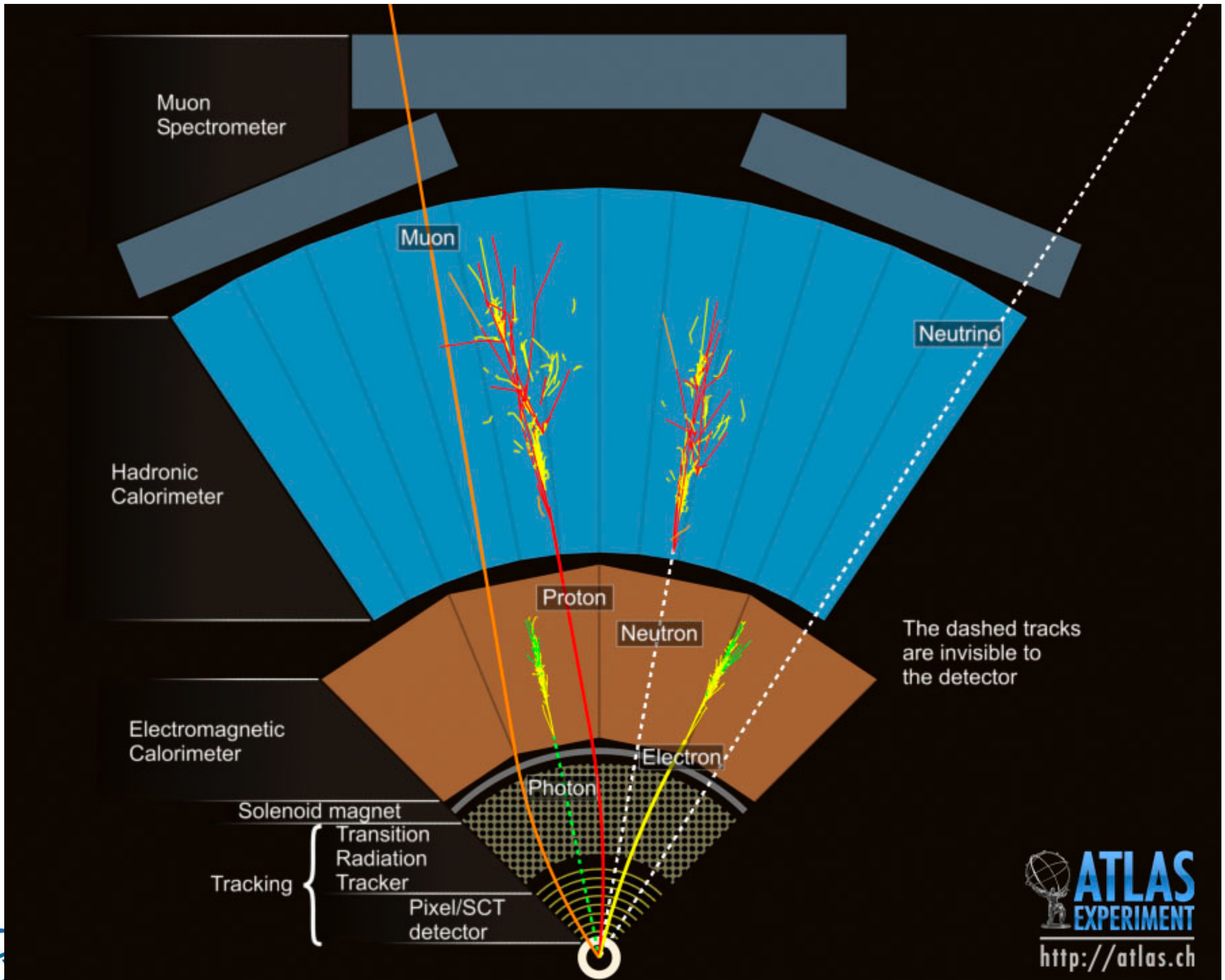
- Identify **photons**
- Measure **photon energy**

