

# 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

# 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

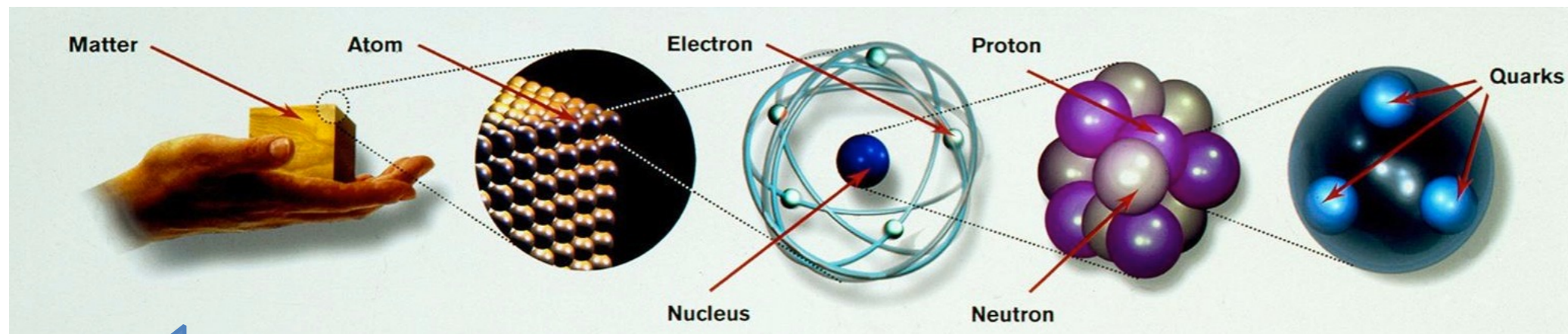
*10' Q&A + break*

## \* 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

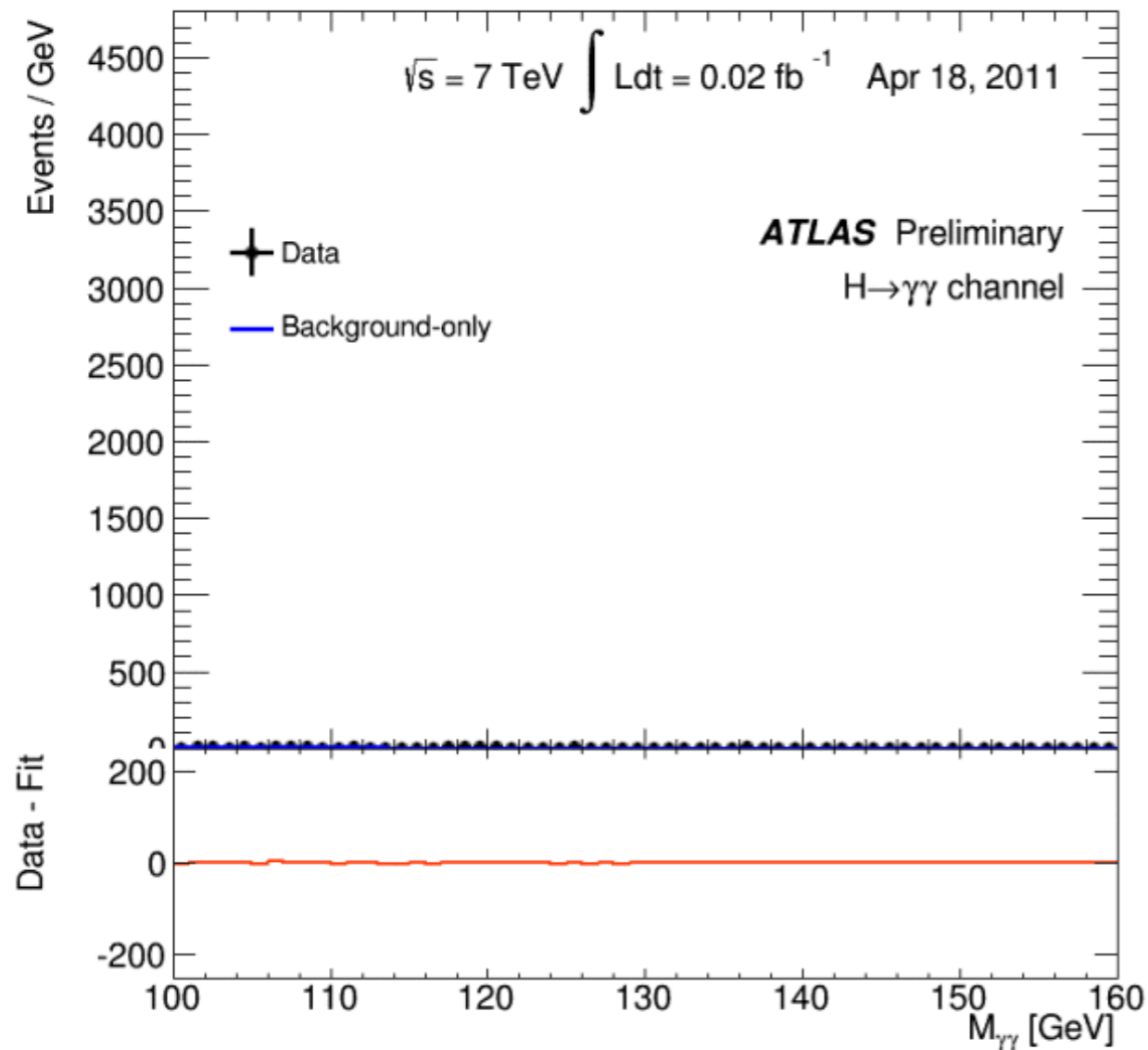
Energy necessary to create and study the smallest components of matter

Smaller

Larger

## Where do we find this energy?

# What does it take for a high energy physics discovery?

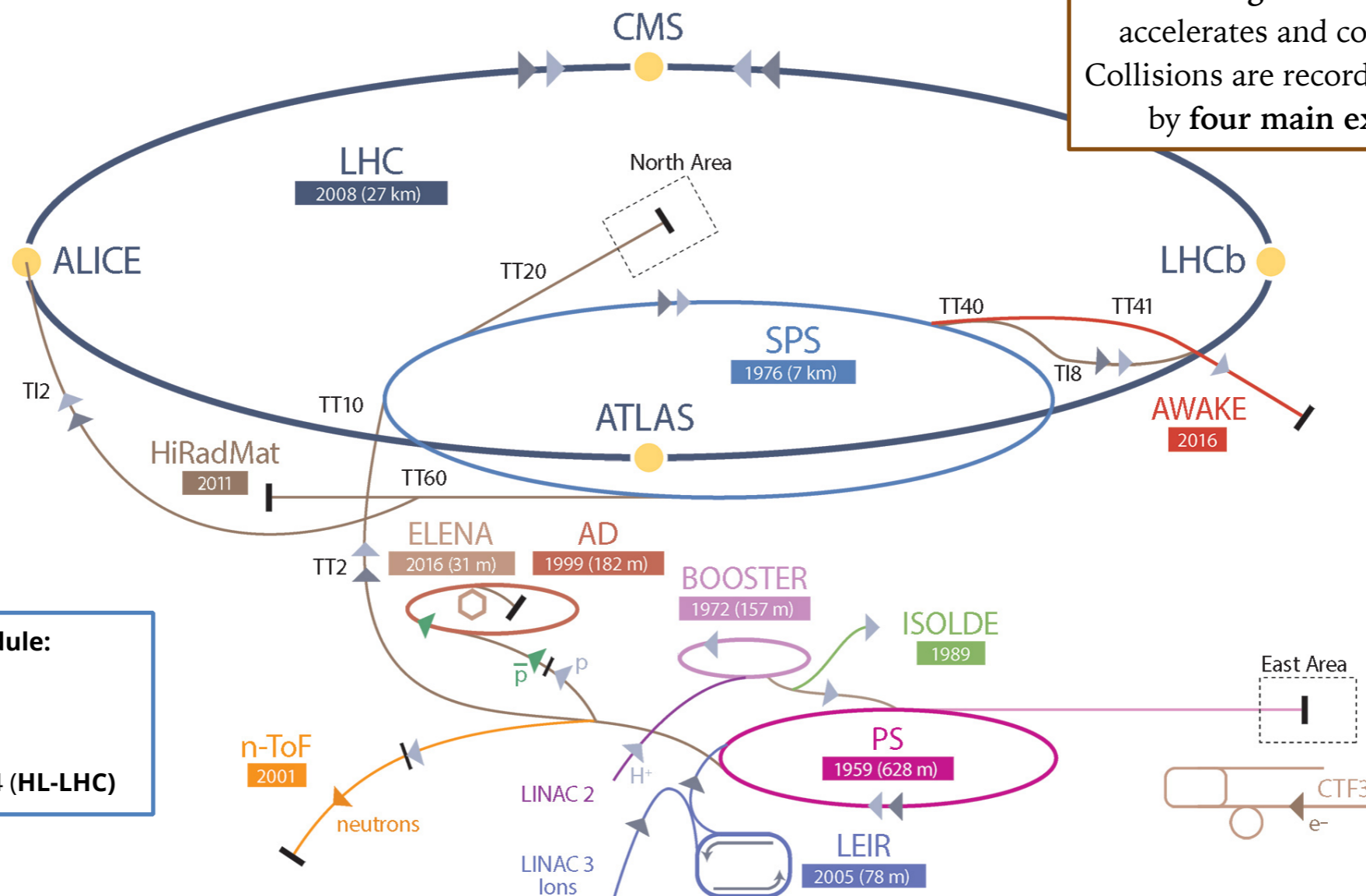


- A particle **collider** (LHC)
  - Many collisions/second
  - Only one in  $10^{13}$  may contain an interesting event (e.g. Higgs boson)
- **Detectors** able to select and precisely measure particles (photons)
  - ATLAS, CMS (LHCb, ALICE)
  - Millions of read-out channels
- Many **teams** that:
  -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



