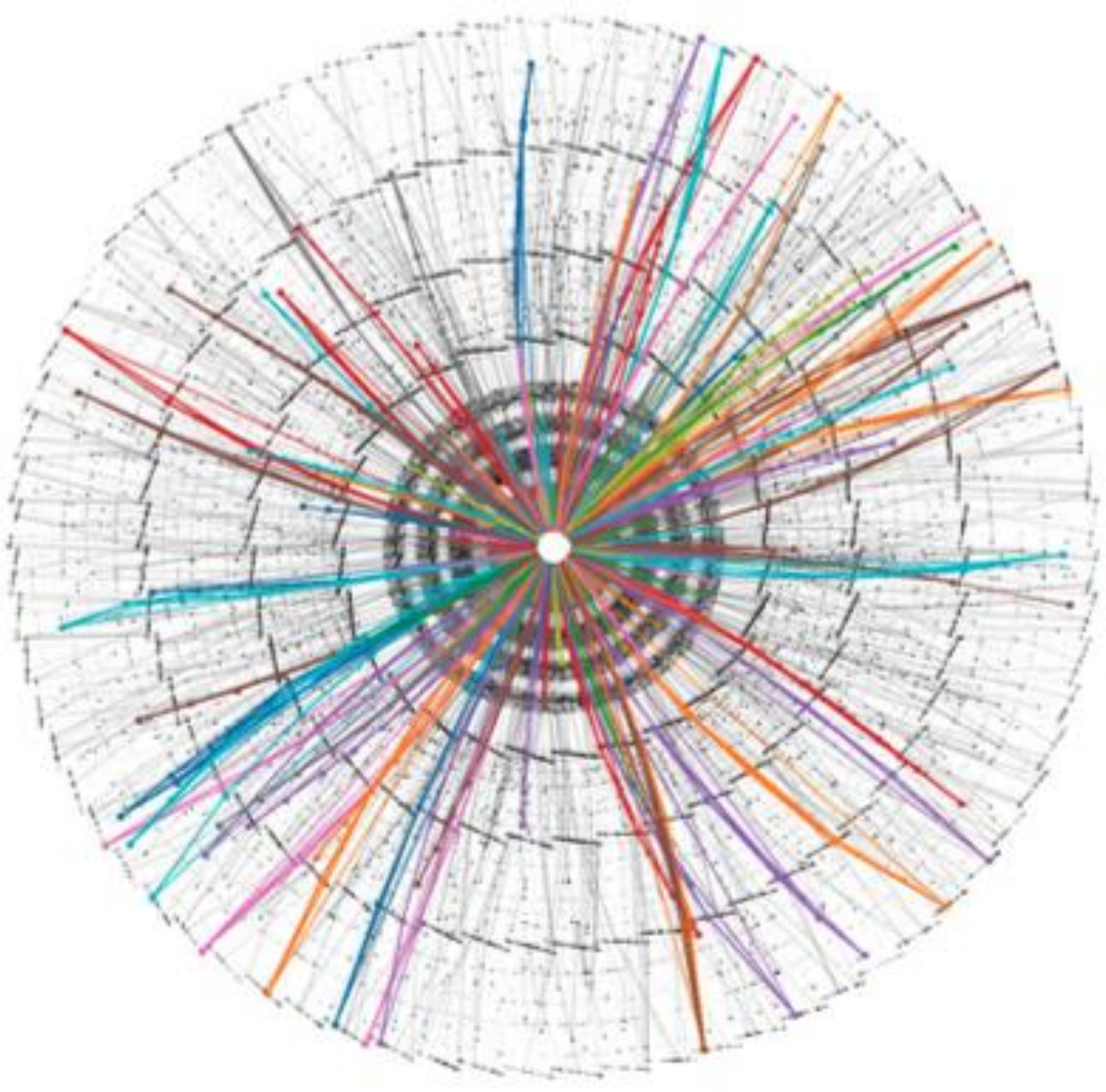


Challenges of Experimental Particle Physics*

*from my very biased point of view.

A. Salzburger (CERN)

from my very biased point of view.

Why biased?

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + \psi_i y_{ij}\psi_j\phi + h.c. + |D_\mu\phi|^2 - V(\phi)$$

Theory

Worldwide distributed Computing

Accelerator

Detector

Data Acquisition

Data Reconstruction

Data Analysis

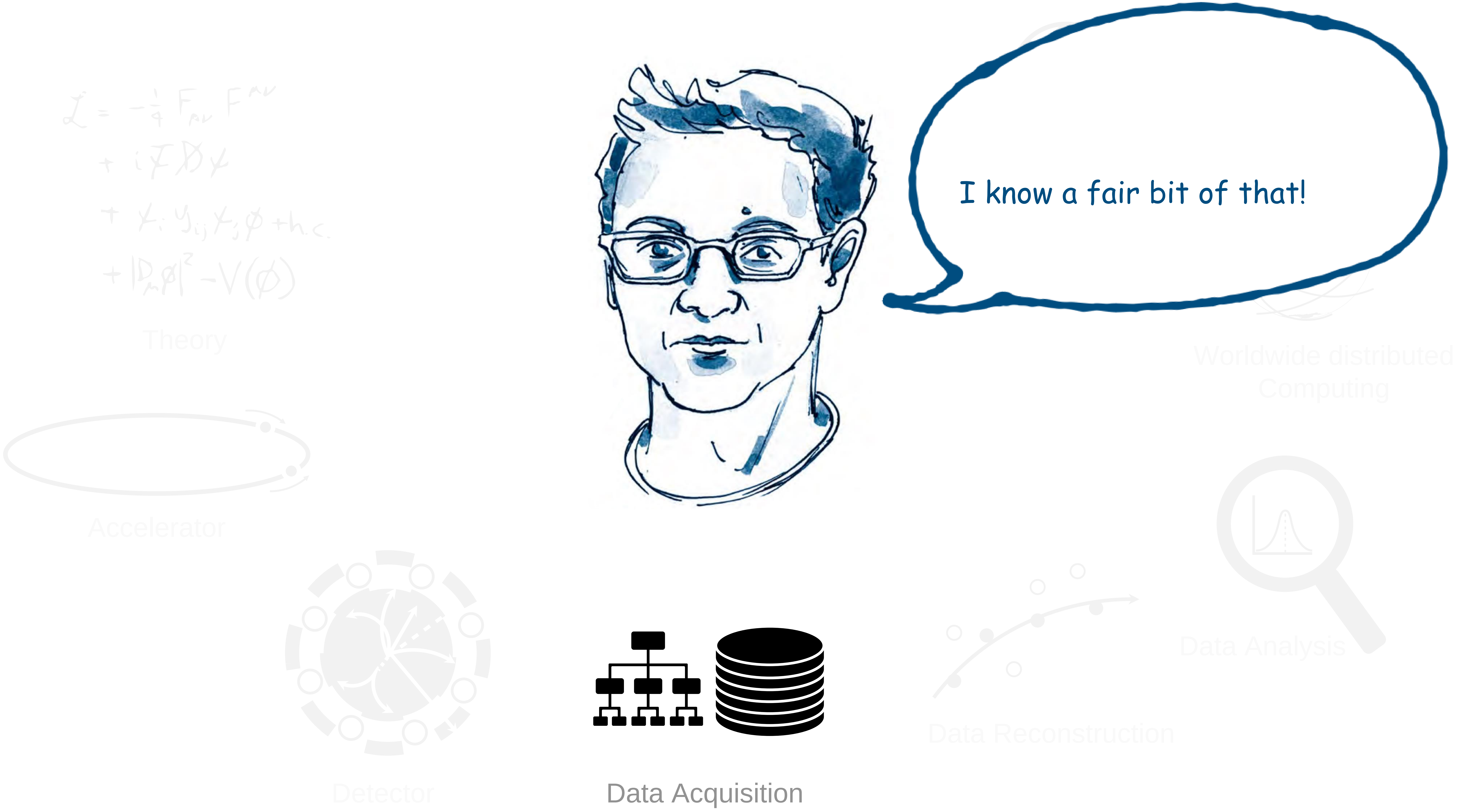
Why biased?


How do these guys even do that?
Seriously!?!?
Theory
Accelerator
Worldwide distributed Computing
Detector
Data Acquisition
Data Reconstruction
Data Analysis

Why biased?


Hey, I designed one!!
And ok, the engineers laughed at me …
Theory
Accelerator
Worldwide distributed Computing
Data Analysis
Data Reconstruction
Detector
Data Acquisition

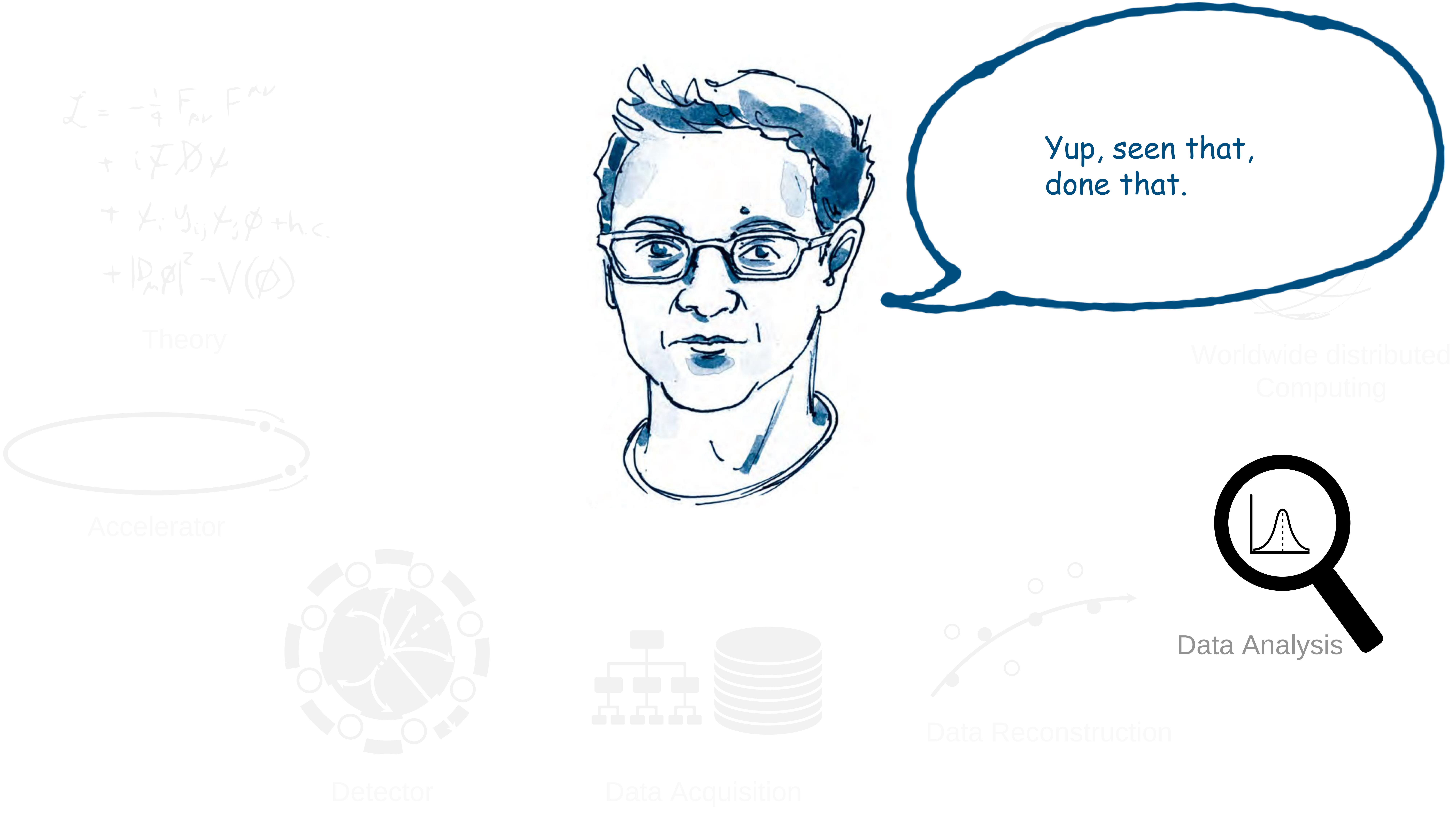
Why biased?