General purpose detectors at the LHC



Wikipedia

General purpose detectors: ATLAS



Is there something missing?
detect **missing transverse momentum**

Let the particle go: **muon spectrometer**

Crash the particle: **calorimeters**

Observe the particle: **tracking detectors**

General purpose detectors at the LHC

Compact **M**uon **S**olenoid

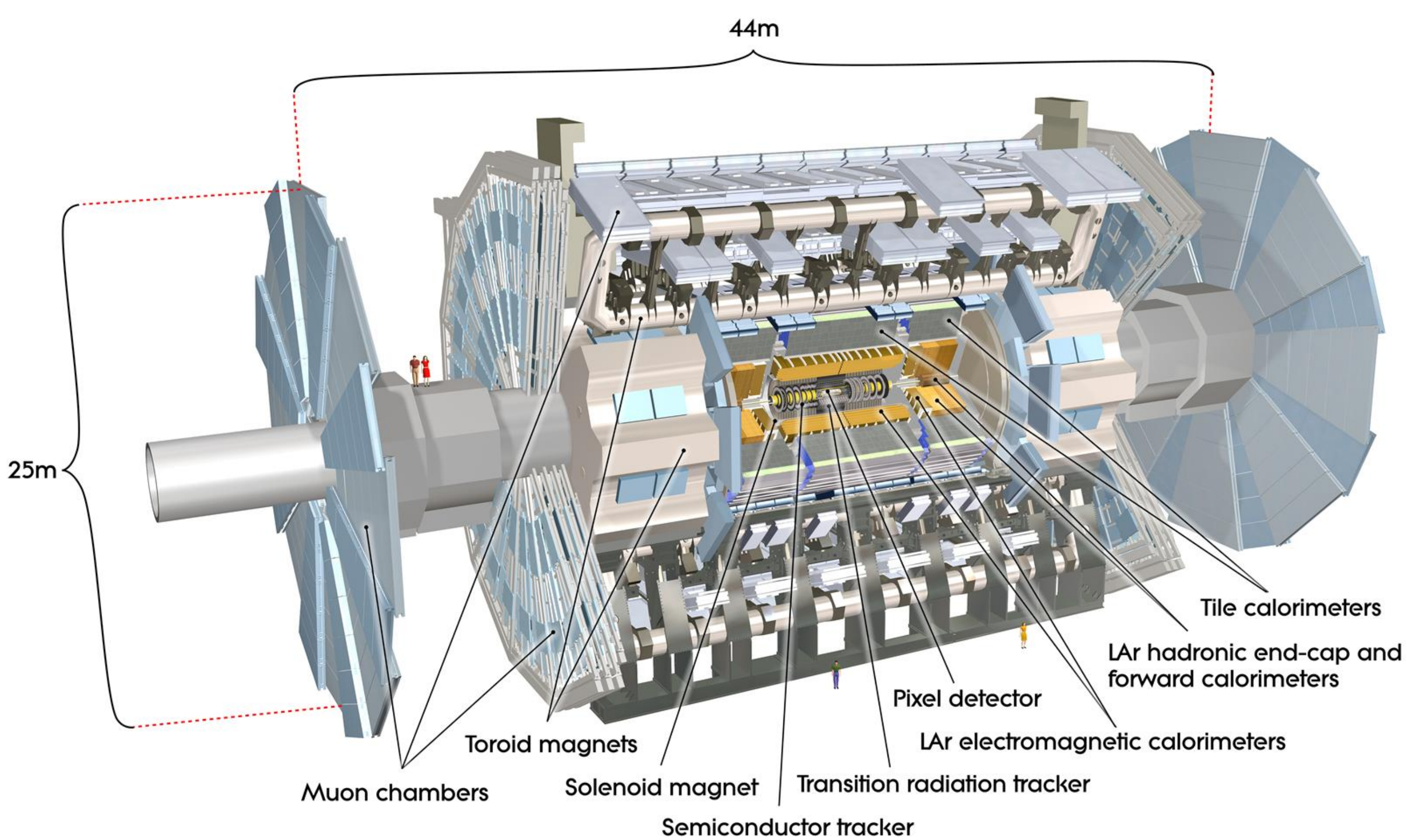
A Toroidal **L**HC **A**pparatu**S**

Peter Glazebrook from Newark with his record breaking giant onion
Source: thetimes.co.uk