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

CERN's Accelerator Complex



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

**LHC collisions schedule:**

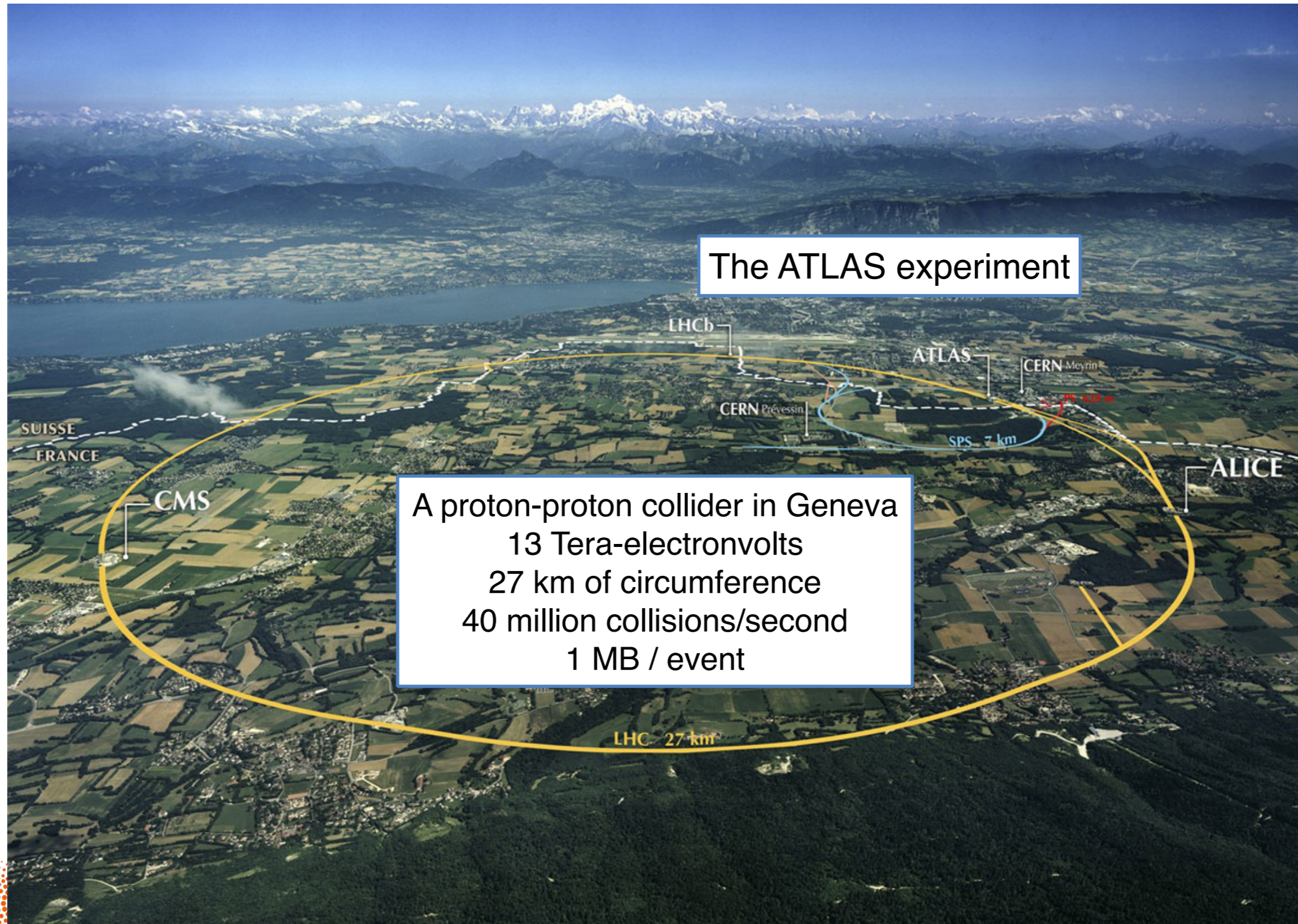
- \* 2010-2012: Run-1
- \* 2015-2018: Run-2
- \* 2022: beginning of Run-3
- \* ~2027: beginning of Run-4 (HL-LHC)

▶ p (proton)    ▶ ion    ▶ neutrons    ▶  $\bar{p}$  (antiproton)    ▶ electron    ▶  $\leftrightarrow$  proton/antiproton conversion



# LHC: the biggest human-made discovery machine

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

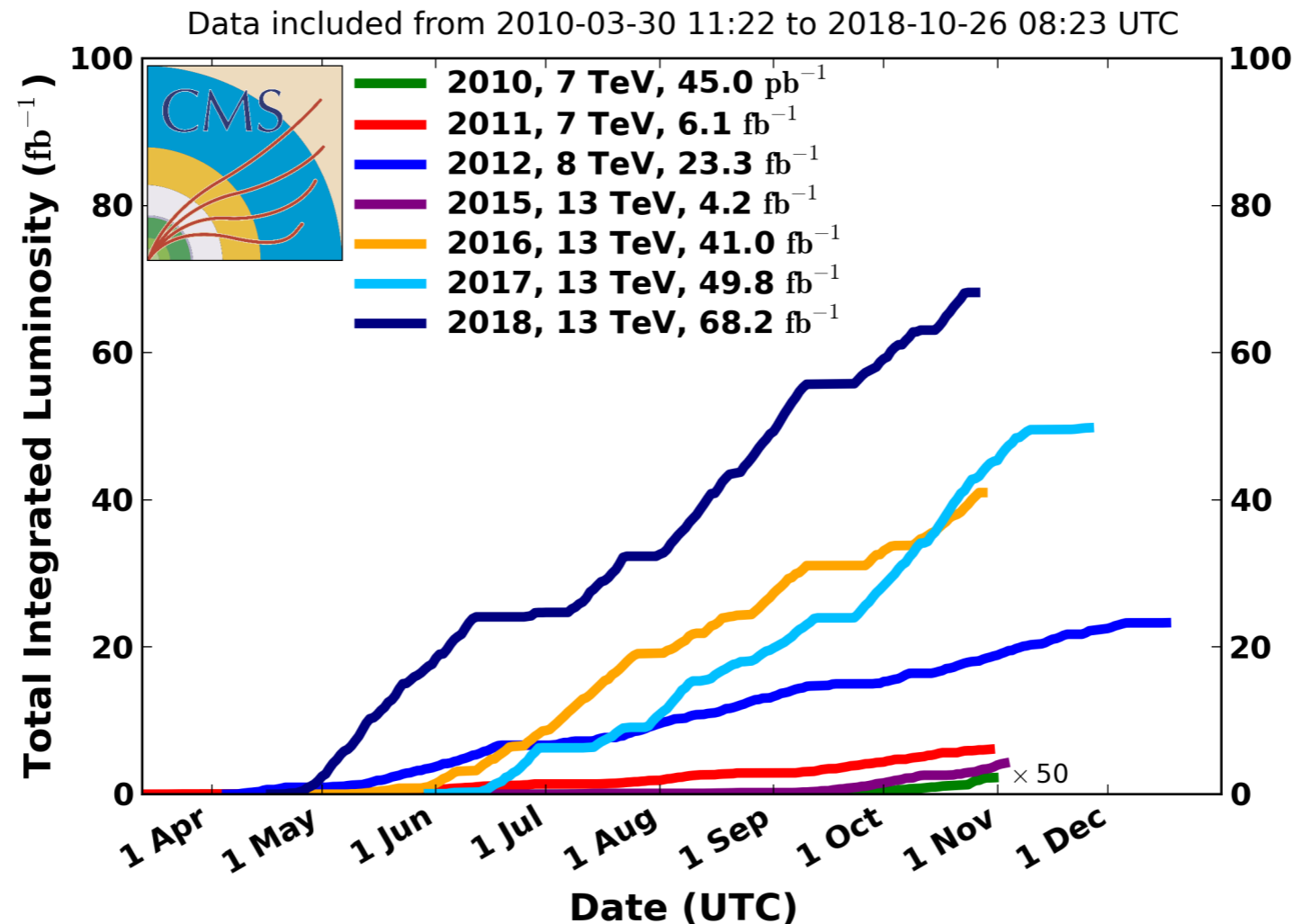


# The Large Hadron Collider



# What does it take for a high energy physics discovery?

## CMS Integrated Luminosity Delivered, pp



$\sqrt{s}$  = Centre of mass energy

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

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

More data  $\Leftrightarrow$  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



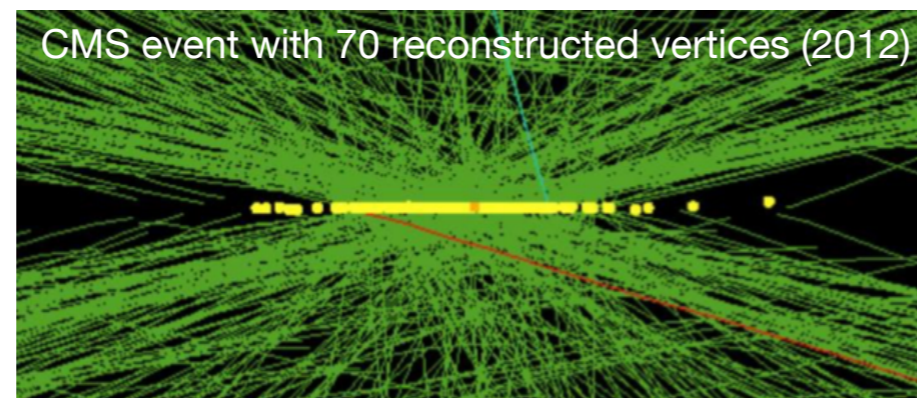
# Some LHC parameters

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	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
No. of bunches per proton beam	2808
No. of protons per bunch (at start)	$1.1 \times 10^{11}$
Number of turns per second	11 245
Number of collisions per second	600 million

(\*) Energy per nucleon

# This means: *a lot* of LHC data

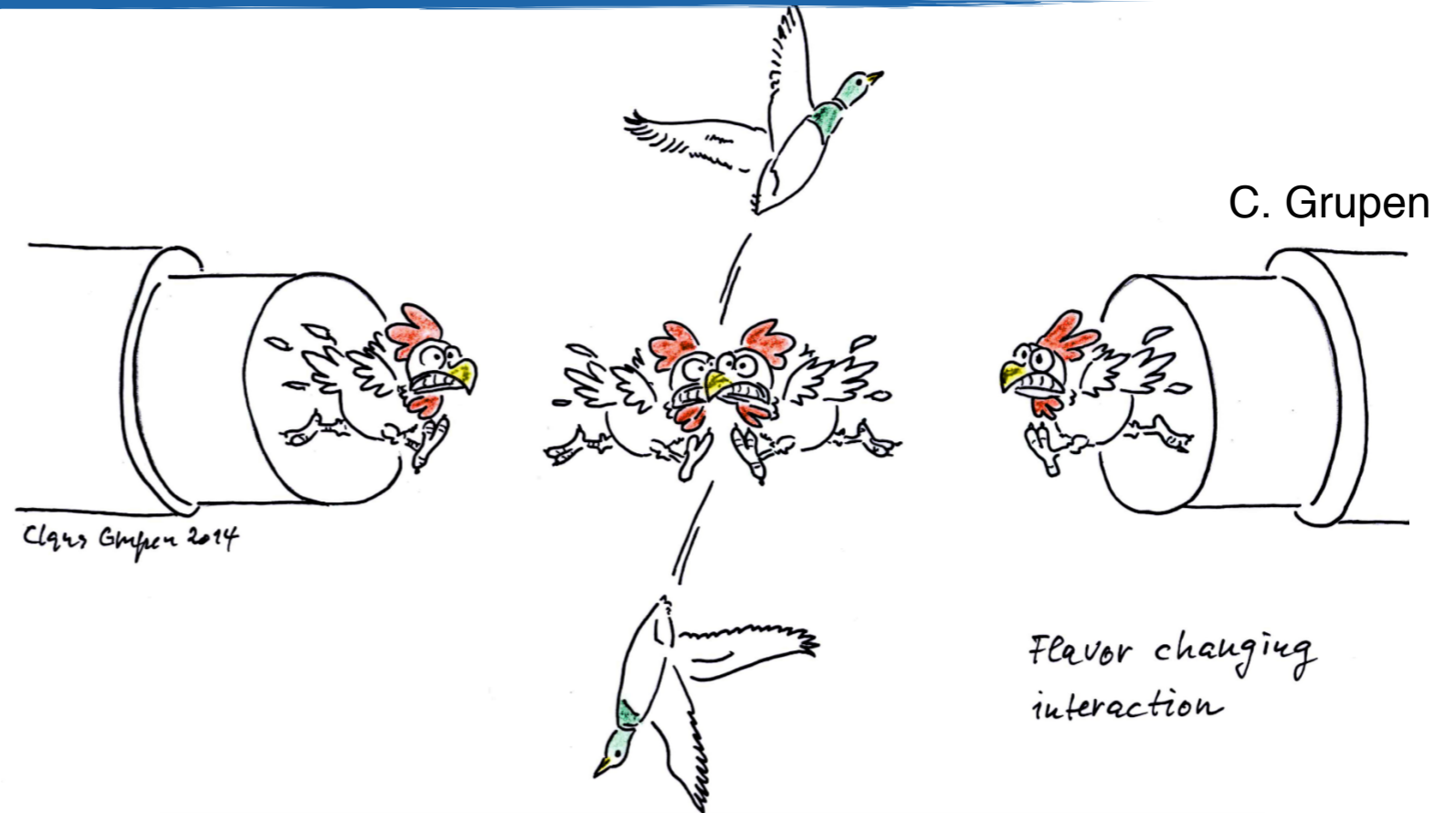
- Bunch crossing frequency: up to 30 MHz
  - A collision of bunches **every 25 nanoseconds**
- **Consequences:** Detectors need fast electronics, good “buffering”
- Up to 2808 bunches of protons per proton beam
  - Each of them with up to  $10^{11}$  protons
    - Try it at home: it is easier to collider 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