I know a fair bit of that!
Theory
Worldwide distributed Computing
Accelerator
Data Analysis
Detector
Data Acquisition
Data Reconstruction

Why biased?

Theory
Accelerator
Detector
Data Acquisition
Data Reconstruction
Data Analysis
Worldwide distributed Computing
Now we are talking, I can preach HOURS about that stuff.

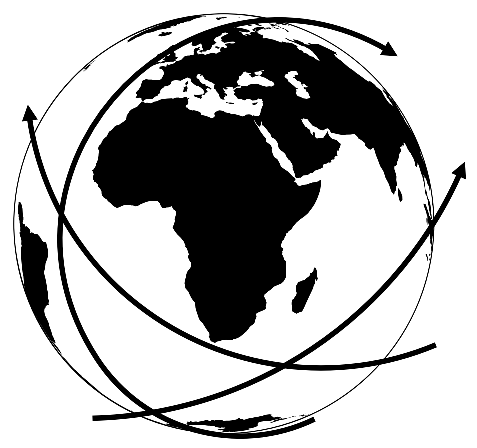
Why biased?


Yup, seen that,
done that.
Theory
Worldwide distributed
Computing
Accelerator
Data Analysis
Data Reconstruction
Detector
Data Acquisition

Why biased?

I really don't care about
the details too much …

… as long as it WORKS!



Worldwide distributed
Computing

Theory

Accelerator

Detector

Data Acquisition

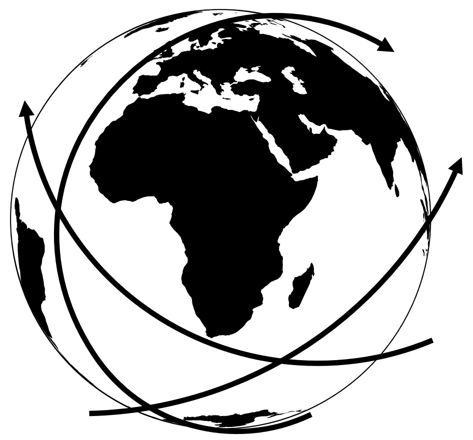
Data Reconstruction

Data Analysis

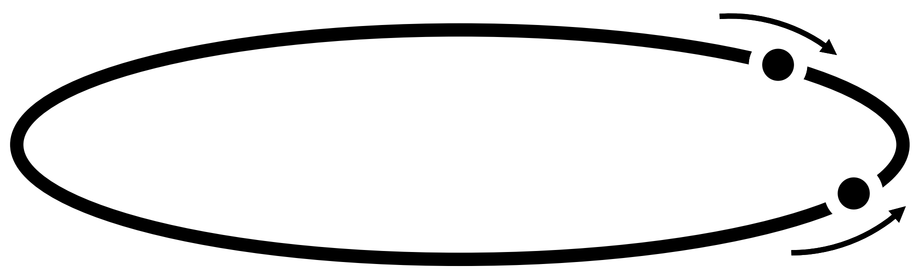
So complex!

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + \psi_i y_{ij}\psi_j\phi + h.c. + |D_\mu\phi|^2 - V(\phi)$$

Theory

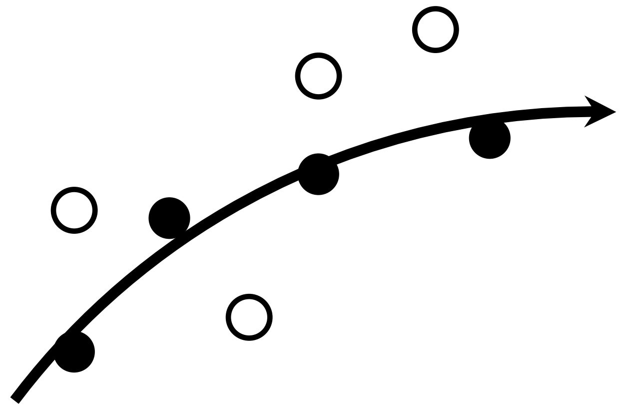


Worldwide distributed Computing

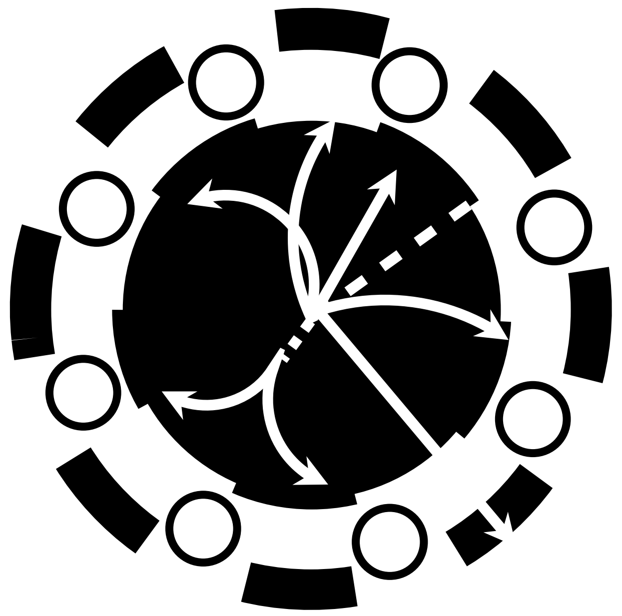


Accelerator

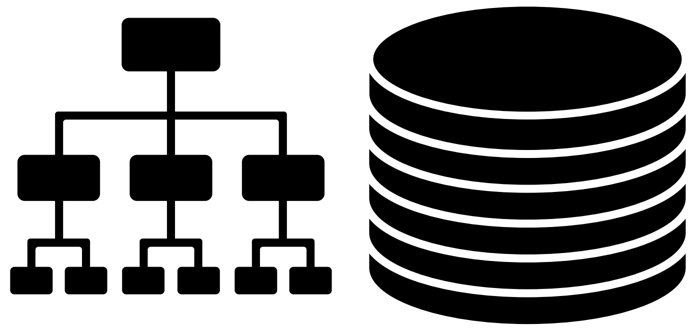
Data Analysis



Data Reconstruction



Detector

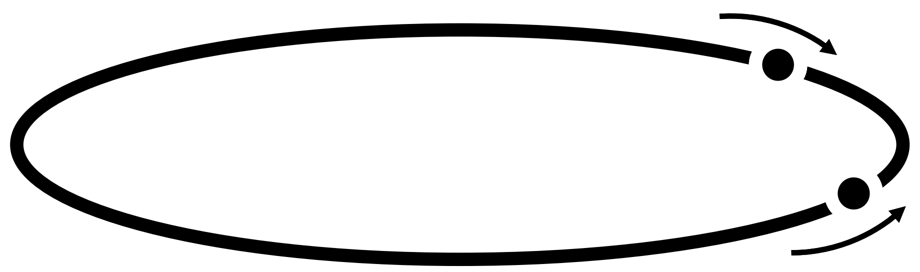


Data Acquisition

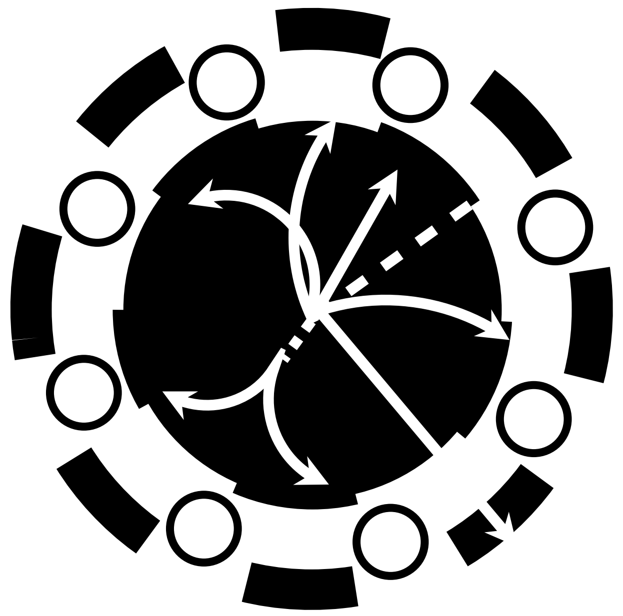
And yet ...

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

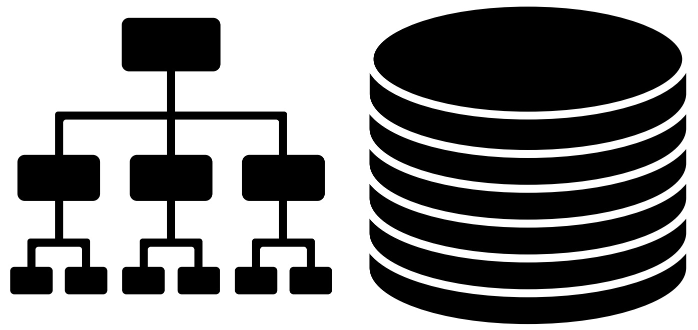
Theory



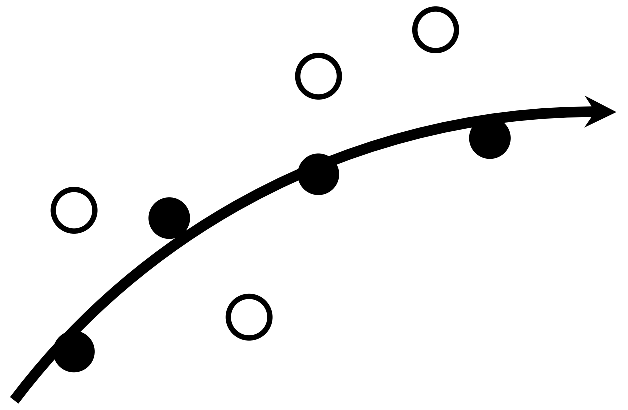
Accelerator



Detector

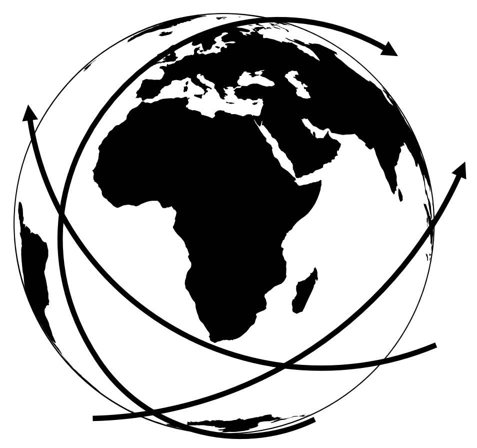


Data Acquisition



Data Reconstruction

Data Analysis



Worldwide distributed Computing

... all of that has to work together!