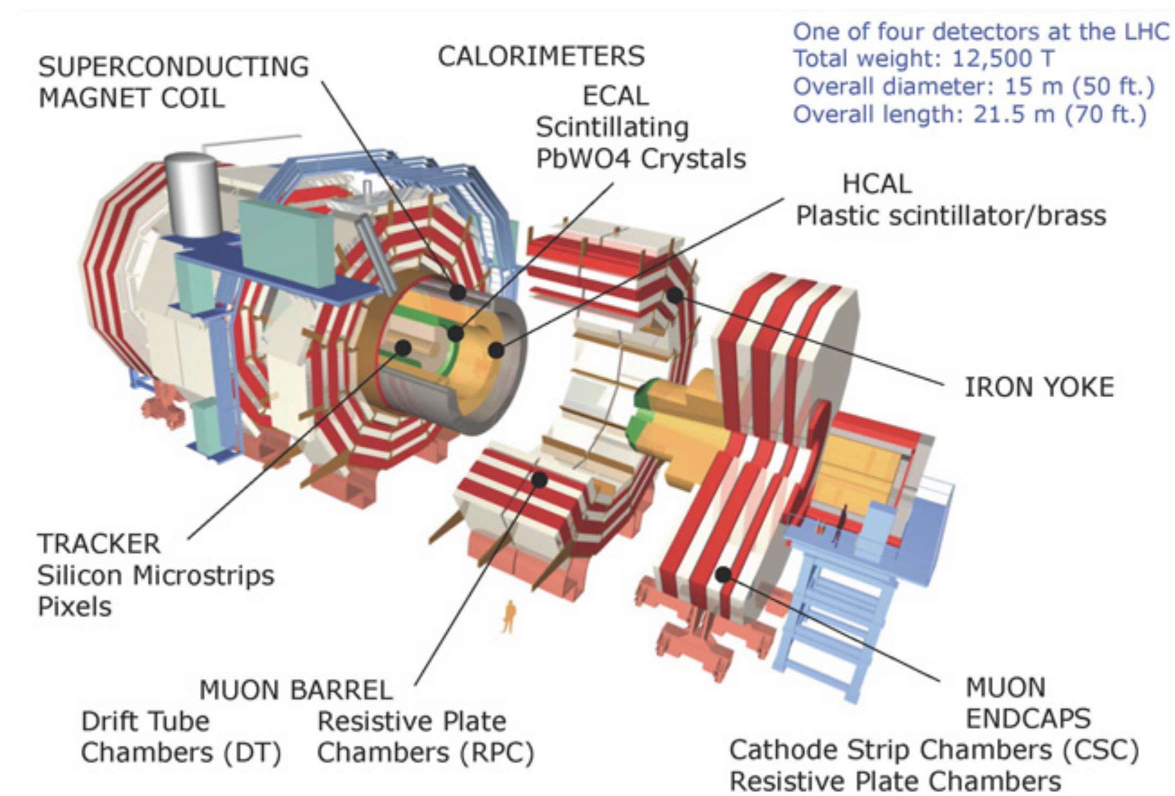
Wikipedia

General purpose detectors at the LHC

A **T**oroidal **L**HC **A**pparatu**S**



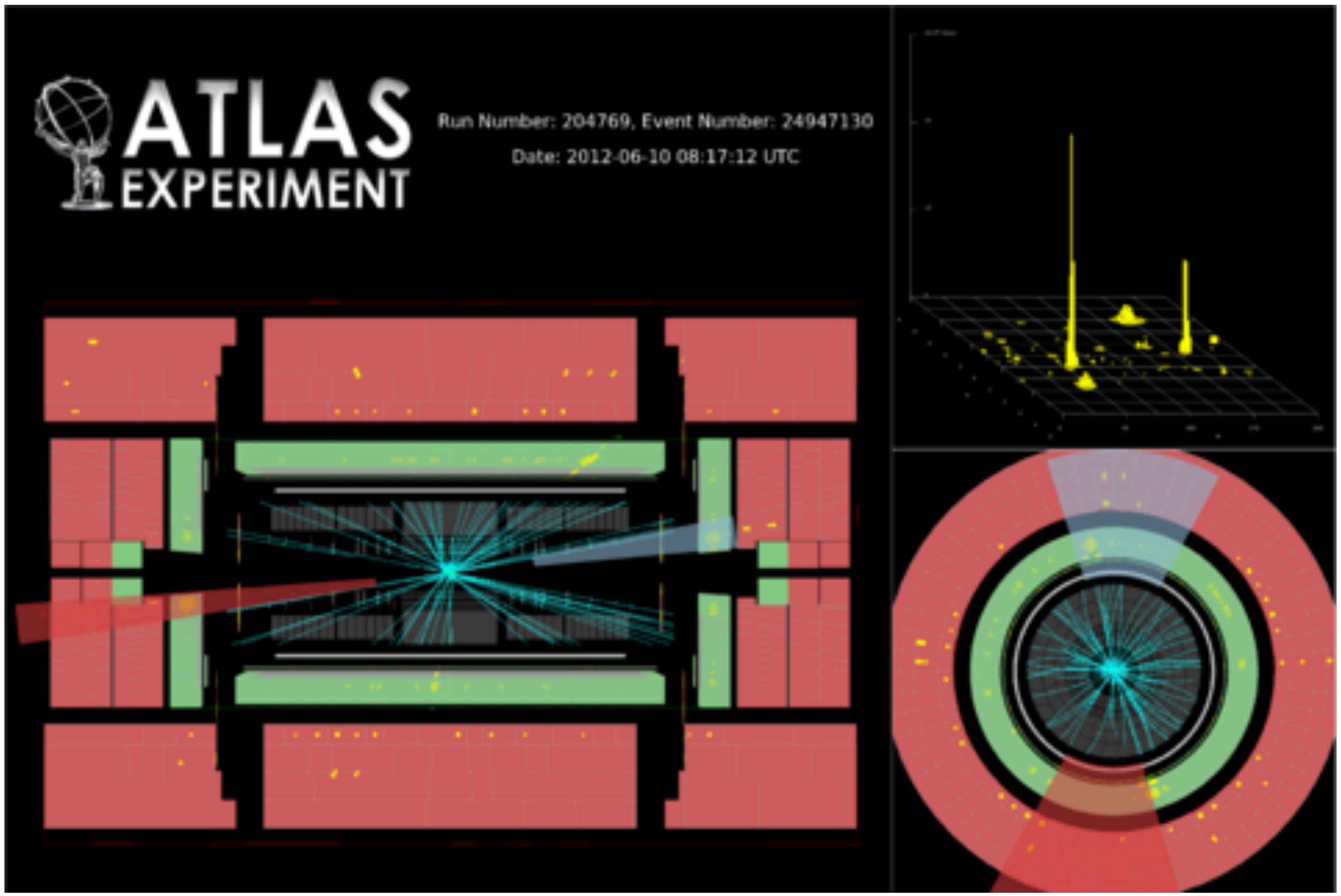
Compact **M**uon **S**olenoid

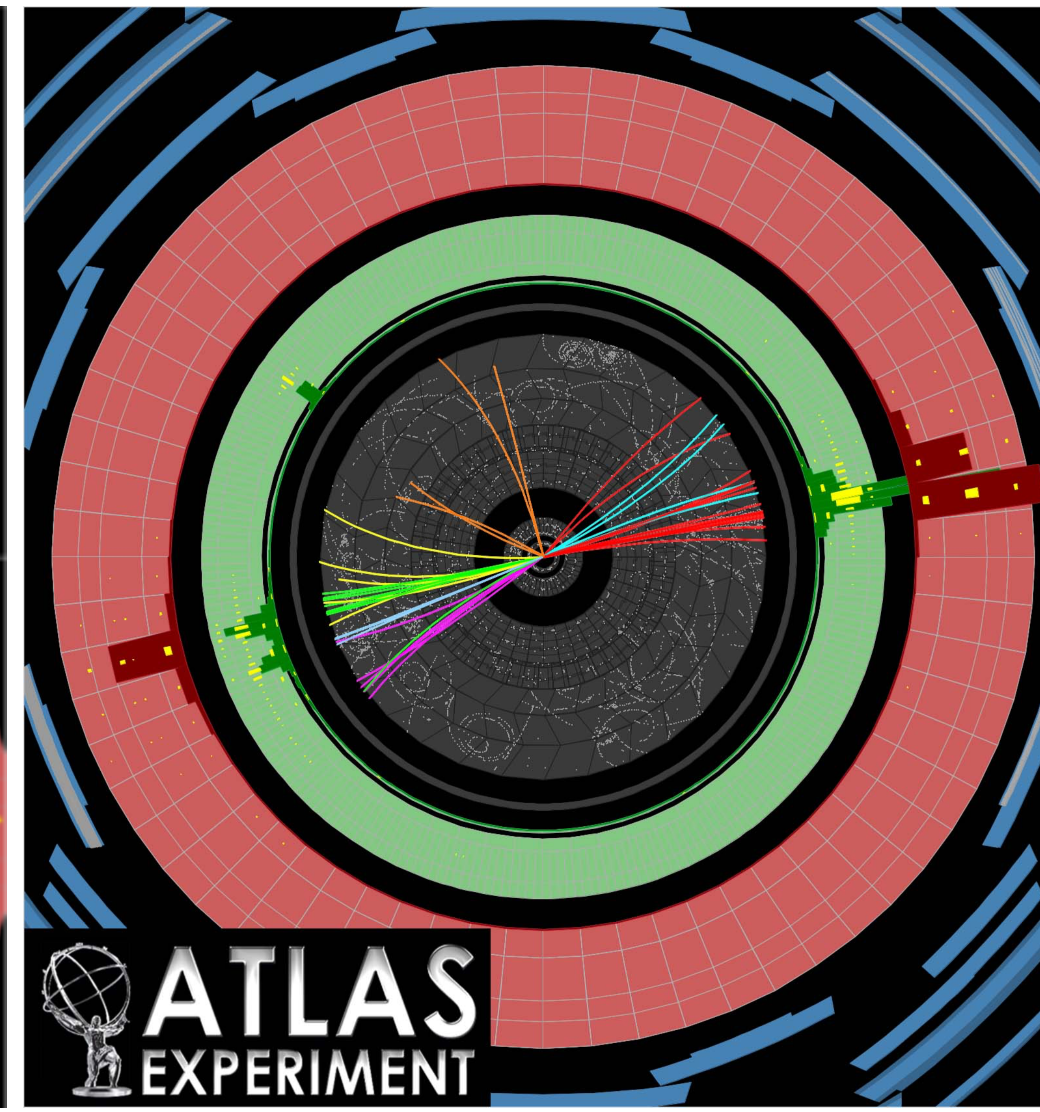


Covering ~all the solid angle around the collision