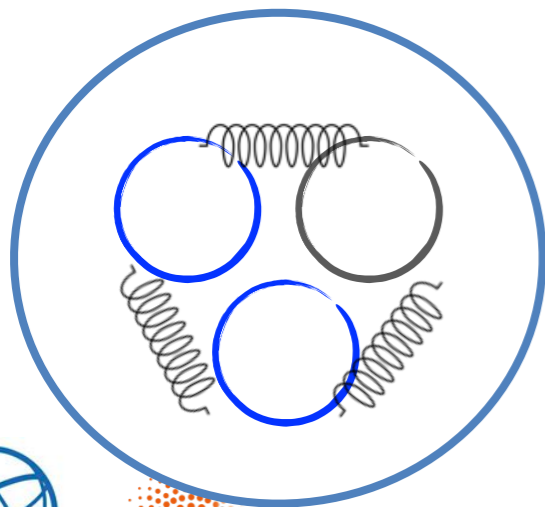
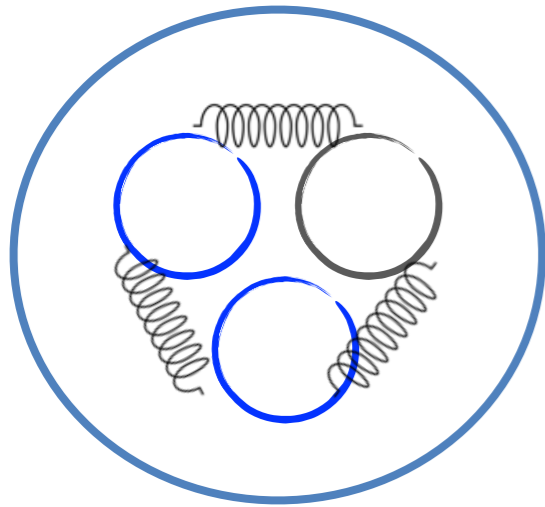


Inelastic collisions: the most interesting

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

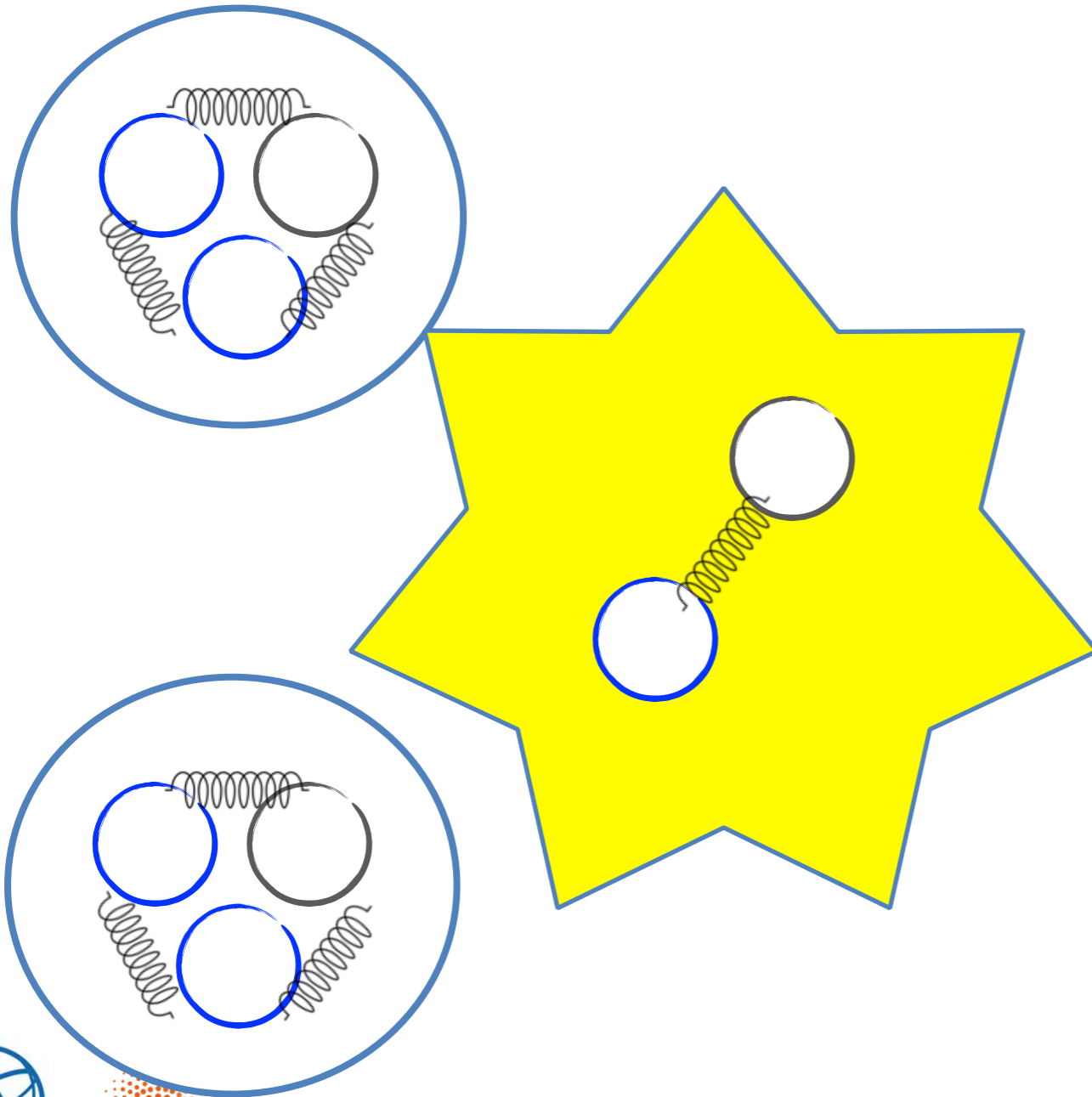
# Proton-proton collisions at the LHC

Protons are made of **quarks and gluons**



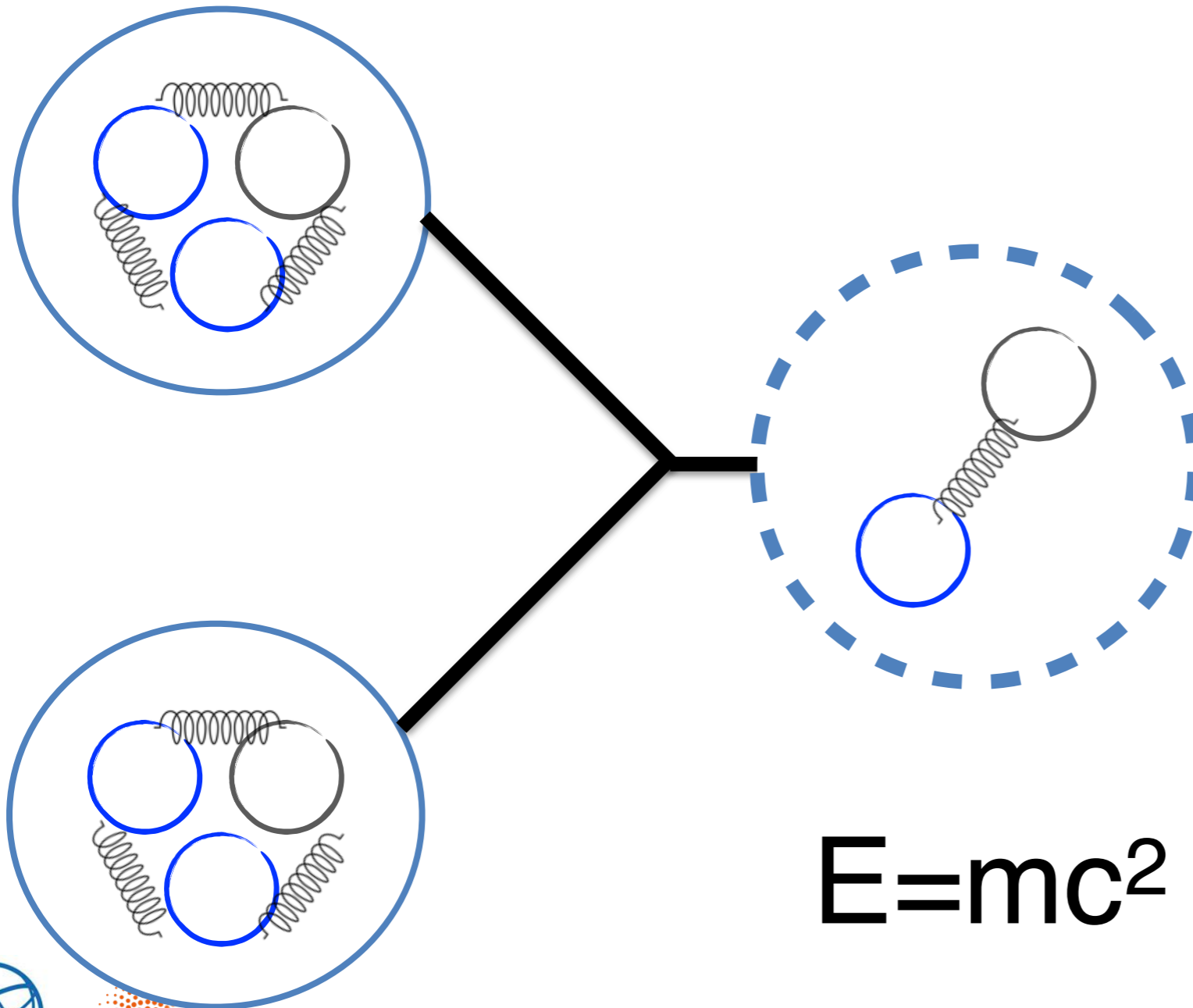
# Proton-proton collisions at the LHC

...it is **quarks** and gluons colliding at the LHC...



# Proton-proton collisions at the LHC

...and can create new particles...