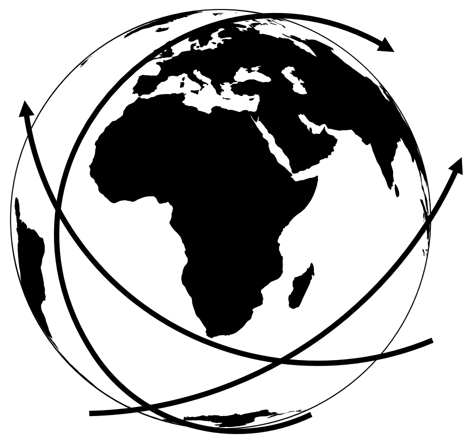
Oh, what …

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}\not{D}\psi + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

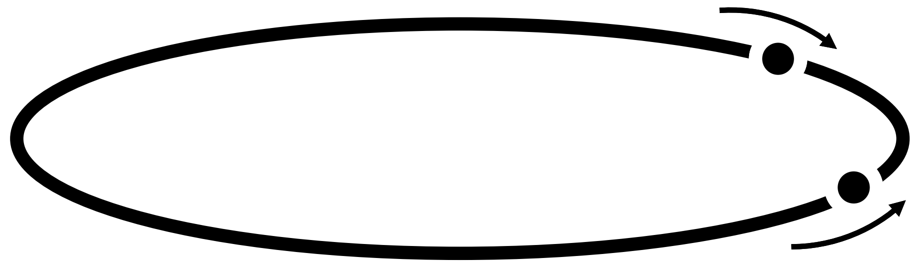
Theory

Laboratory

YOU

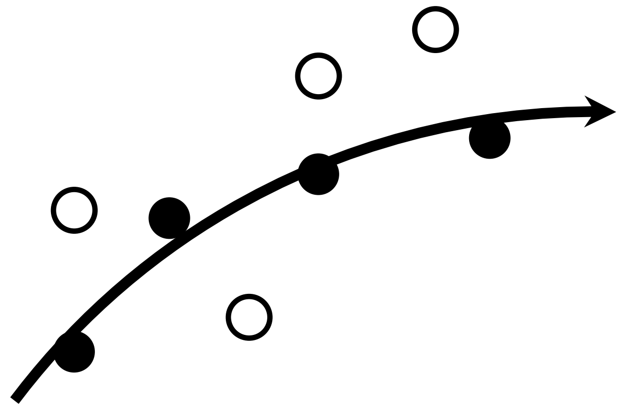


Worldwide distributed Computing

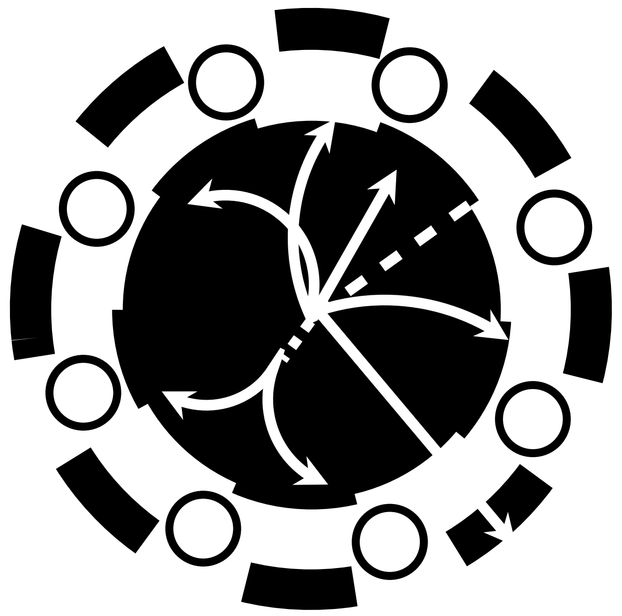


Accelerator

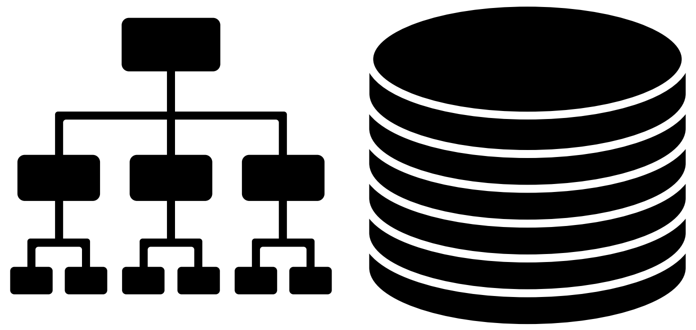
Data Analysis



Data Reconstruction



Detector



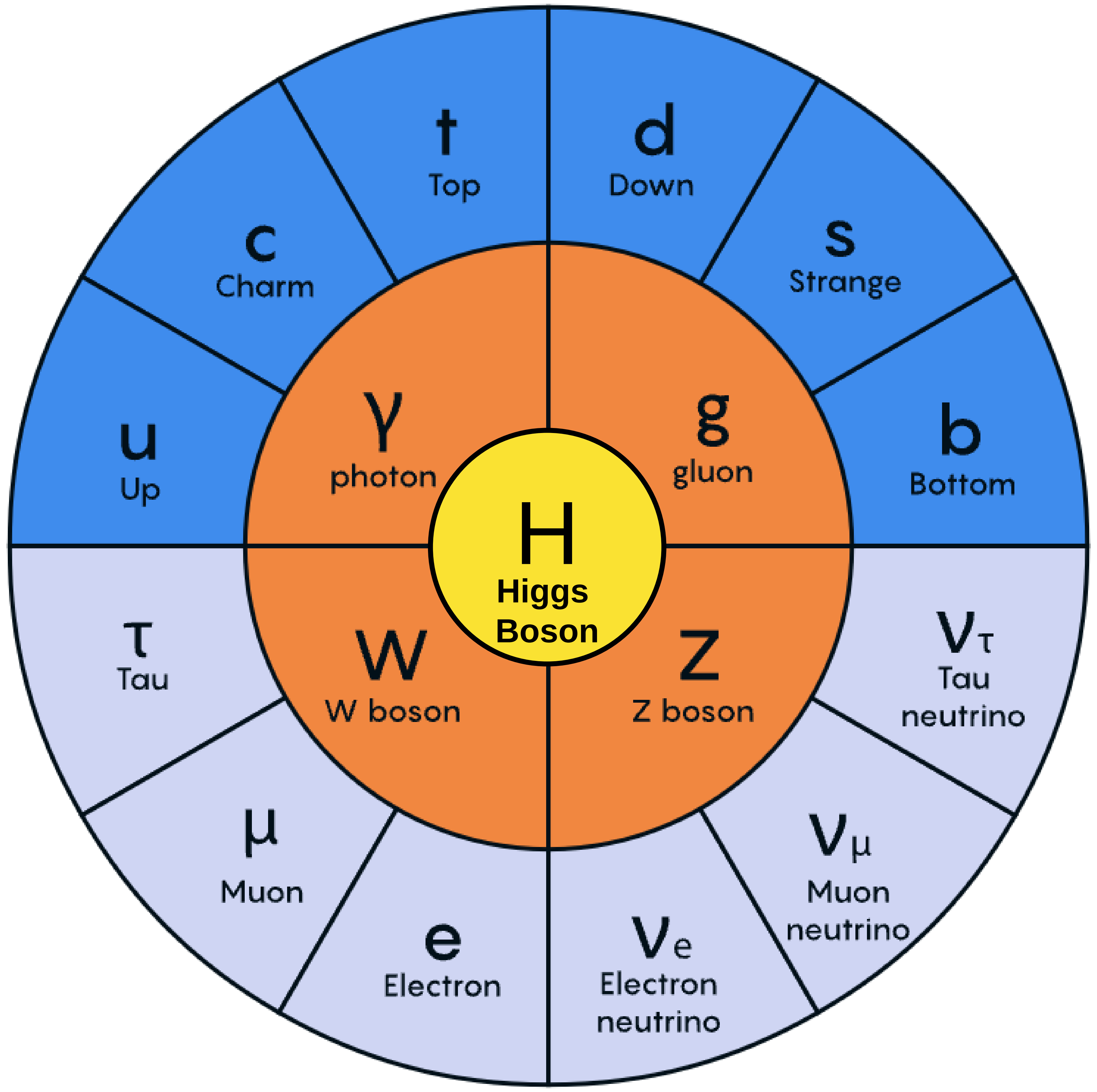
Data Acquisition

The theory

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

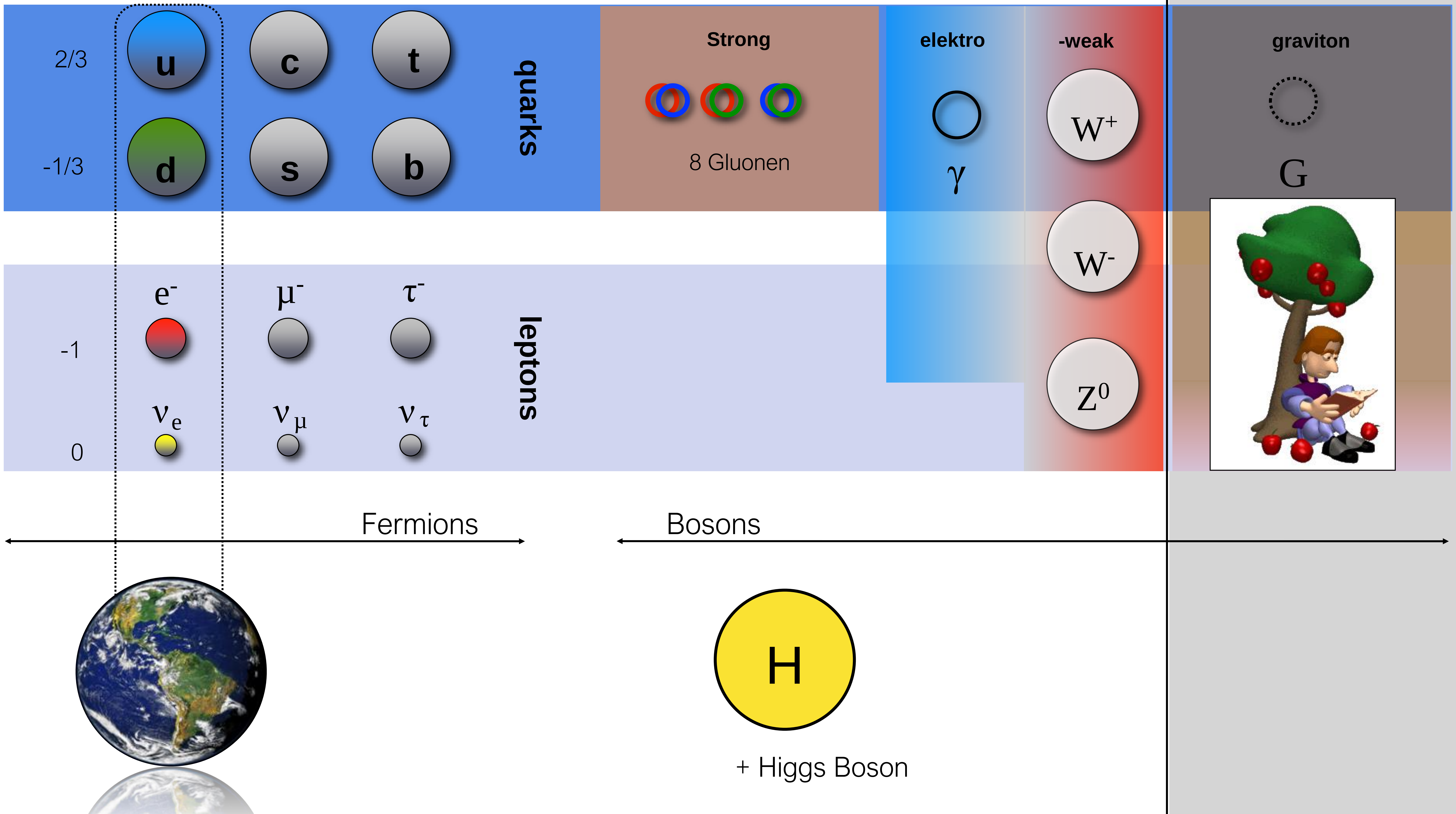
The Lagrangian of the Standard Model:
It describes the particles, and how they interact with another

The particles?