How to build ATLAS: https://www.youtube.com/watch?v=ckARmttkTS4
How to build CMS: https://www.youtube.com/watch?v=rcsYxWa_T2s

Seems easy…real diphoton (???) events





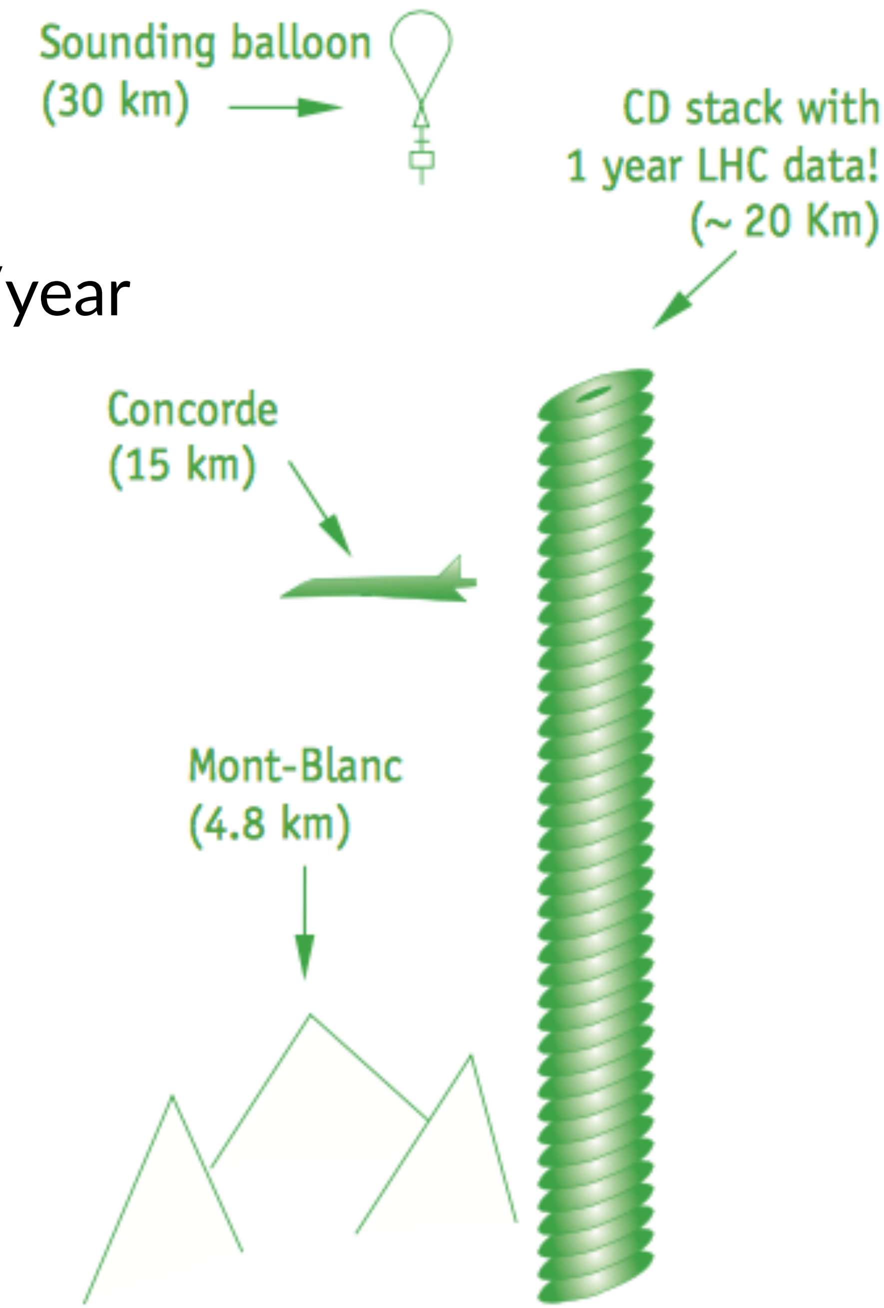
Data analysis crucial, innovative techniques needed (e.g. machine learning)