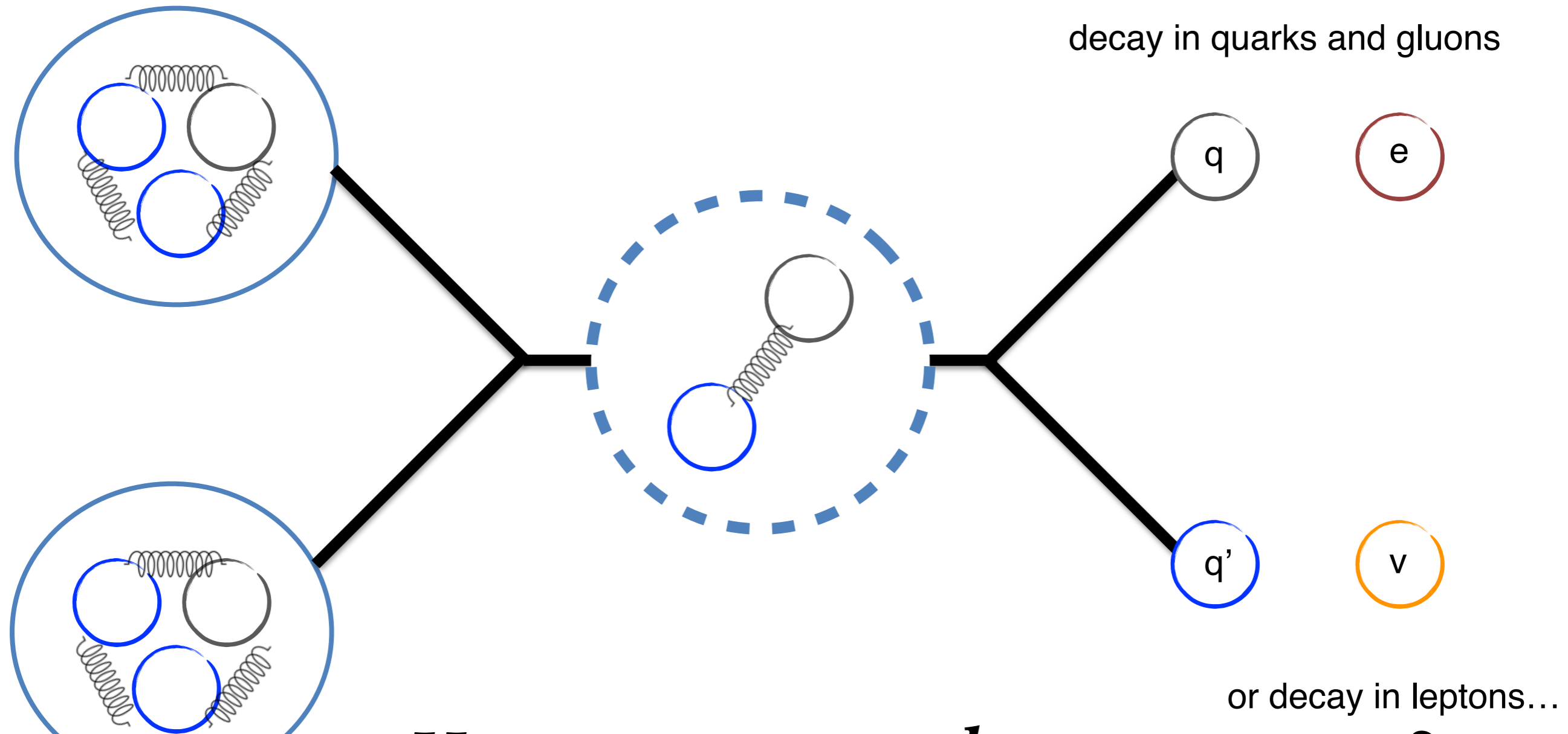


$$E=mc^2$$



# 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?



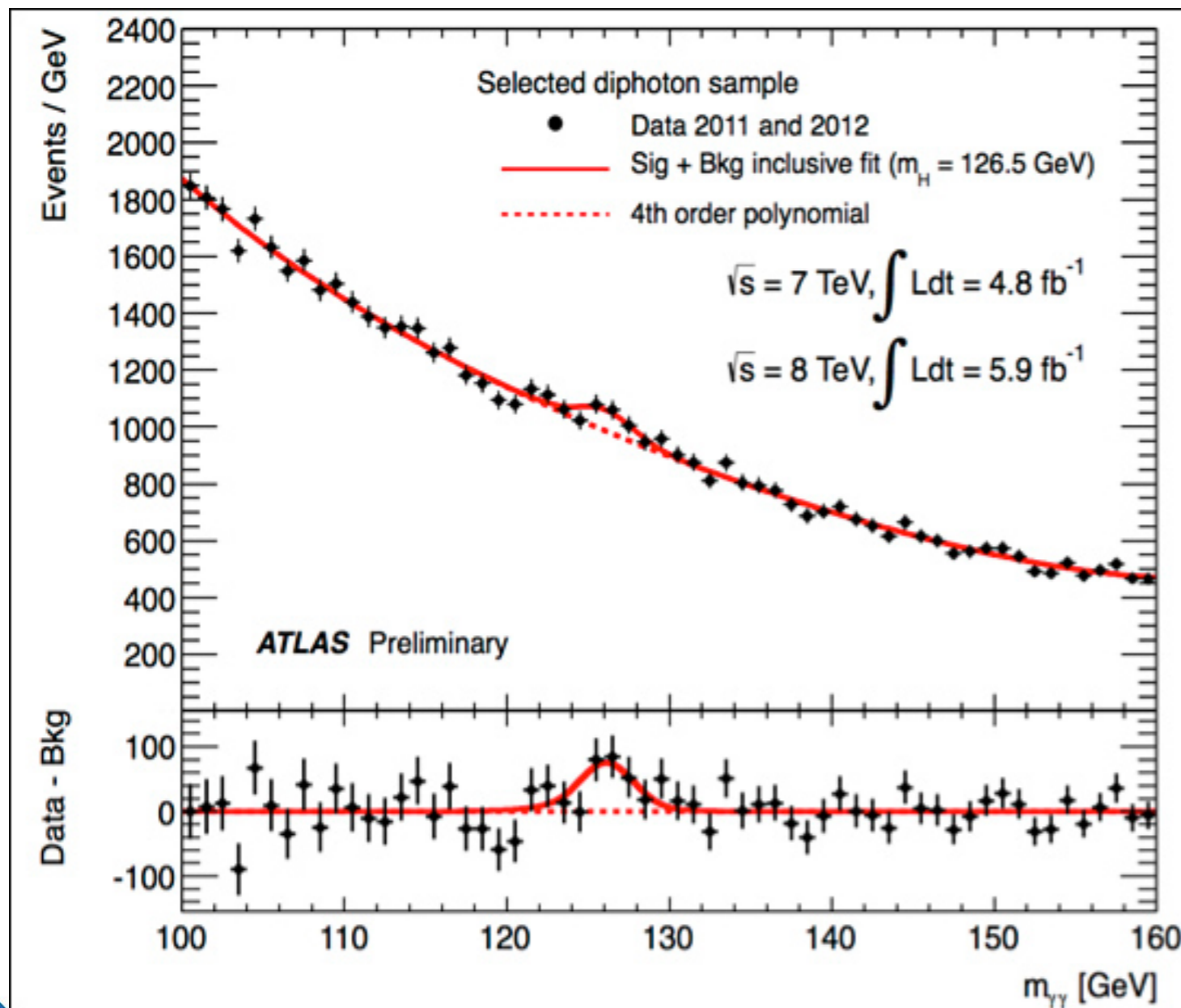
**At least:**

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

This already existed on the internet

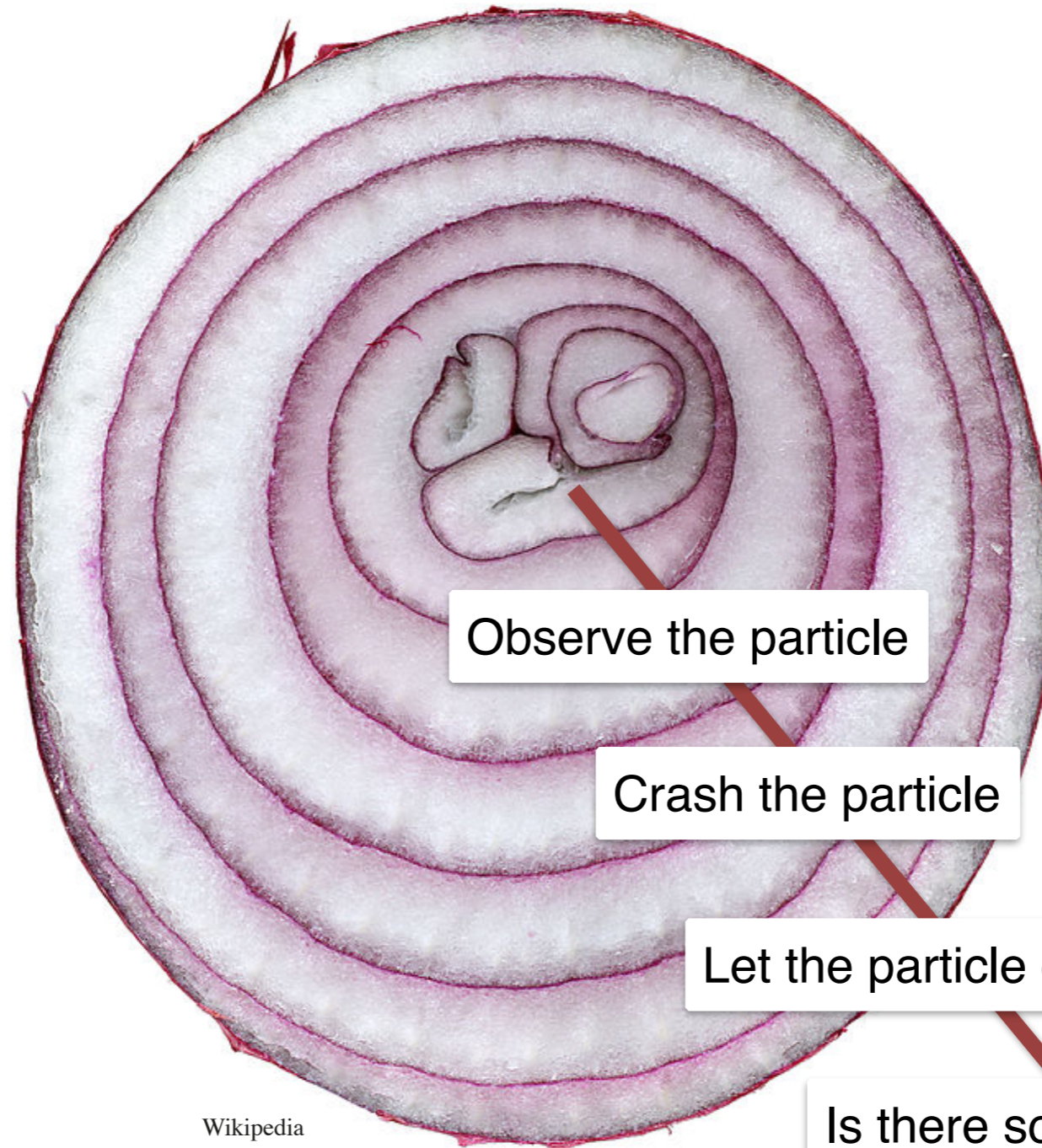
# An example: the Higgs boson

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



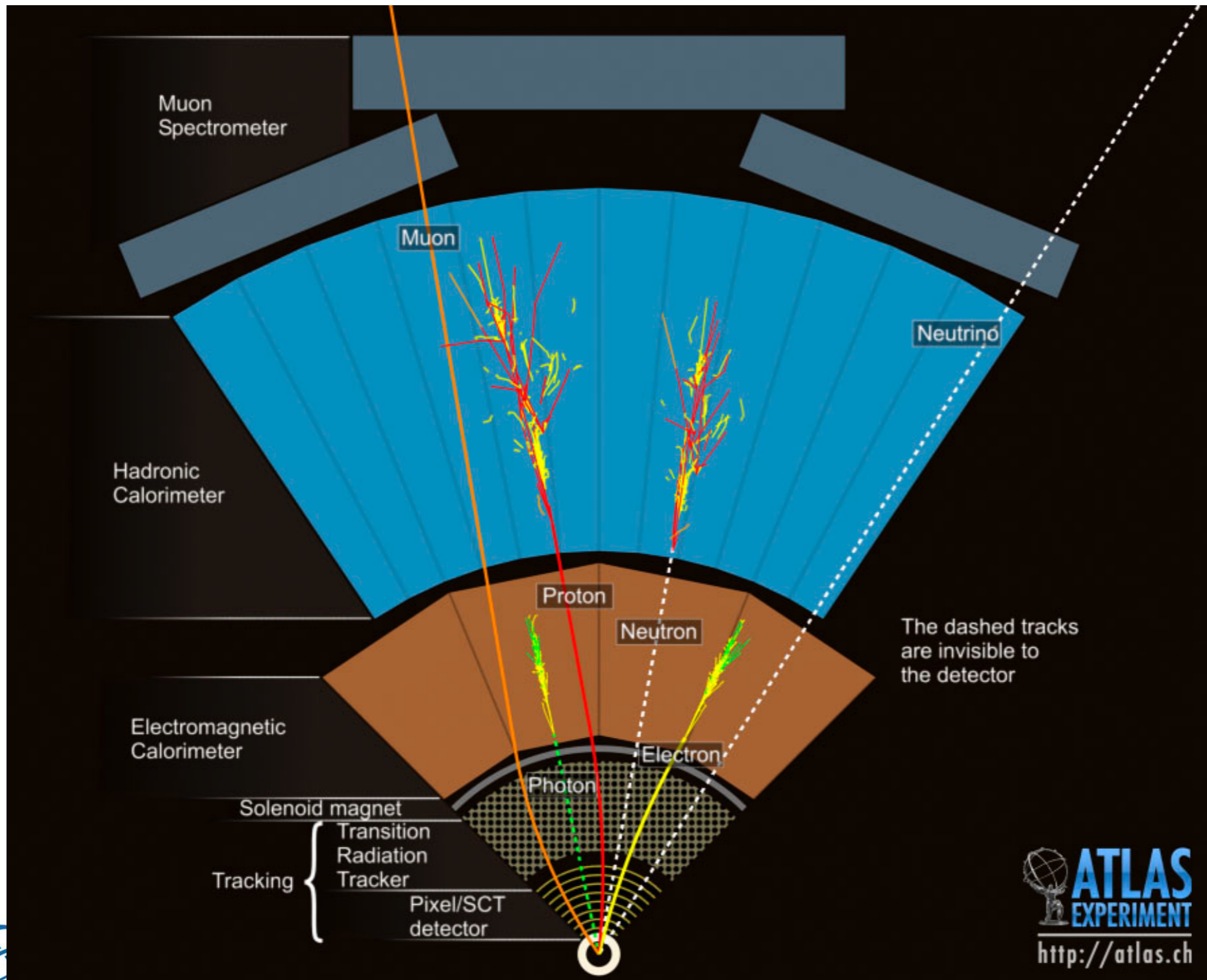
- Identify **photons**
- Measure **photon energy**

# 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 Muon Solenoid

### A Toroidal LHC ApparatuS



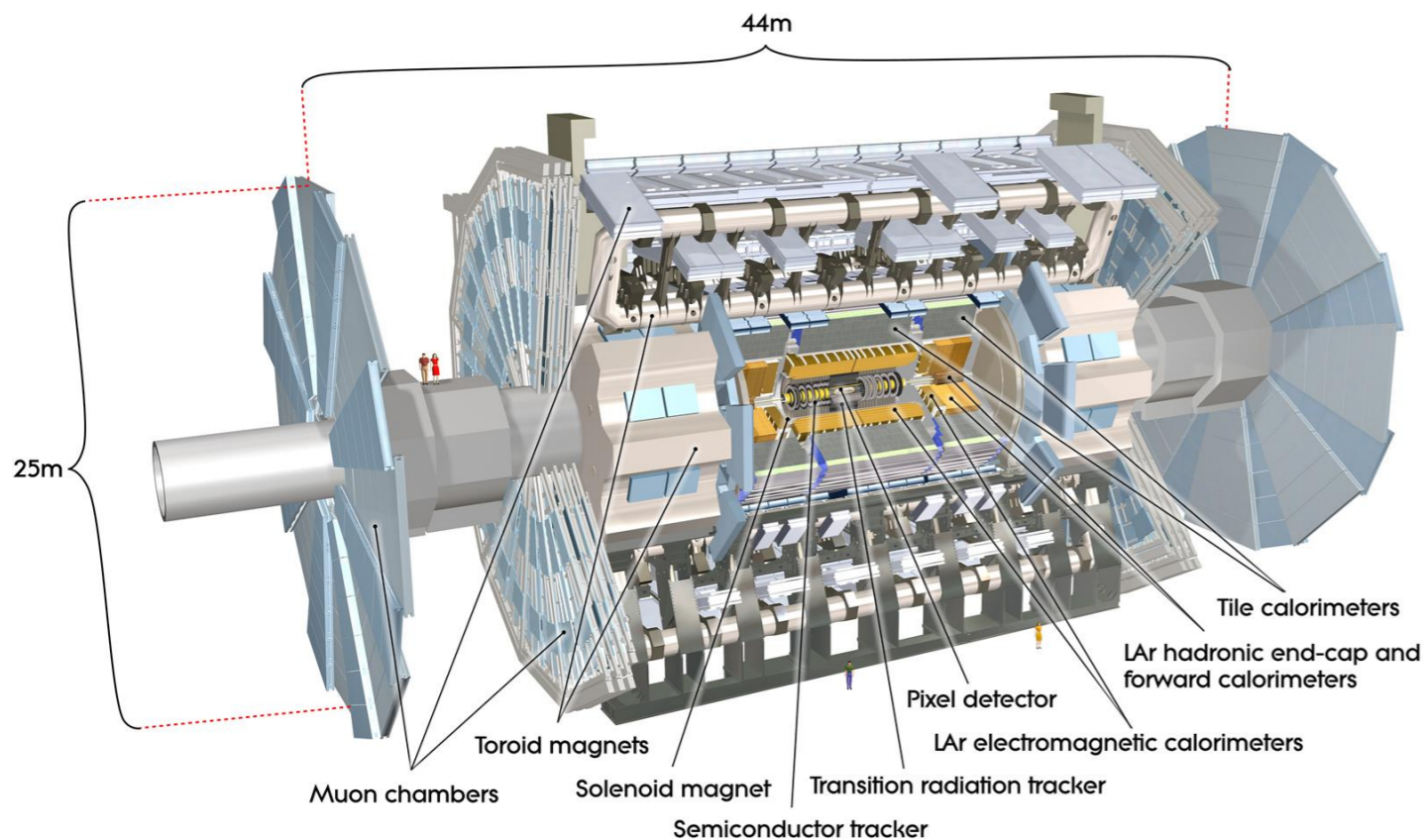