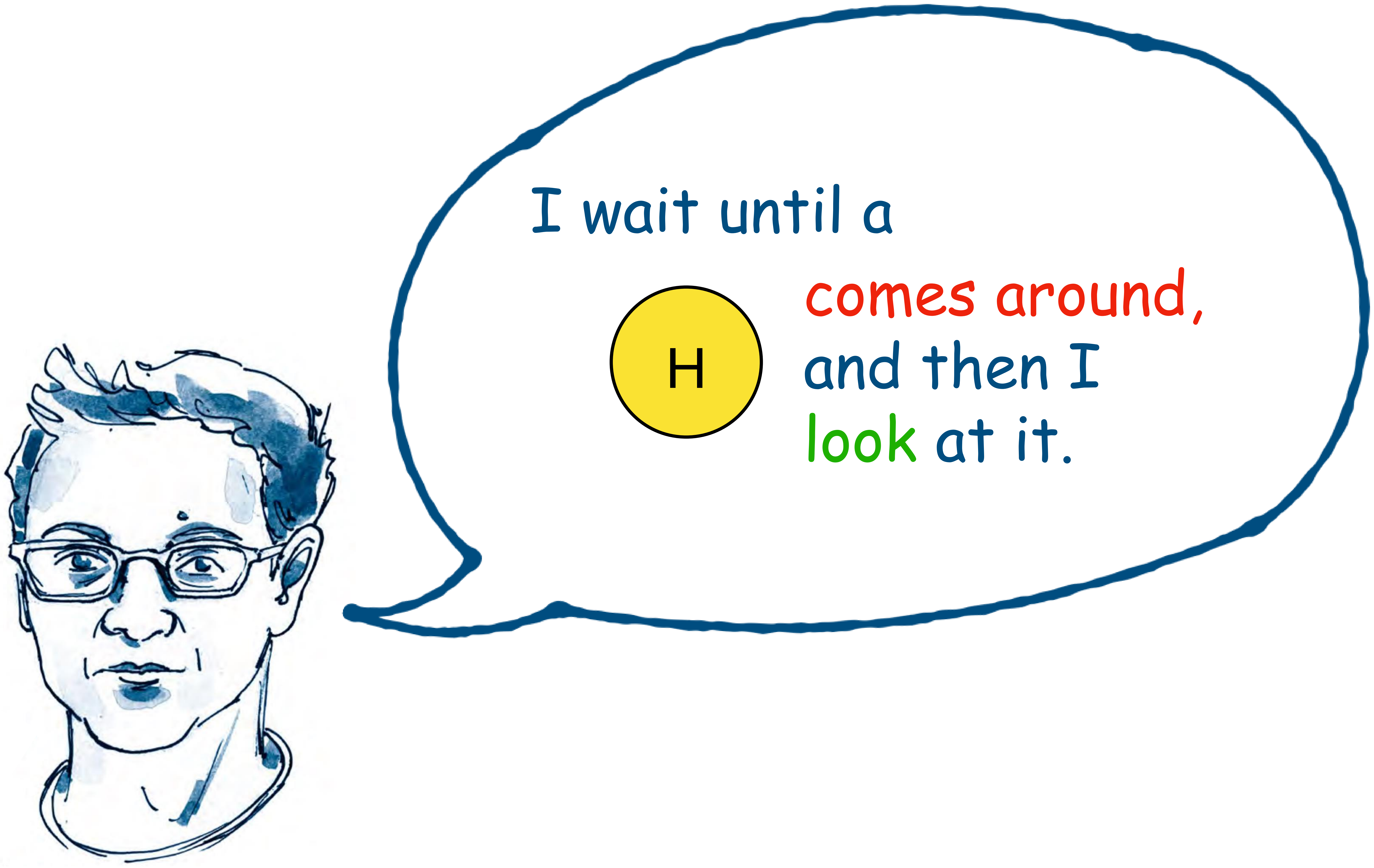


Particles and mediators

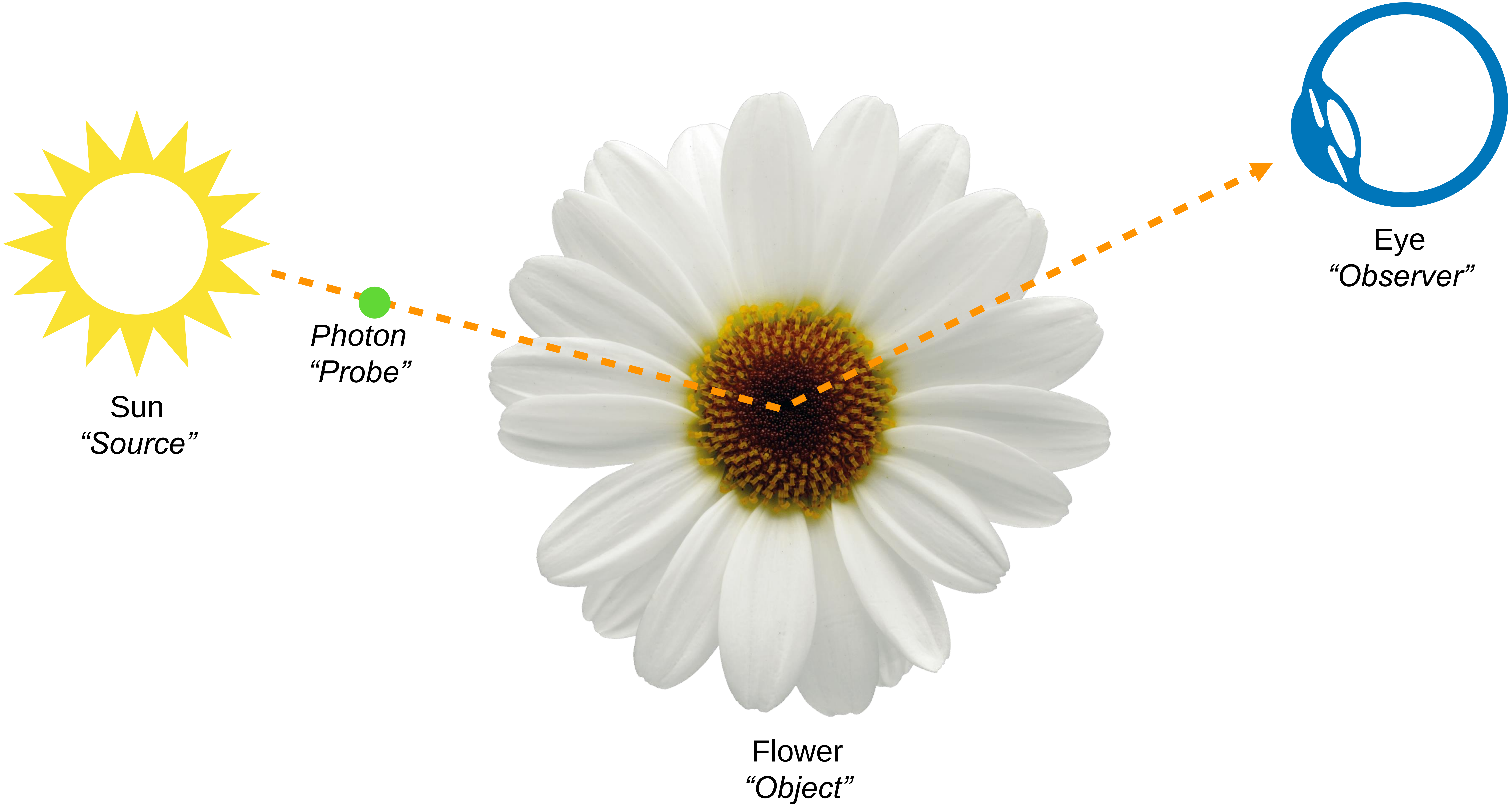
Not described by the Standard Model



Finding the Higgs Boson



A daily observation



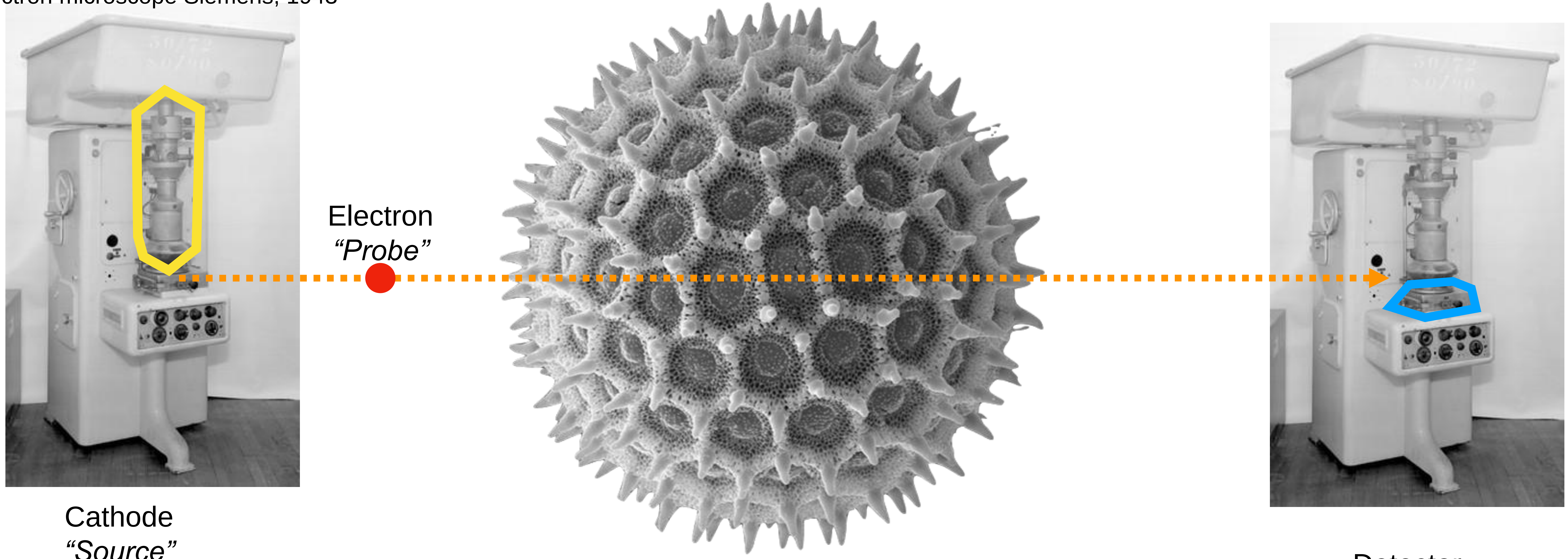
[Image source]

A good microscope

[Image Source]