Seems easy…the need for a *trigger system*

- LHC: if everything was recorded…
  - up to 40 million collisions/second (MHz)
  - 1-1.5 MB/data per collision
  - 40 MHz * 1 MB = 40 TB/s
  - 40 TB/s * 10e+6 s/year (day & night) = 0.05 ZB/year

- Facebook:
  - 600 TB/day ~ 200 PB/year [Facebook 2014]
  - "There's always a bigger fish"

  [C. Tull's talk @ siRTDM18]



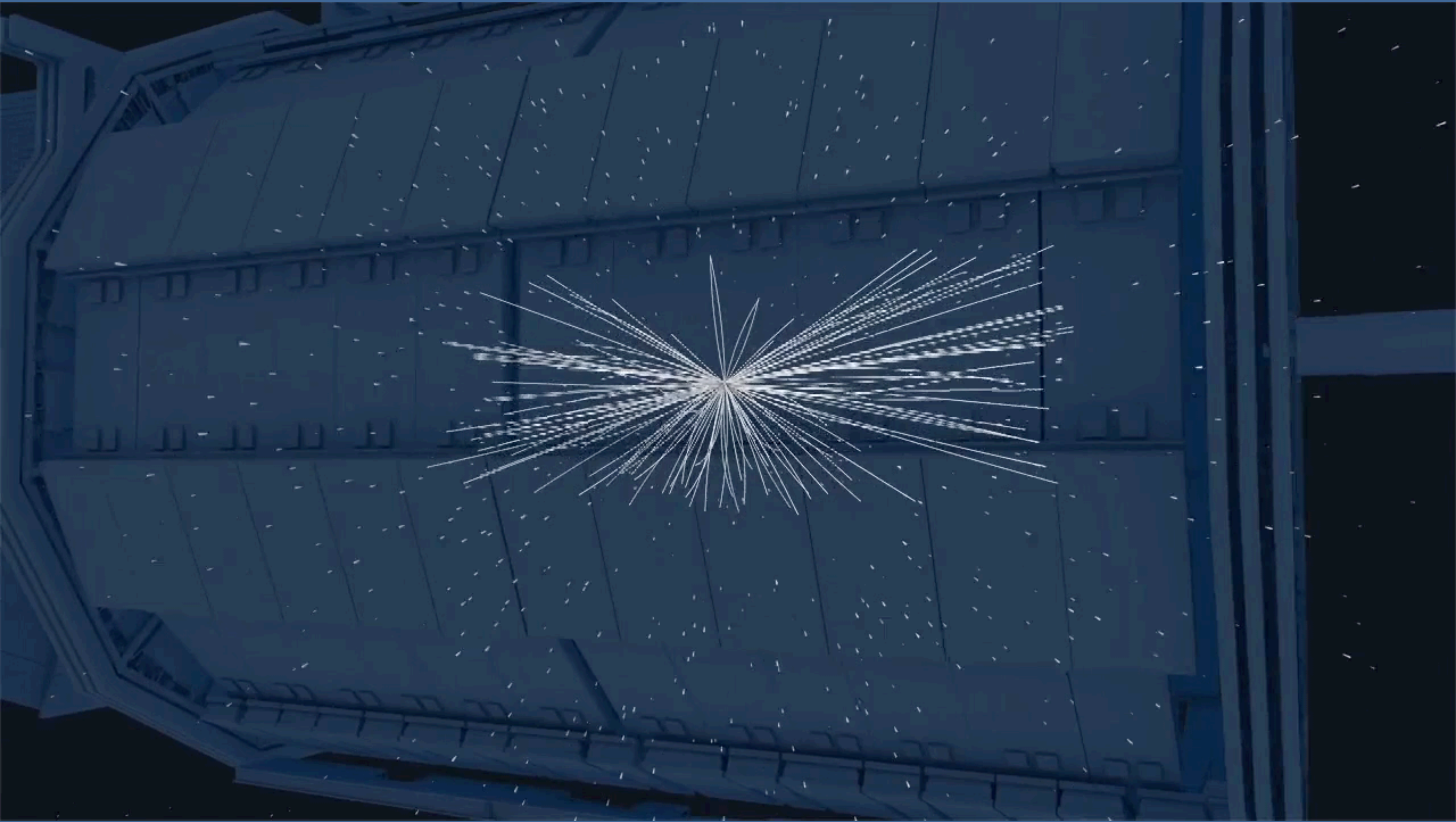
(**after** selecting interesting events)

LHC experiments need to:

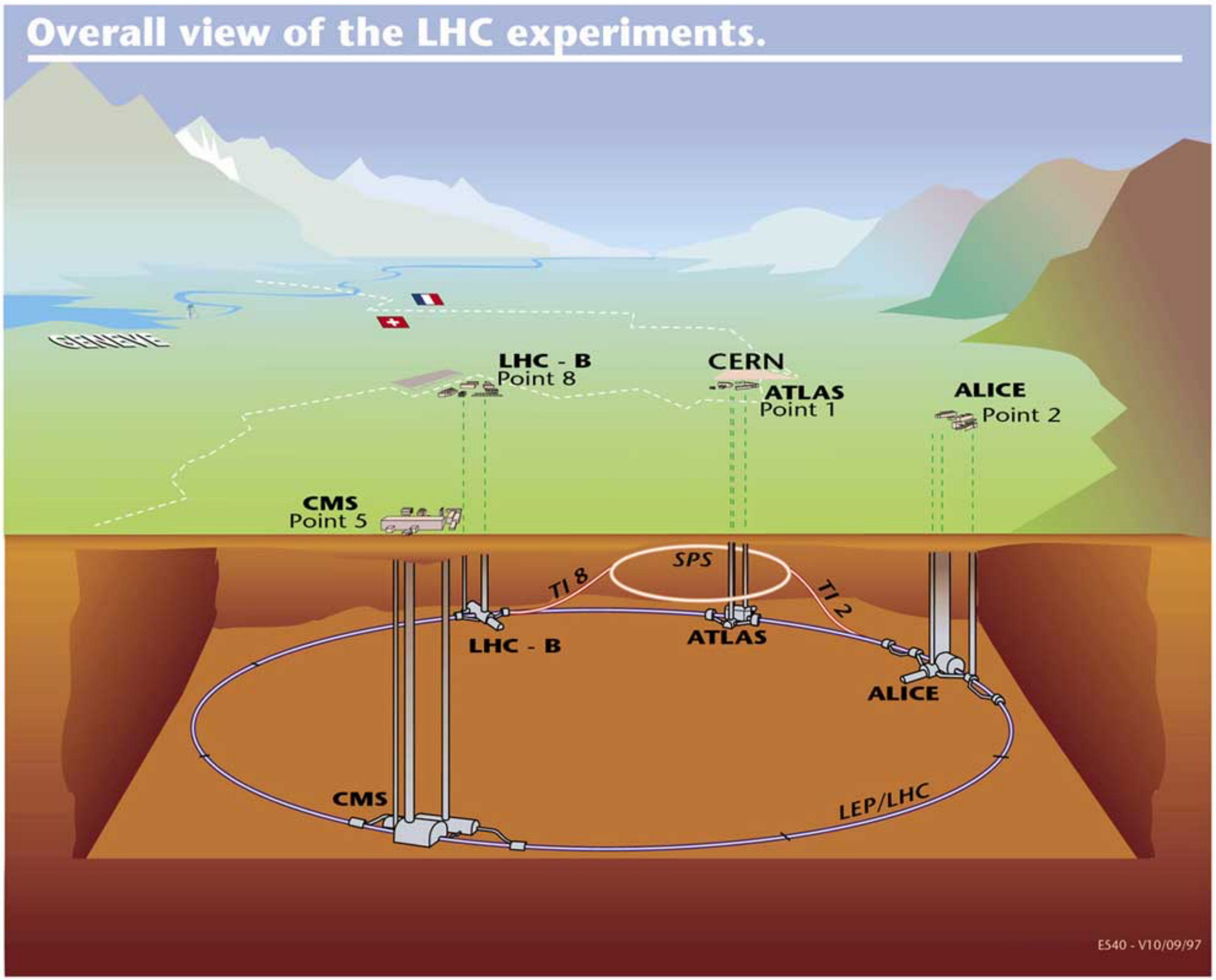
1. frequently **process** all data, fast (this includes calibrating and aligning the detectors!)
2. **select** only interesting events (problem: we don't yet know what **interesting** means)