Peter Glazebrook from Newark with his record breaking giant onion  
Source: [thetimes.co.uk](http://thetimes.co.uk)



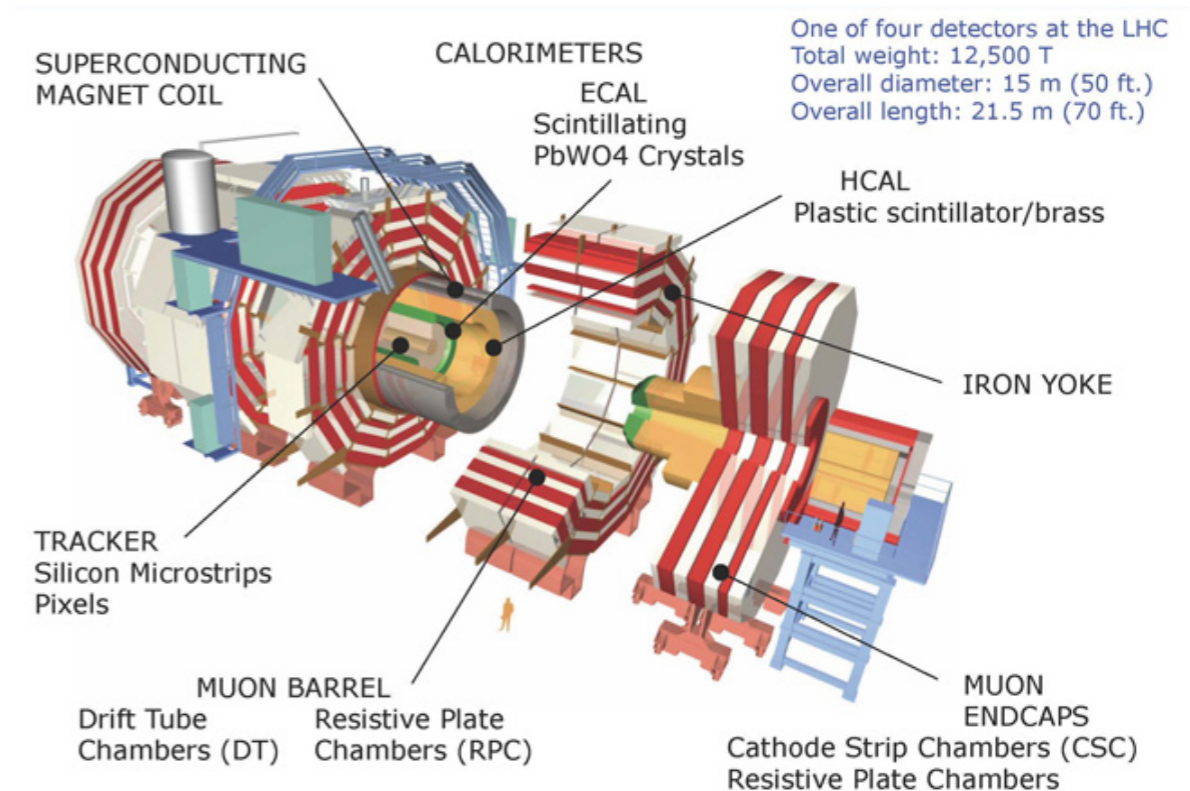
Wikipedia

# General purpose detectors at the LHC

## A Toroidal LHC Apparatus



## Compact Muon Solenoid

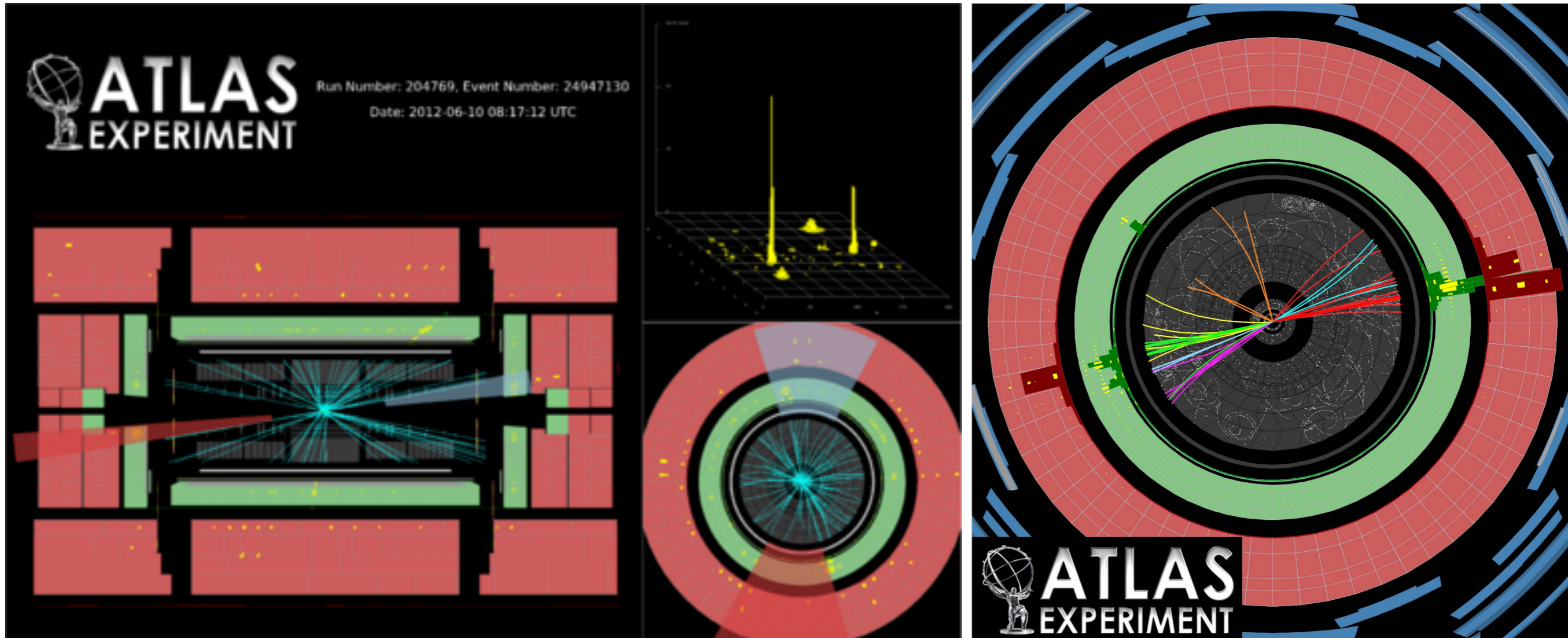


Covering ~all the solid angle around the collision

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

How to build CMS: [https://www.youtube.com/watch?v=rCsYxWa\\_T2s](https://www.youtube.com/watch?v=rCsYxWa_T2s)