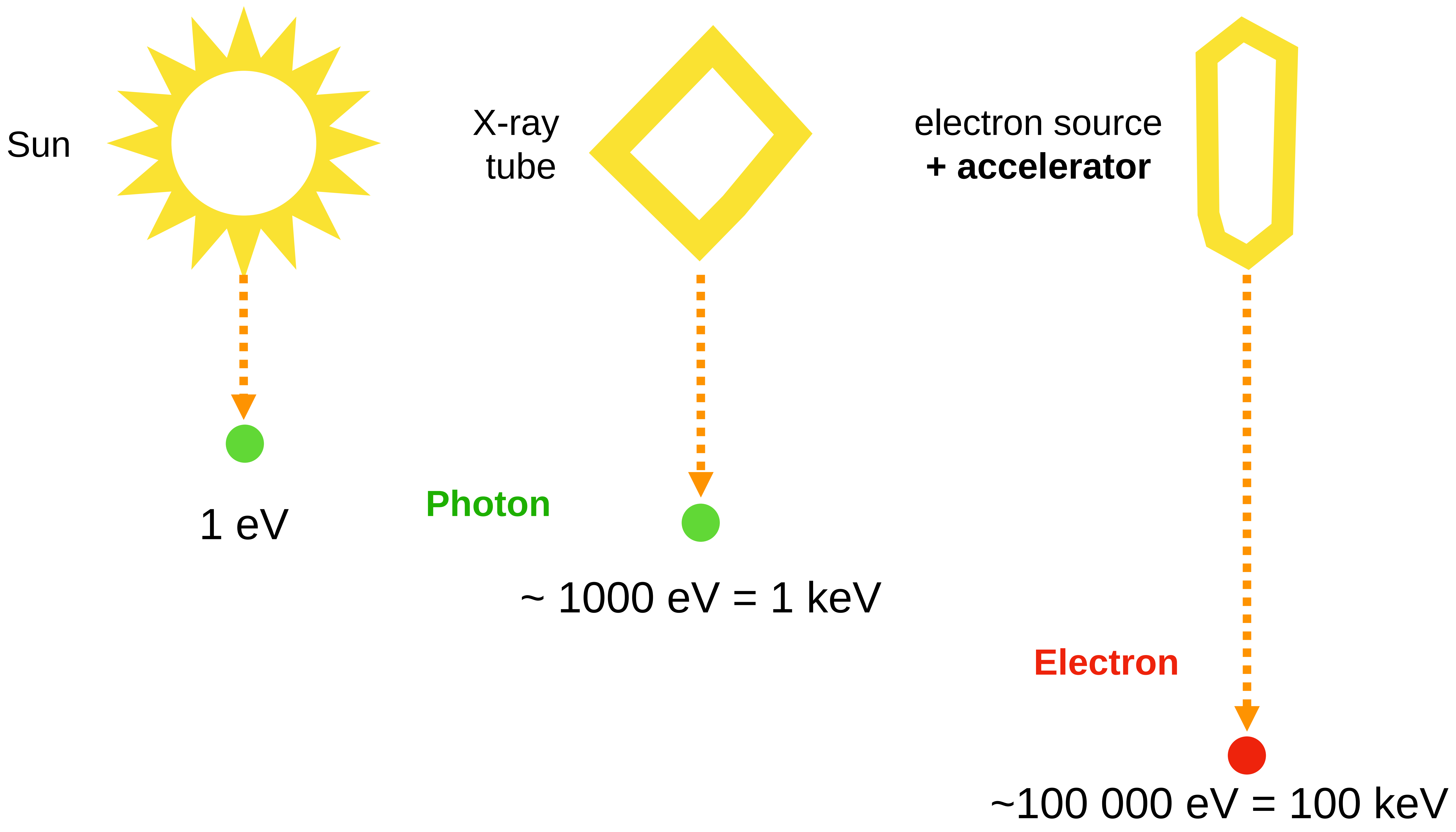
A very good microscope

Electron microscope Siemens, 1943

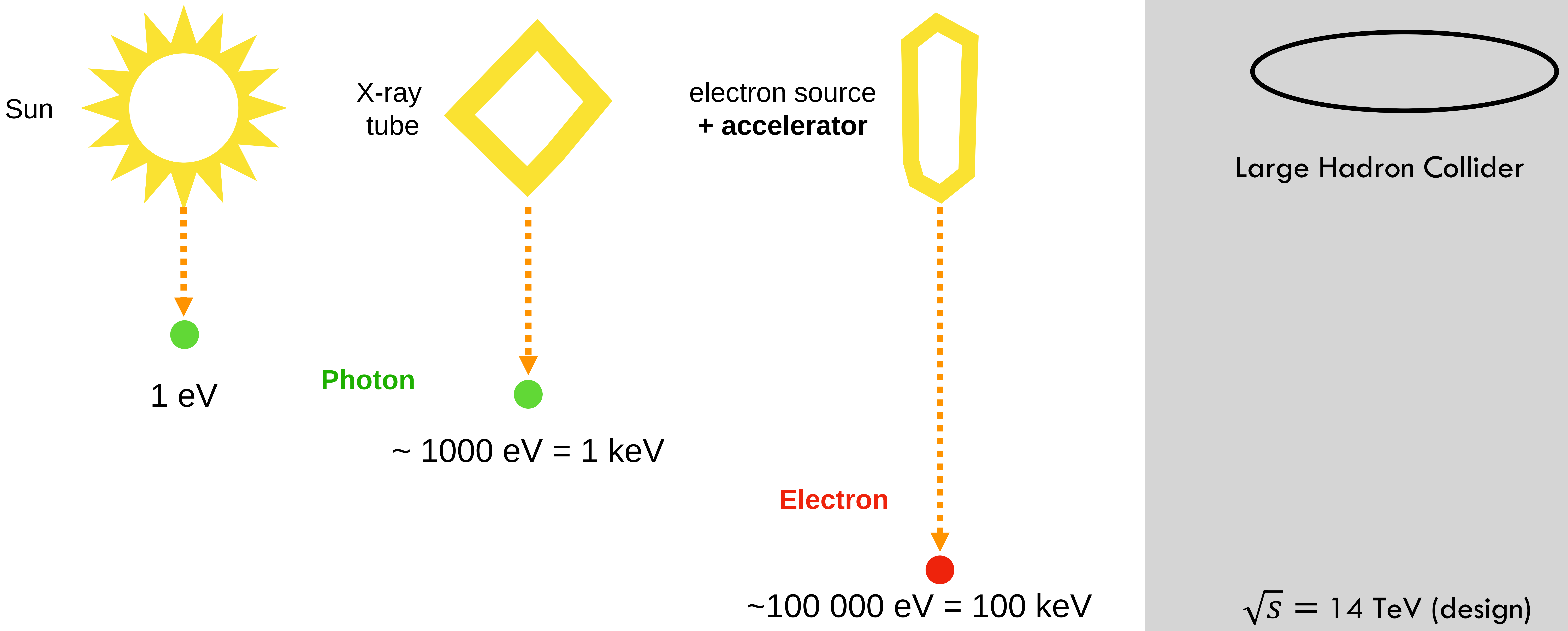


[Image source: EM]
[Image source: Pollen]

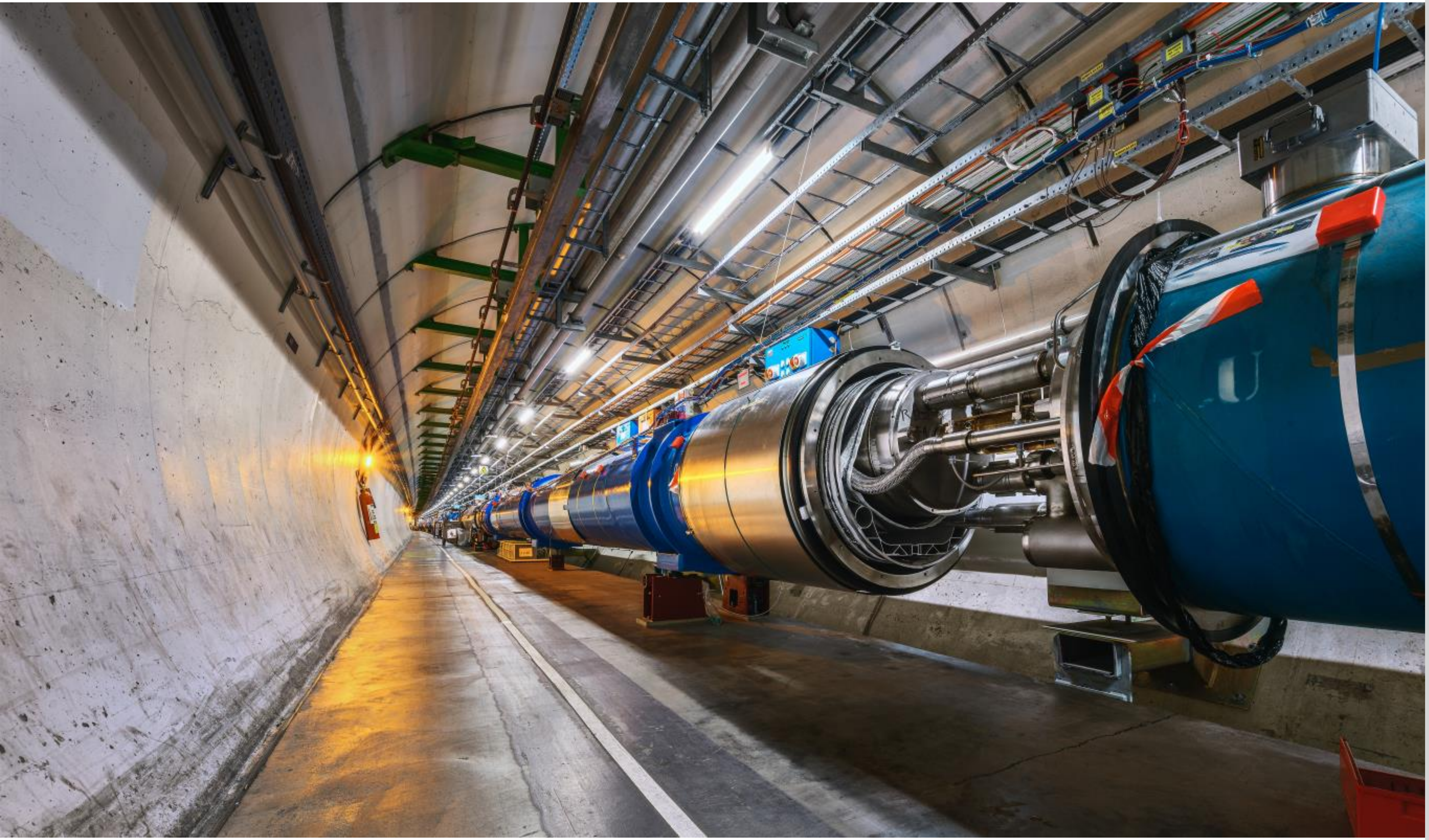
My experiments so far …

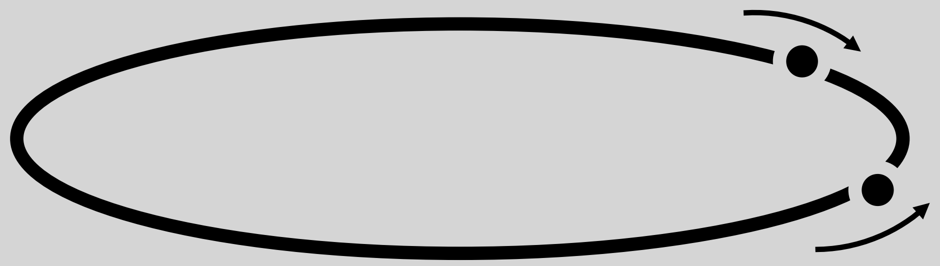


My experiments so far ...