Video: triggering and processing data

CERN-MOVIE-2013-041-001

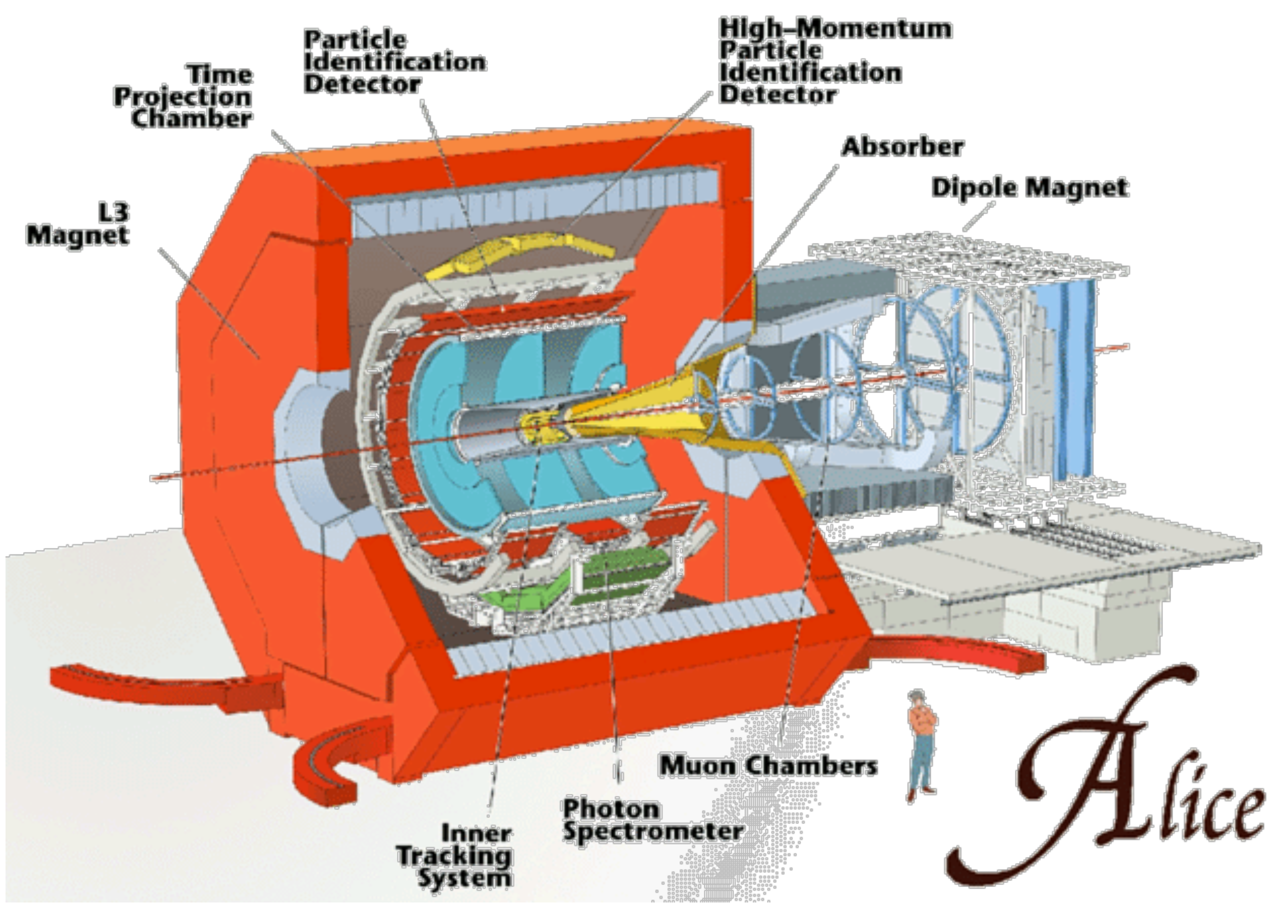


LHC experiments at CERN

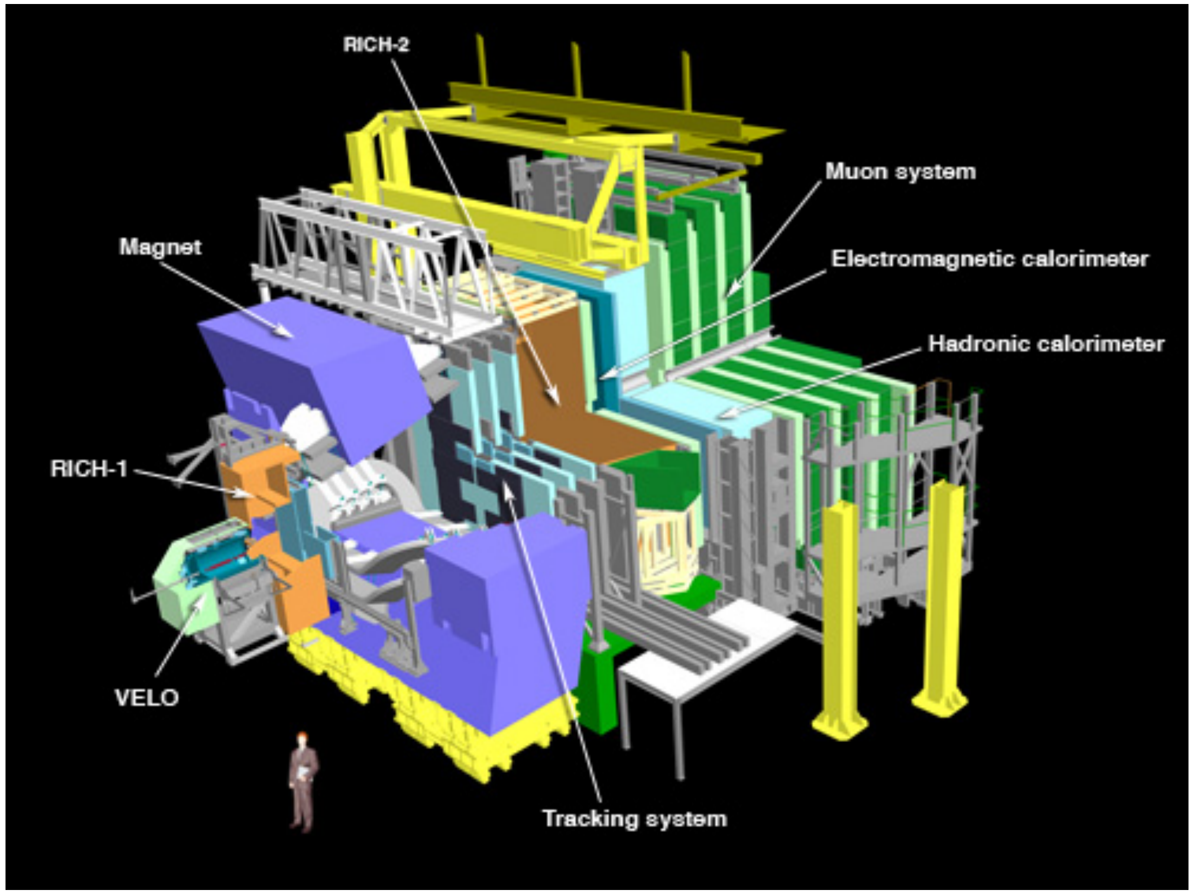


More specialized LHC detectors

A Large **I**on **C**ollider **E**xperiment



LHC beauty apparatus



The CERN laboratory in Geneva

Founded in 1954, 21 member states

Fabiola Gianotti,
Director General

The ATLAS Collaboration

Only 1/10 of the collaboration is on this picture

38 countries, ~180 universities,

>1000 students!enti

An ATLAS scientific paper


Physics Letters B

Search for new phenomena in dijet mass and angular distributions from pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

ATLAS Collaboration

The author-list of an ATLAS paper

Open-access papers!