# Seems easy...real diphoton (???) events

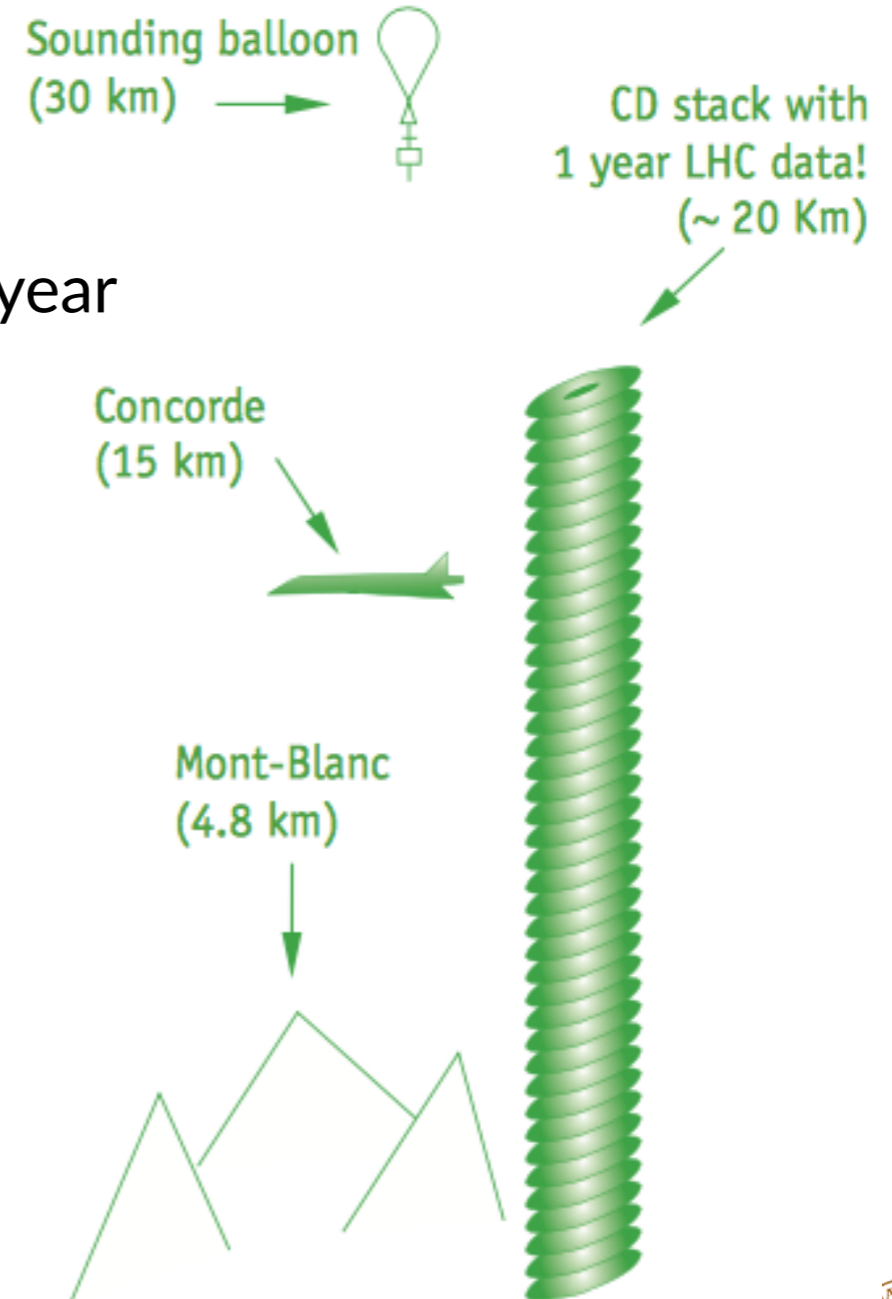


Data analysis crucial, innovative techniques needed (e.g. machine learning)



# 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
  - $40 \text{ MHz} * 1 \text{ MB} = 40 \text{ TB/s}$
  - $40 \text{ TB/s} * 10^{10} \text{ s/year (day \& night)} = 0.05 \text{ ZB/year}$
- Facebook:
  - 600 TB/day ~ 200 PB/year [\[Facebook 2014\]](#)
  - “There’s always a bigger fish”
  - [\[C. Tull’s talk @ siRTDM18\]](#)

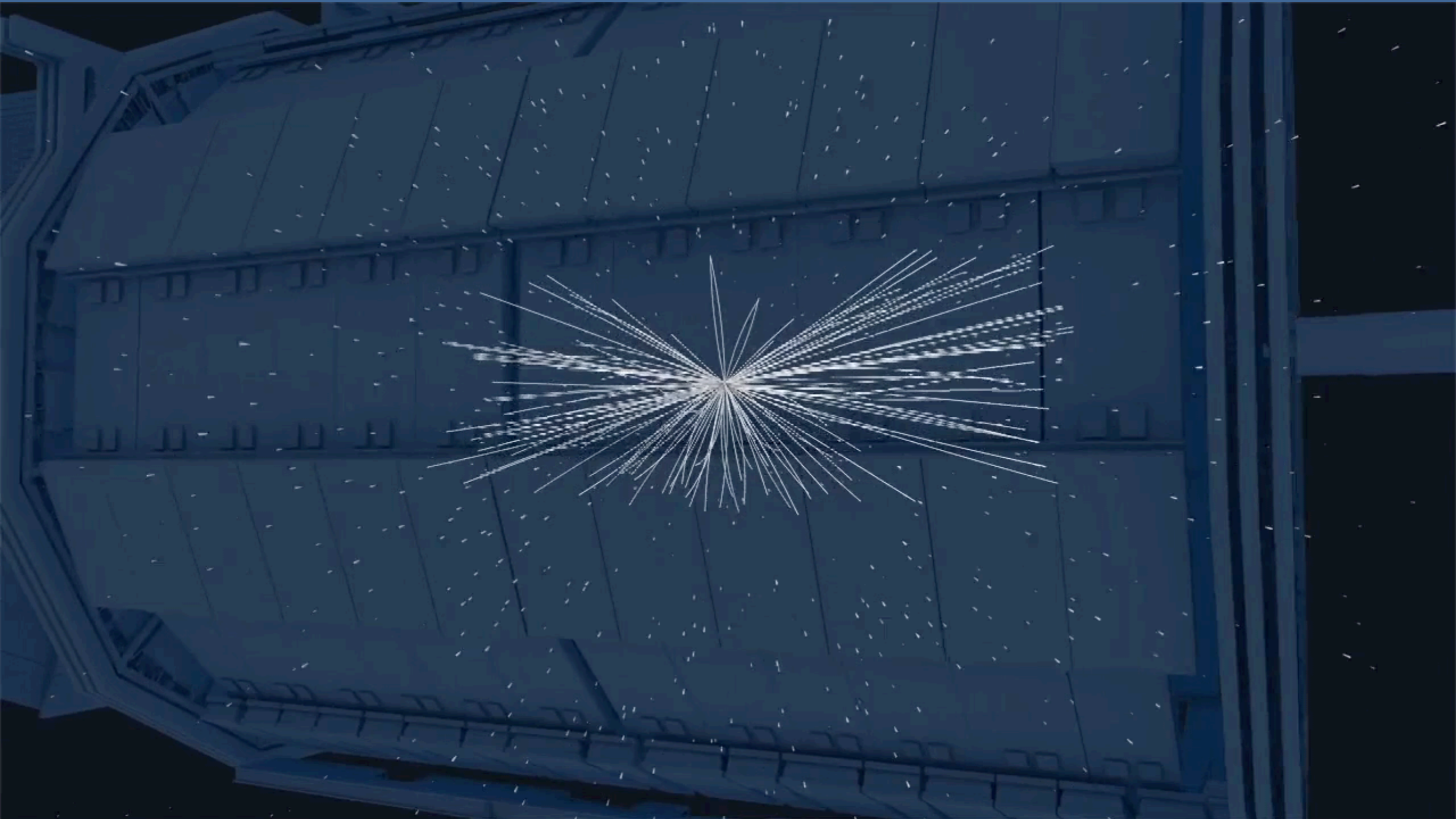


- LHC experiments need to:**
1. frequently **process** all data, fast (this includes calibrating and aligning the detectors!)
  2. **select** only interesting events (**problem**: we don't yet know what **interesting** means)