The collider

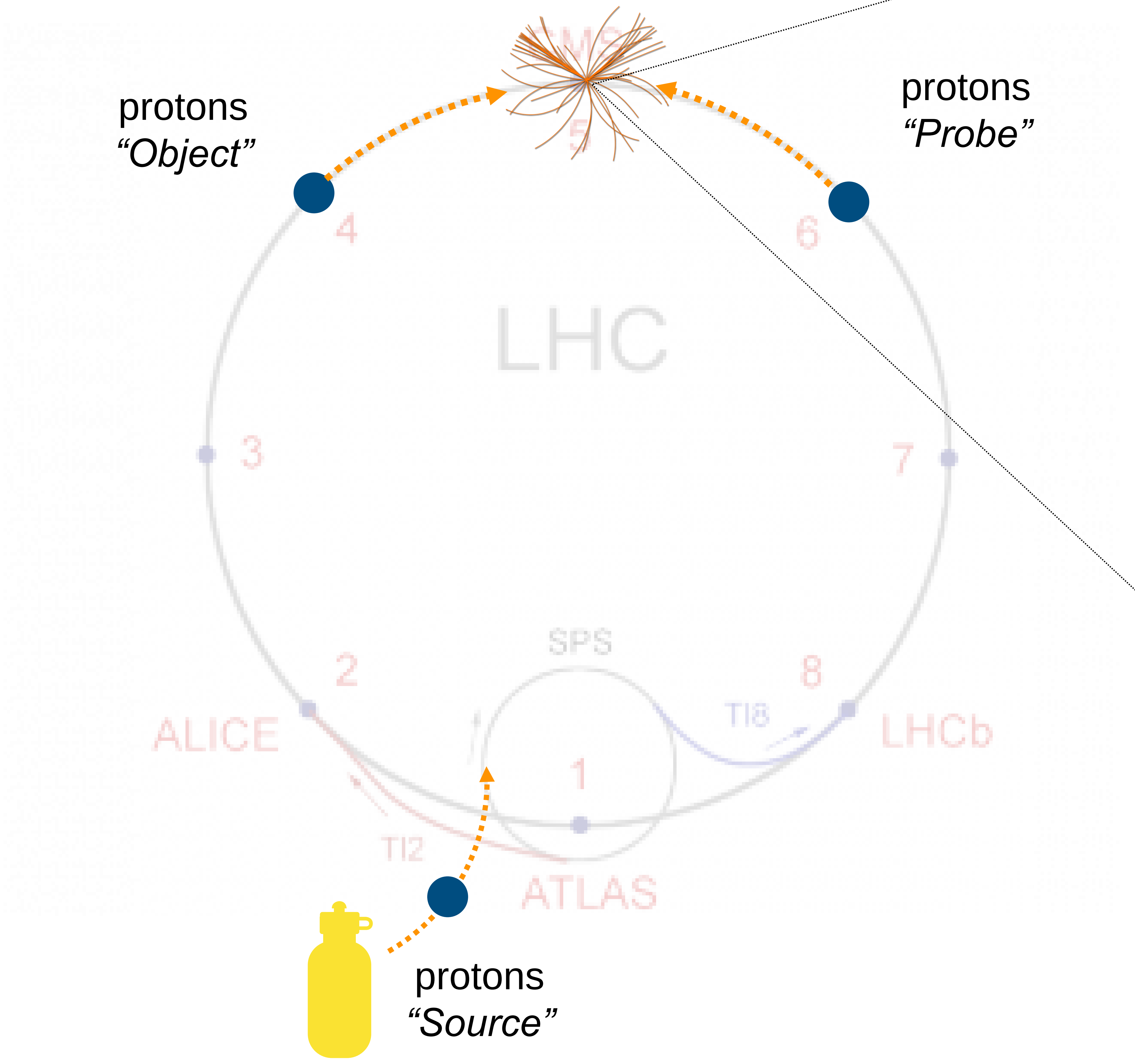


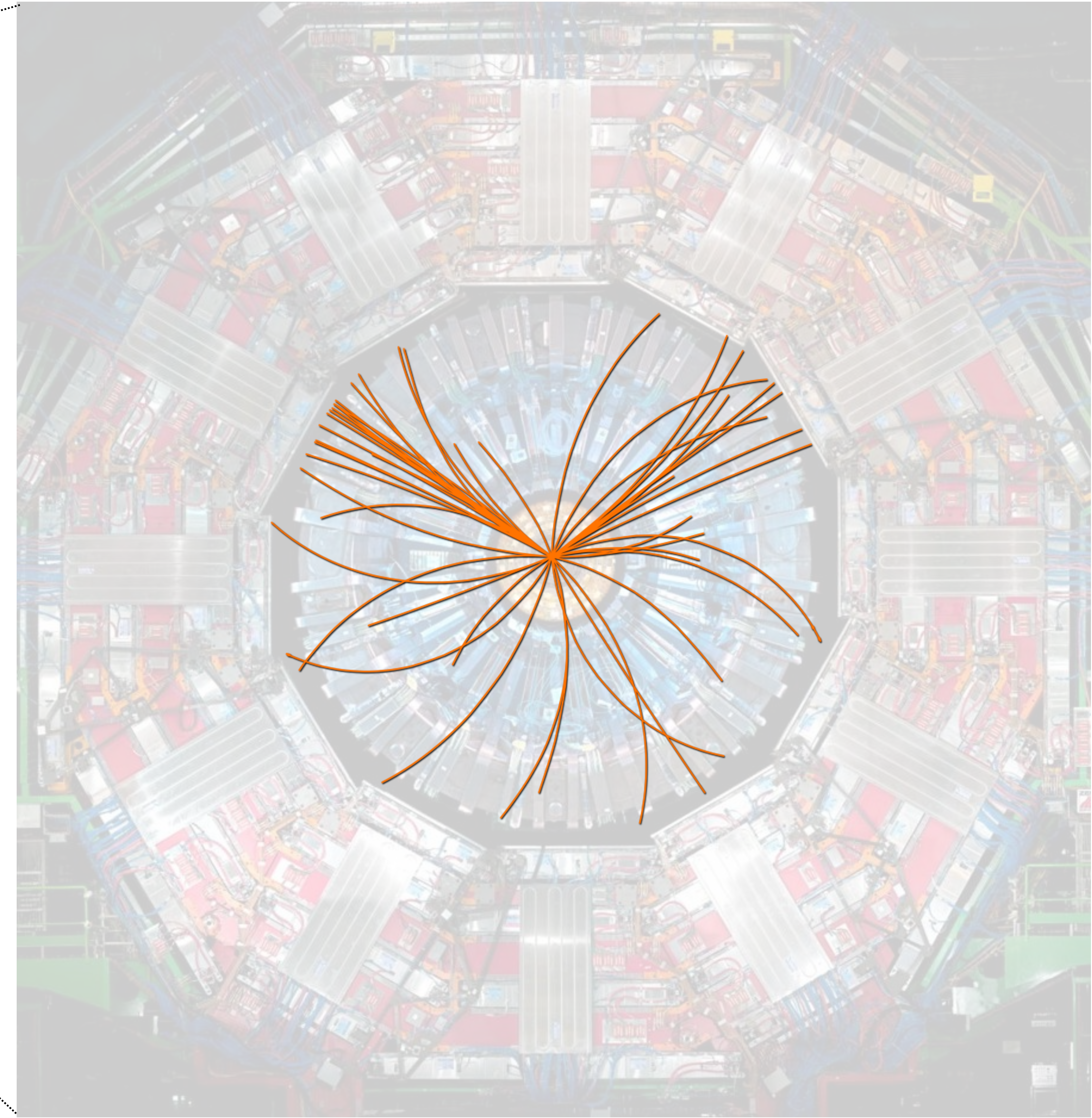


Large Hadron Collider

$\sqrt{s} = 14$ TeV (design)

A very large microscope

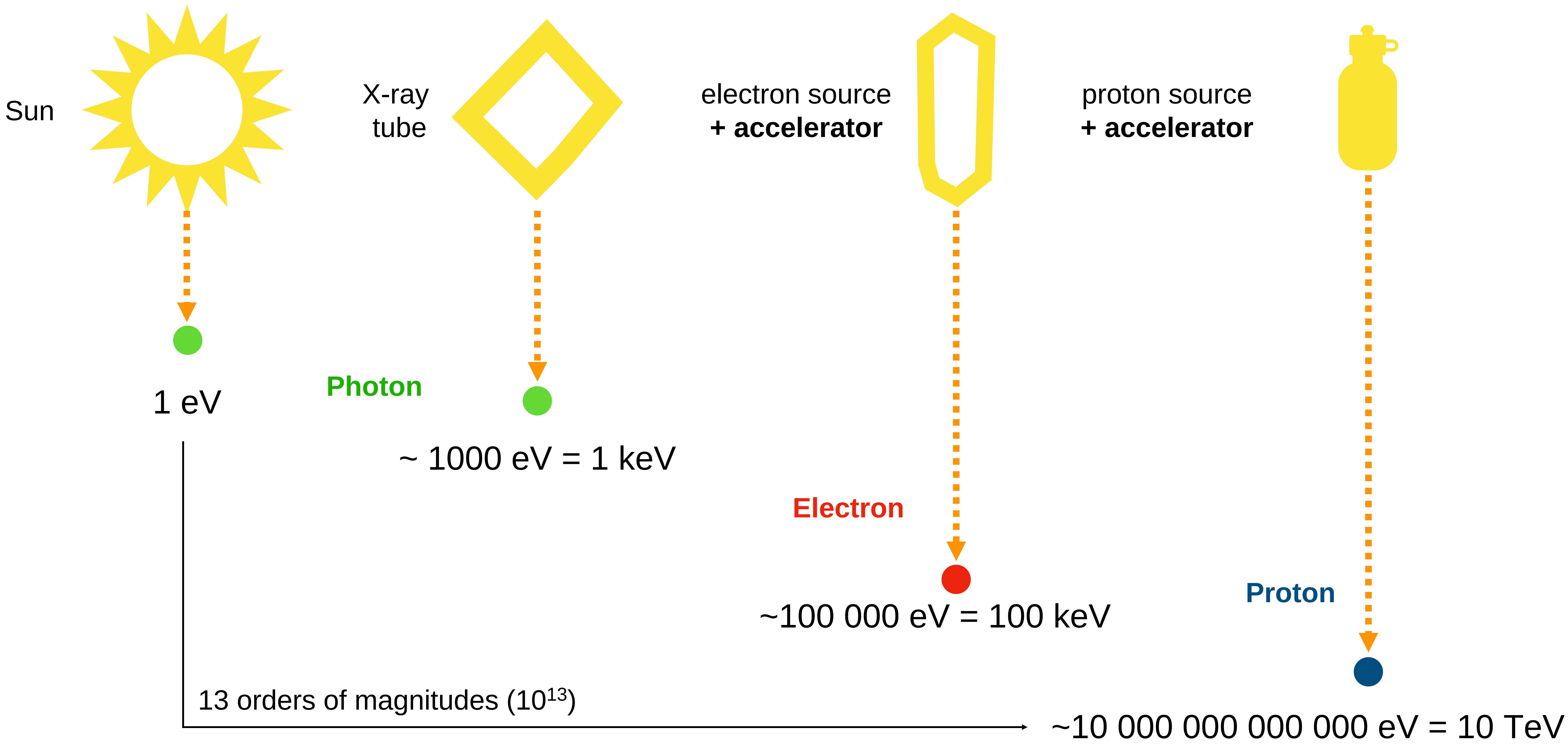




Detector
"Observer"