Search for new phenomena in dijet mass and angular distributions from *pp* collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

ATLAS Collaboration*,

Open Access funded by SCOAP³ - Sponsoring Consortium for Open Access Publishing in Particle Physics

http://www.sciencedirect.com/science/article/pii/S0370269316000447

Particle physics research (& data & software) wants to be **collaborative, open and *open-source***

A few words from Fabiola Gianotti

https://www.youtube.com/watch?v=UiSd8QXxrAE

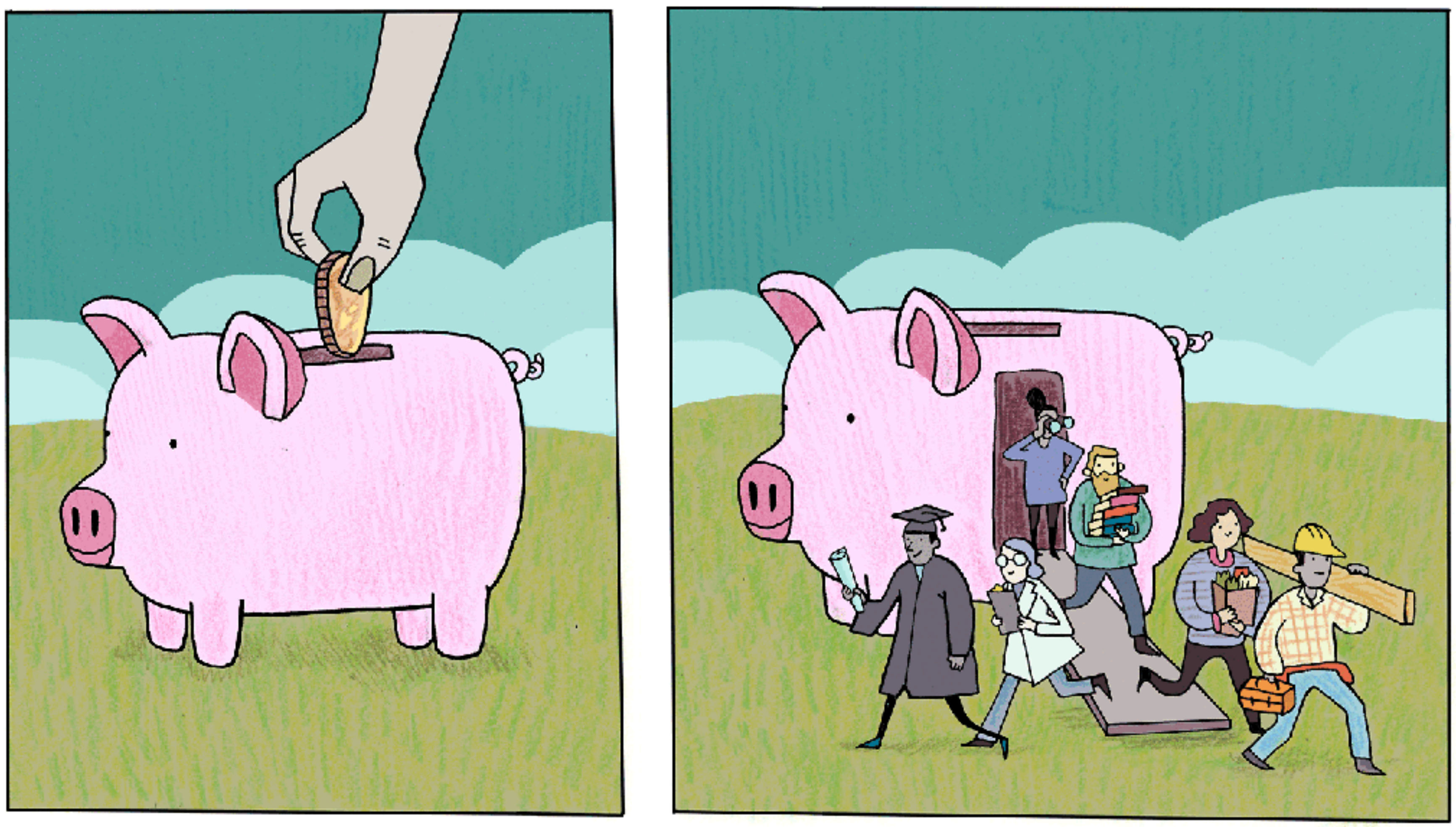
https://home.cern/about/what-we-do/our-impact

See also: Outreach without borders, CERN news

The main ATLAS person for this is UK: Kate Shaw, Sussex

What's the value of science?

Asking really big questions and designing tools to answer them has many repercussions on society and its GDP



OECD report

In medicine: https://www.nigms.nih.gov/education/fact-sheets/Pages/curiosity-creates-cures.aspx
In high energy physics: https://www.symmetrymagazine.org/article/the-value-of-basic-research
Knowledge transfer at CERN: https://www.sciencedirect.com/science/article/pii/S0040162516000639 (https://kt.cern)

5-10’ for a break (or questions)