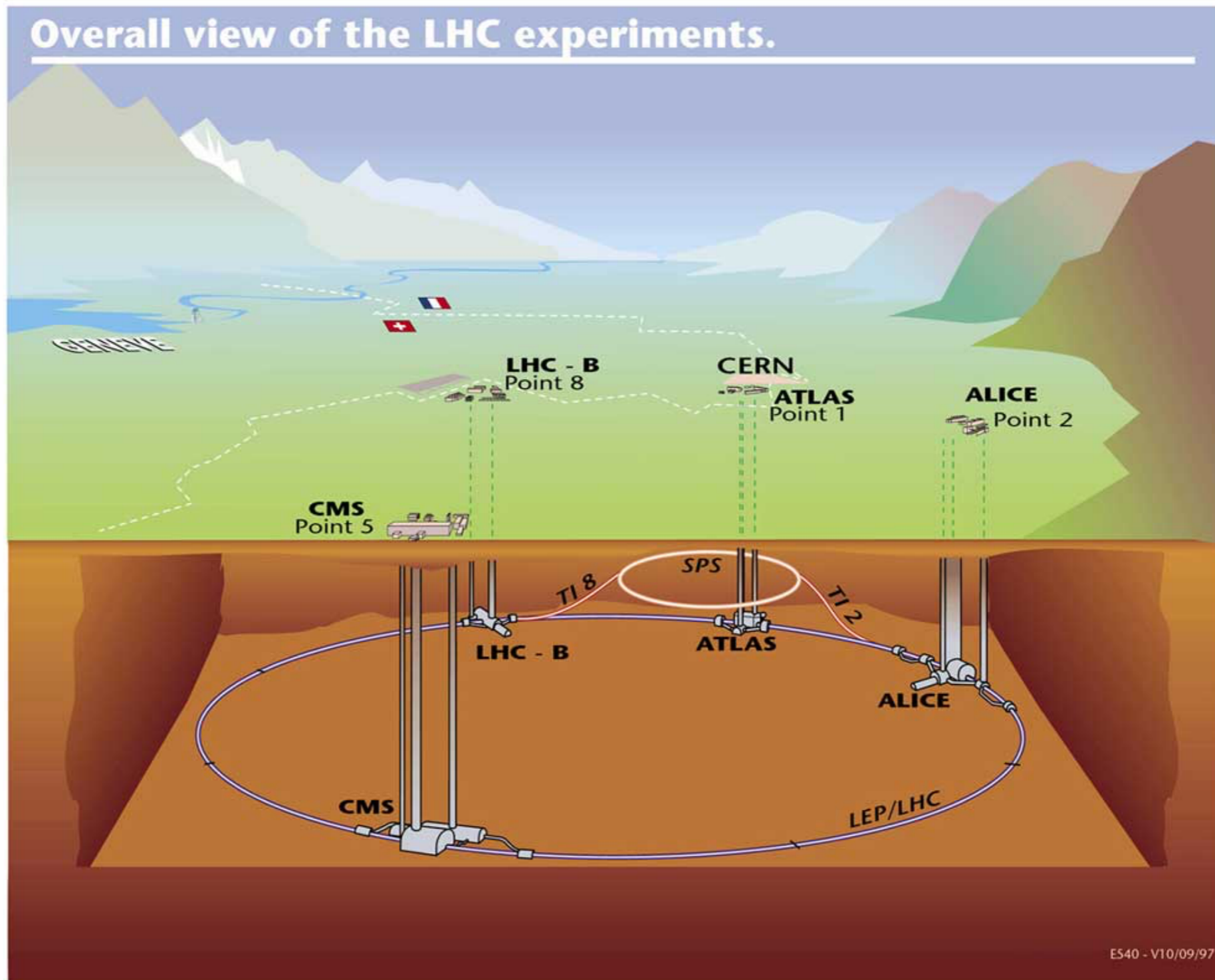
(after selecting interesting events)