[Image source]

eV



Sun
X-ray
tube
electron source
+ accelerator
proton source
+ accelerator
1 eV
Photon
~ 1000 eV = 1 keV
Electron
~100 000 eV = 100 keV
Proton
13 orders of magnitudes (10^13)
~10 000 000 000 000 eV = 10 TeV

eV … and what you can see

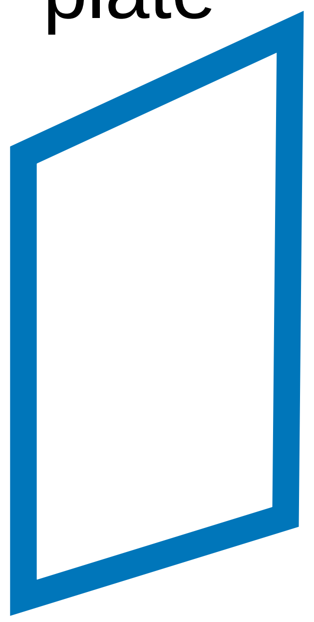
1 eV Photon

eye

1 keV Photon

photo plate

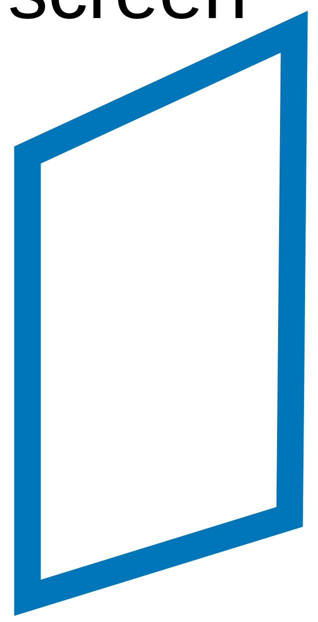
low energy sensor

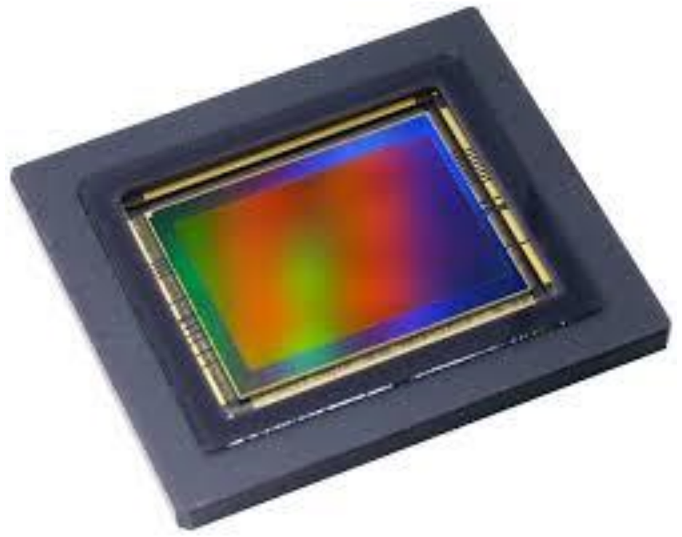


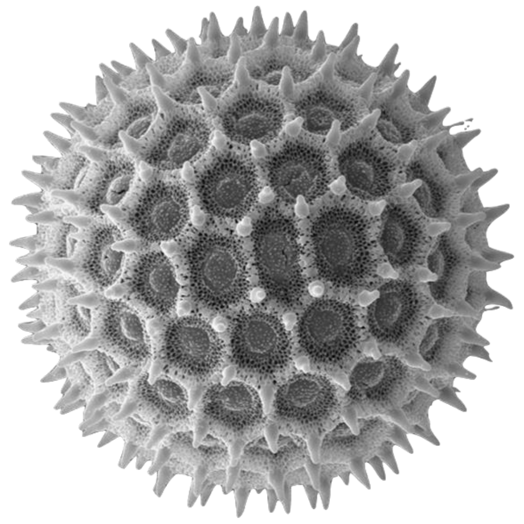
100 keV Electron

fluorescent screen

electron detector

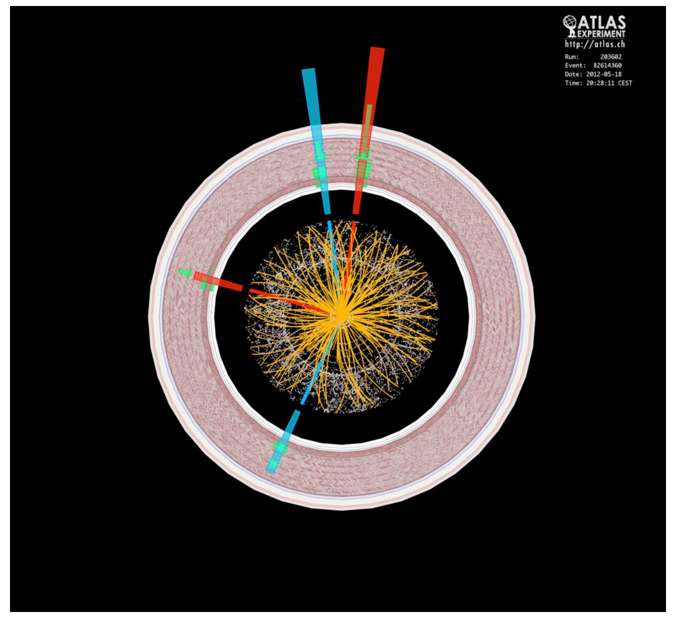


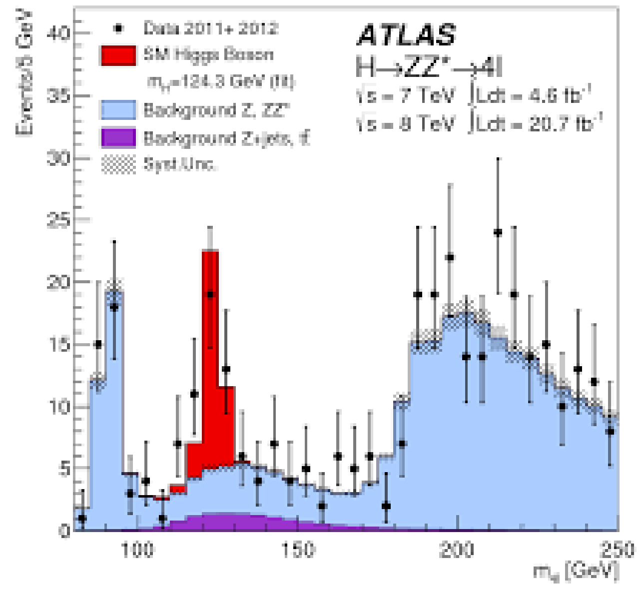




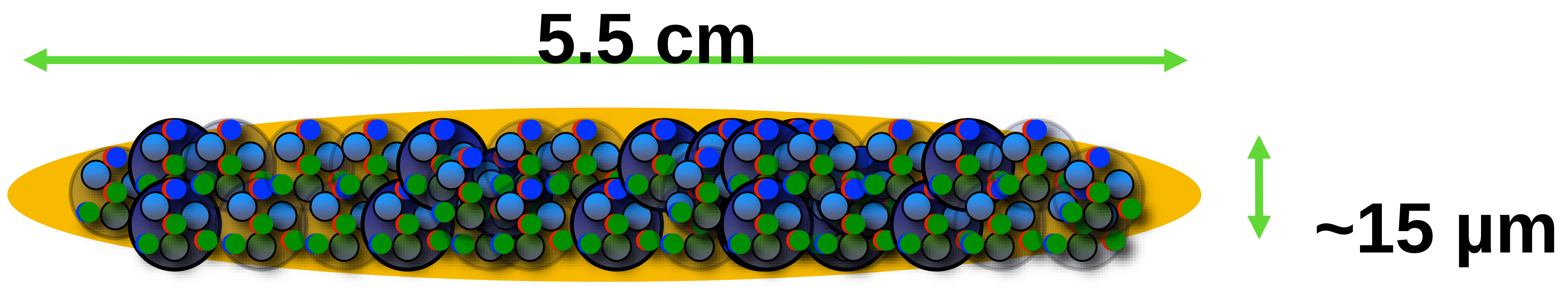
10 TeV Proton

particle detector



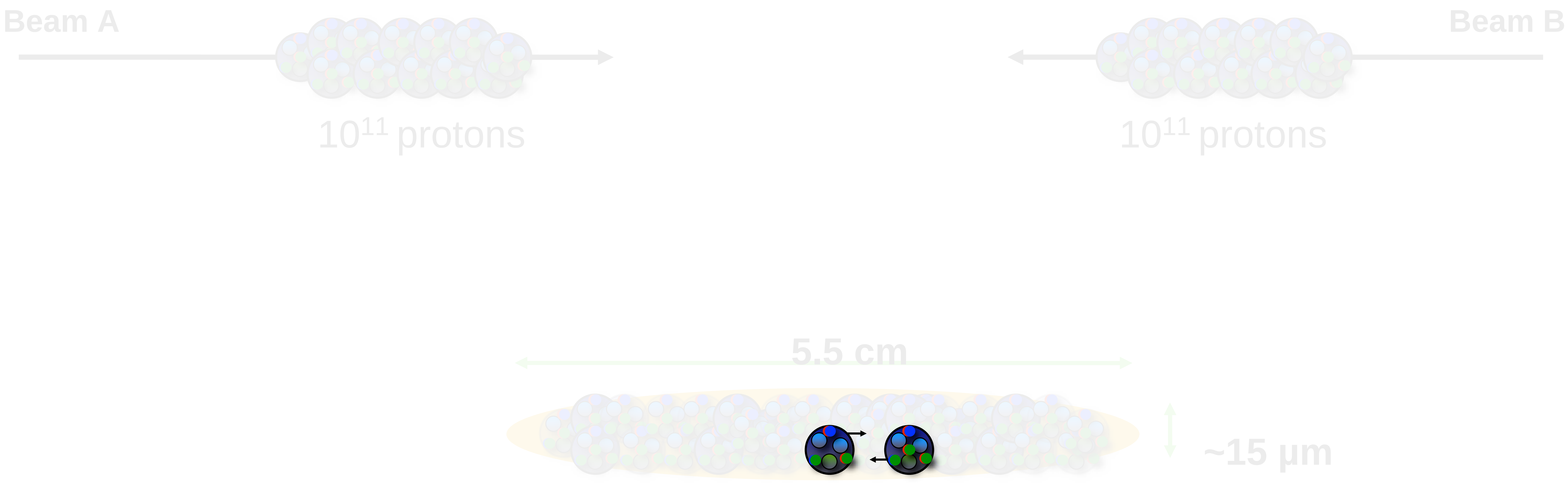


Creating the Higgs Boson



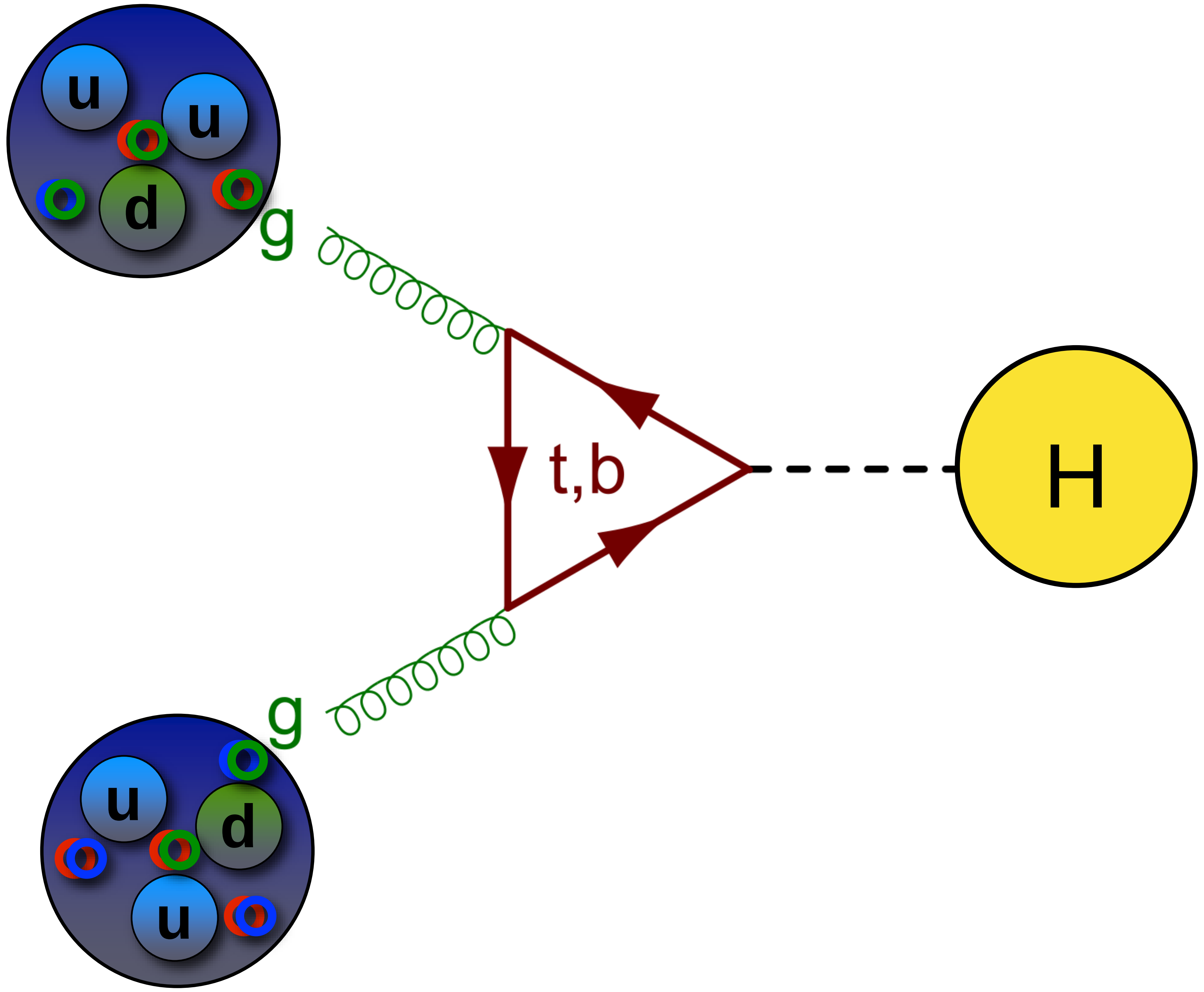
~ 60 individual proton-proton interactions

Creating the Higgs Boson



individual proton-proton interactions

Creating the Higgs Boson



Unfortunately … this does not happen often.