# Video: triggering and processing data

CERN-MOVIE-2013-041-001



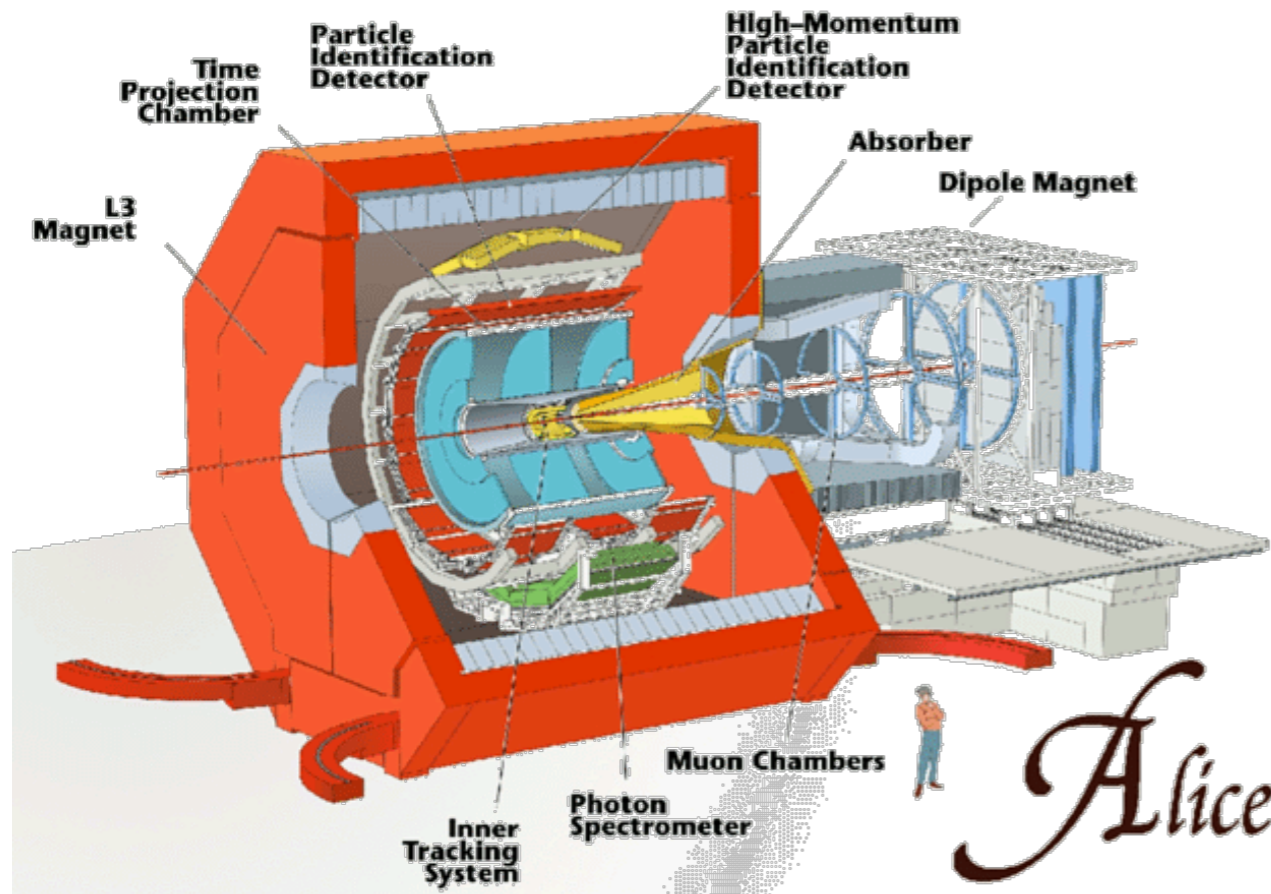
# LHC experiments at CERN



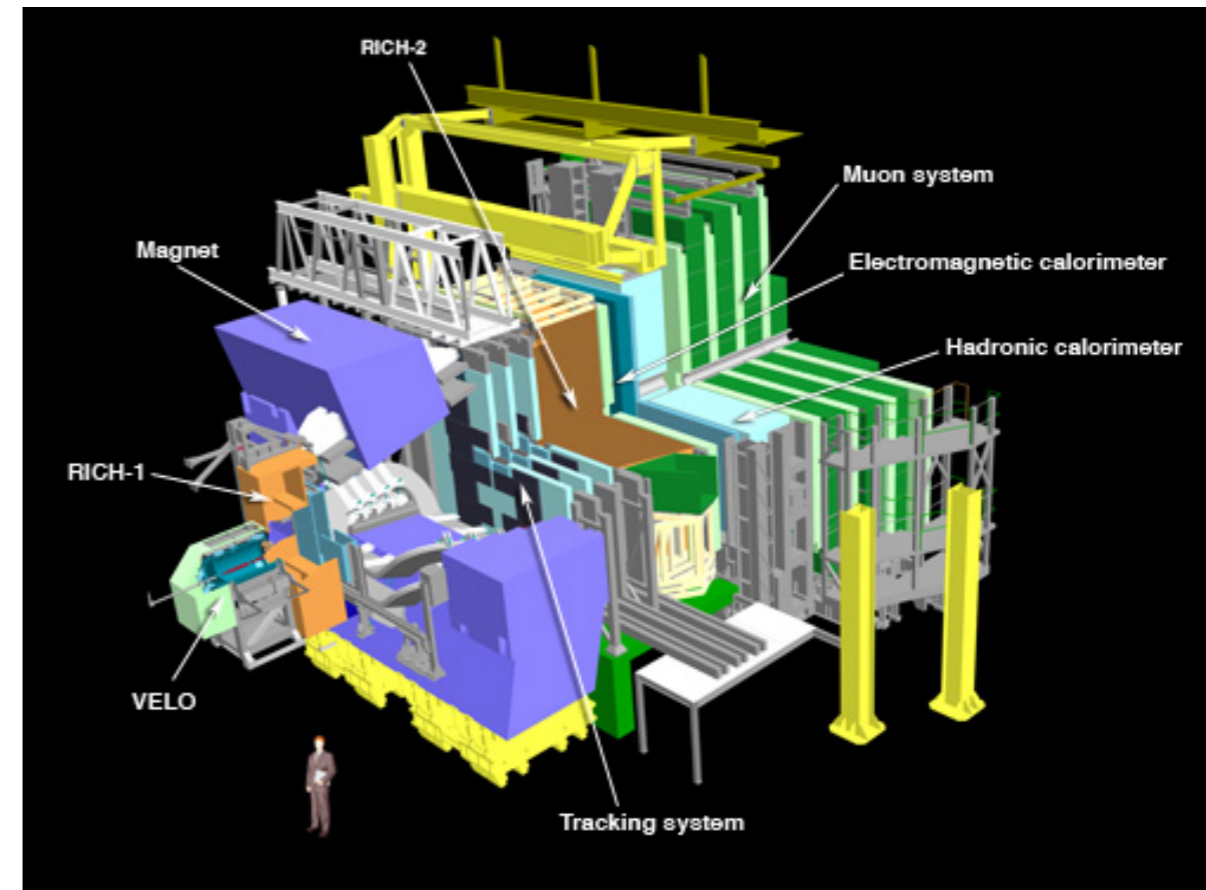
E540 - V10/09/97

# More specialized LHC detectors

## A Large Ion Collider Experiment



## LHC beauty apparatus



# The CERN laboratory in Geneva

Founded in 1954, 21 member states



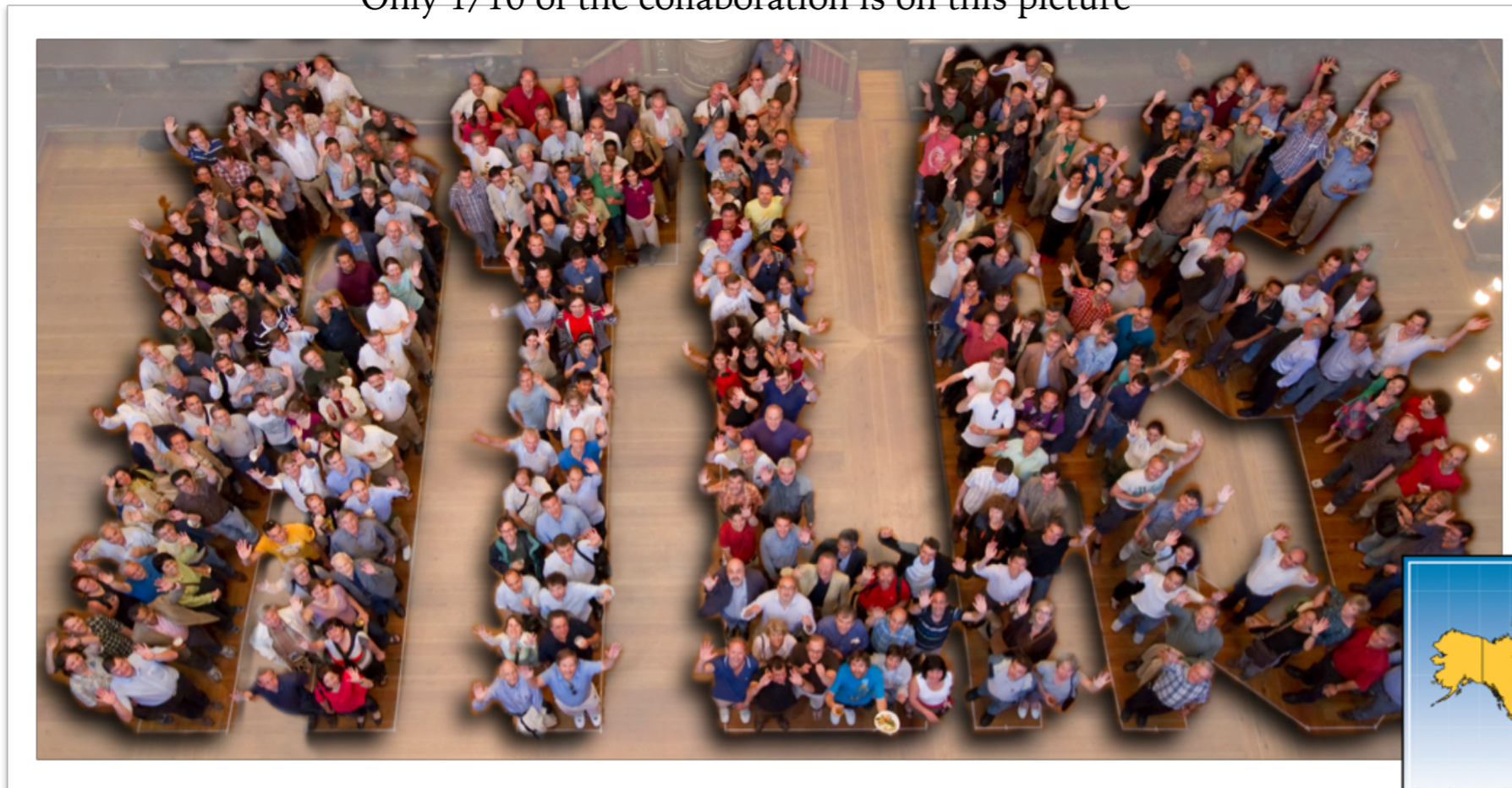
Fabiola Gianotti,  
Director General

A WORD  
FROM THE DIRECTOR-GENERAL



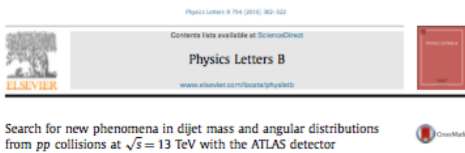
# The ATLAS Collaboration

Only 1/10 of the collaboration is on this picture



38 countries, ~180 universities,  
> 1000 students!

An ATLAS scientific paper



Search for new phenomena in dijet mass and angular distributions for pp collisions at sqrt(s) = 13 TeV with the ATLAS detector

1. Introduction
The centre-of-mass energy of proton-proton (pp) collisions at the Large Hadron Collider (LHC) at CERN has been increased from 8 TeV to sqrt(s) = 13 TeV, opening a new energy regime to the experiment.

threshold mass of 6.5 TeV is 53% (52%) for both generators. The dijet mass is defined as m(jj) = sqrt((m1 + m2)^2 - (p1z + p2z)^2)...

2. Simulation
The dijet distribution can also be modified by new mediating particles with a mass much higher than the dijet mass...

3. Results
Starting from the m(jj) distribution obtained with the Monte Carlo simulation, a Bayesian method [14] is applied to the data and simulation of signals with a fixed background...

4. Conclusions
The ATLAS detector has been used to search for new phenomena in dijet mass and angular distributions for pp collisions at sqrt(s) = 13 TeV with the ATLAS detector.

ATLAS Collaboration/Physics Letters B 774 (2018) 302-322
The energy deposit over calorimeter noise [22]. Topological clusters are grouped into jets using the anti-kT algorithm [23,24] with radius parameter R = 0.4. Jet four-momenta are computed by summing over the topological clusters that constitute each jet, treating the energy of each cluster as a four-momentum with zero transverse momentum.

4. Simulated collisions
For this search, events from QCD processes are simulated with Pythia 8 [30] using the AS4 [31] set of tuned parameters for the underlying event and the leading-order NNPDF2.1 [32] parton distribution functions (PDFs).

5. Selection for the mass distribution analysis
The m(jj) distribution of events with |y1| = 0.4 < |y2| < 3.3 is analysed for evidence of contributions from resonant BSM phenomena. The requirement on |y1| restricts the background from QCD processes to be dominated by the 2- and 3-jet production channels.

6. Selection for the angular distribution analysis
The dijet (angular) distributions of events with |y1| = 0.7 < |y2| < 3.0 (|y1| = 1.1) are also analysed for contributions from BSM signals. Fig. 2 shows the angular distributions of the data in different regions, the SM prediction for the shape of the angular distributions, and examples of the signals described in Section 7. The data with |y1| = 0.7 < |y2| < 3.0 are shown in the top panel, while the data with |y1| = 1.1 are shown in the bottom panel.

7. Results
The ATLAS detector has been used to search for new phenomena in dijet mass and angular distributions for pp collisions at sqrt(s) = 13 TeV with the ATLAS detector. The results are shown in Figs. 1 and 2.

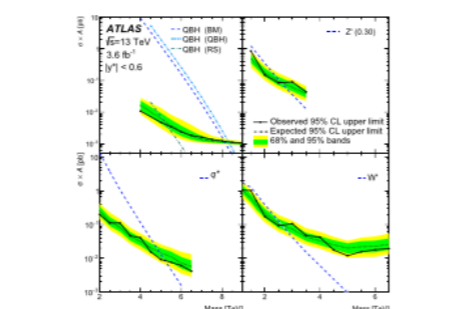
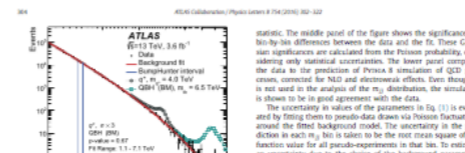


Fig. 1. The 95% confidence-level upper limits obtained from the m(jj) distribution on cross-sections sigma(pp -> X jj) for the dijet distribution in the ATLAS detector.



8. Conclusions
The ATLAS detector has been used to search for new phenomena in dijet mass and angular distributions for pp collisions at sqrt(s) = 13 TeV with the ATLAS detector. The results are shown in Figs. 1 and 2.

9. Acknowledgments
We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

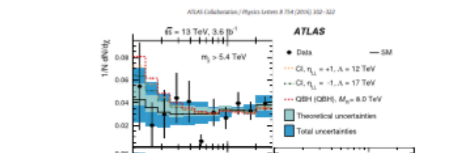
10. References
[1] ATLAS Collaboration, Search for new phenomena in the dijet mass distribution with collision data at sqrt(s) = 13 TeV with the ATLAS detector, Phys. Lett. B 774 (2018) 302-322.

11. Appendix
Detailed information on the ATLAS detector and the simulation of signals with a fixed background is provided in the ATLAS detector description and the ATLAS simulation manual.

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21. Appendix
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# 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 SCOAP<sup>3</sup> - Sponsoring Consortium for Open Access Publishing in Particle Physics

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<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>



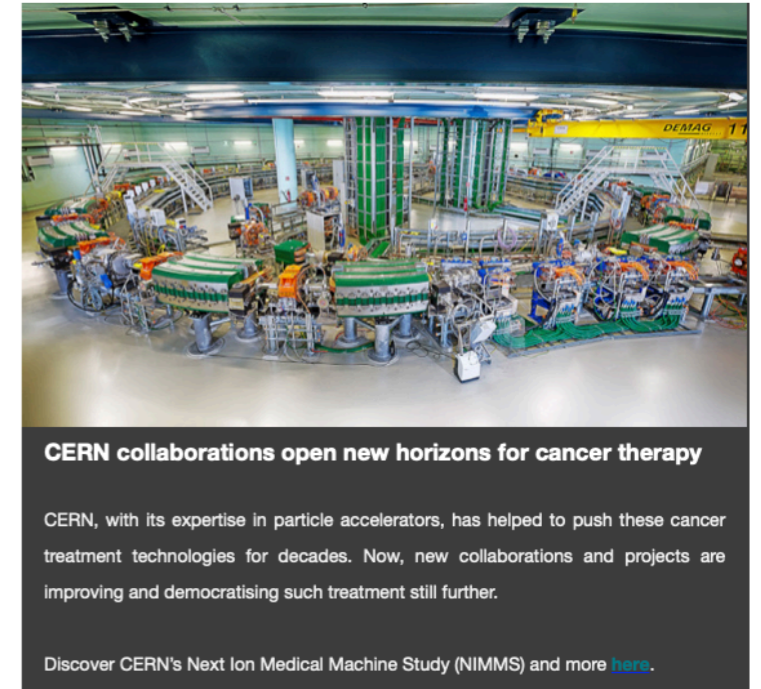
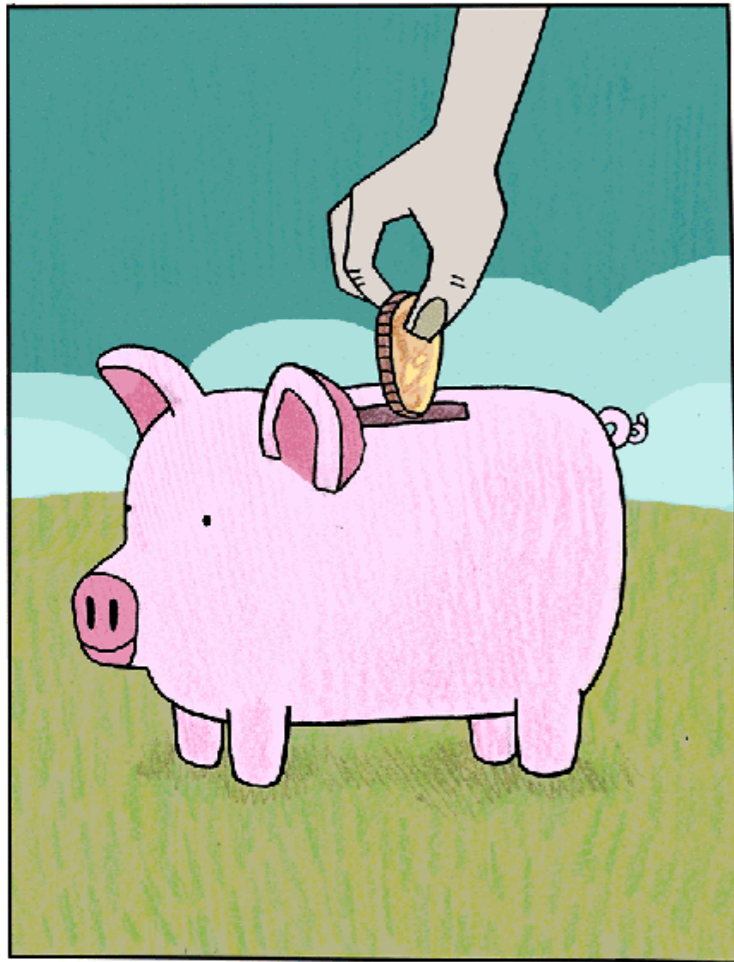
See also: [Outreach without borders, CERN news](#)

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

Caterina Doglioni - HASCO school 2021 - Introduction to hadron collider physics

# What's the value of science?

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



## CERN collaborations open new horizons for cancer therapy

CERN, with its expertise in particle accelerators, has helped to push these cancer treatment technologies for decades. Now, new collaborations and projects are improving and democratising such treatment still further.

Discover CERN's Next Ion Medical Machine Study (NIMMS) and more [here](#).

## OECD report

In medicine: <https://www.nigms.nih.gov/education/fact-sheets/Pages/curiosity-creates-cures.aspx>

In high energy physics: <https://www.symmetrismagazine.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)