The boring regime:
"probability" of
any interaction

10^{10}

The exciting regime:
"probability" of
a Higgs boson
production

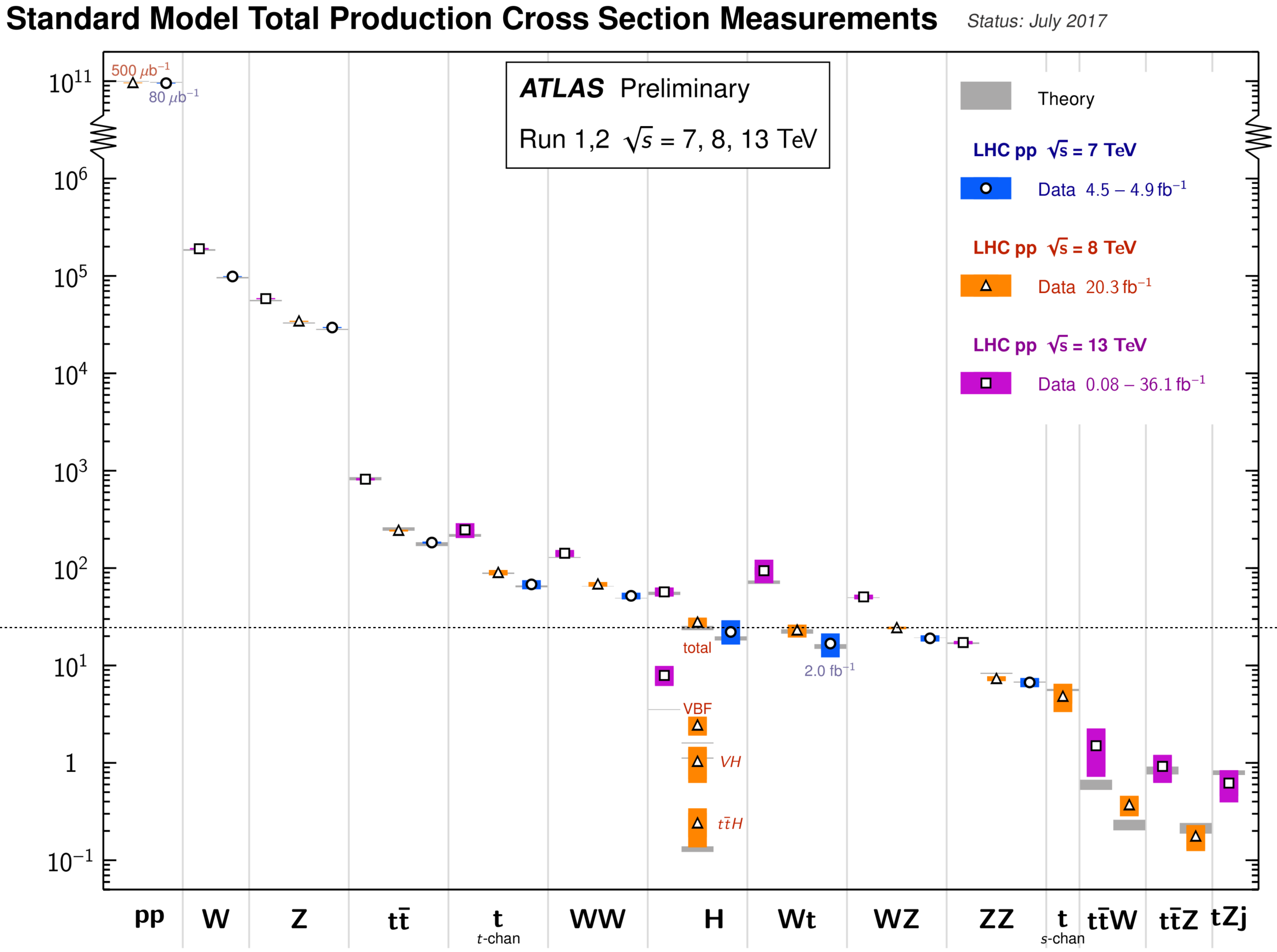
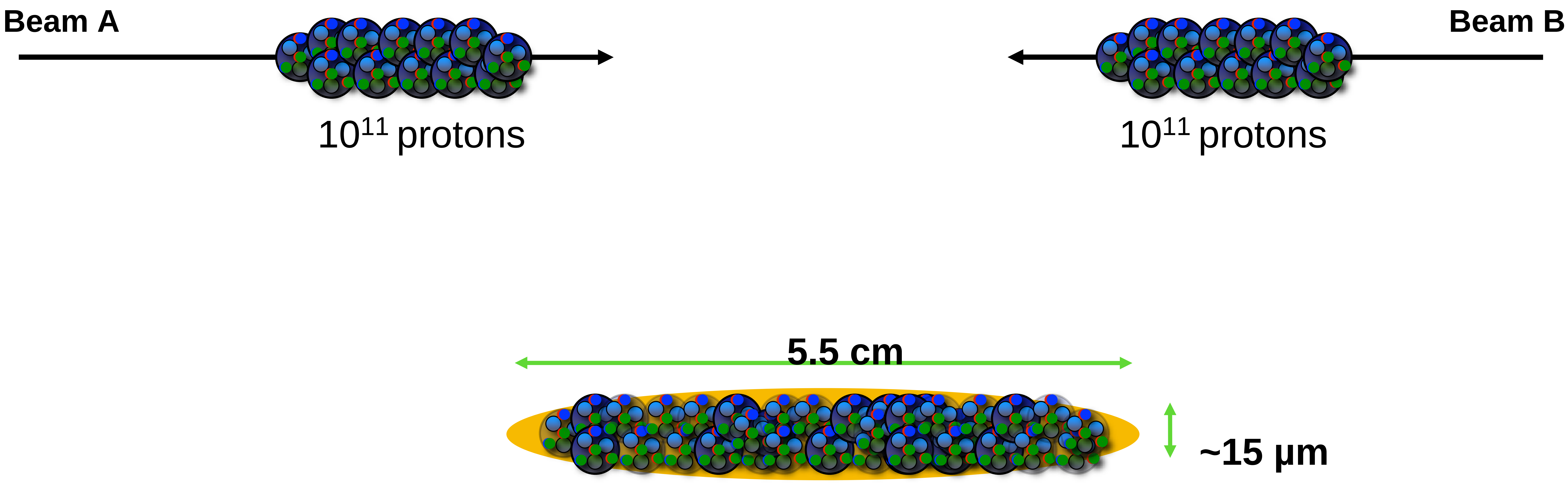


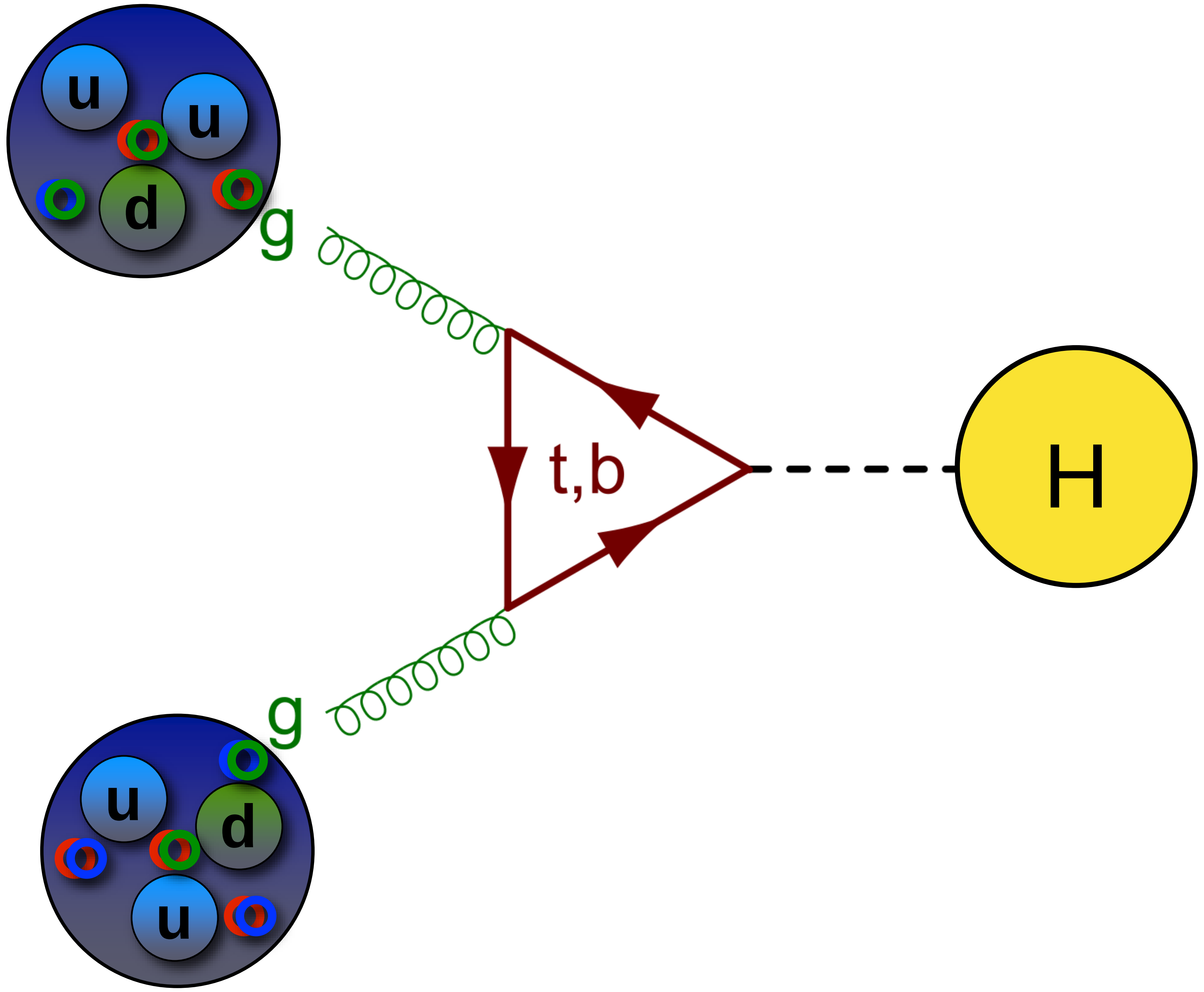
Figure:
Standard Model cross sections measured with the ATLAS experiment
and compared to theoretical predictions, July 2017

This is why we do this every 25 nanoseconds!

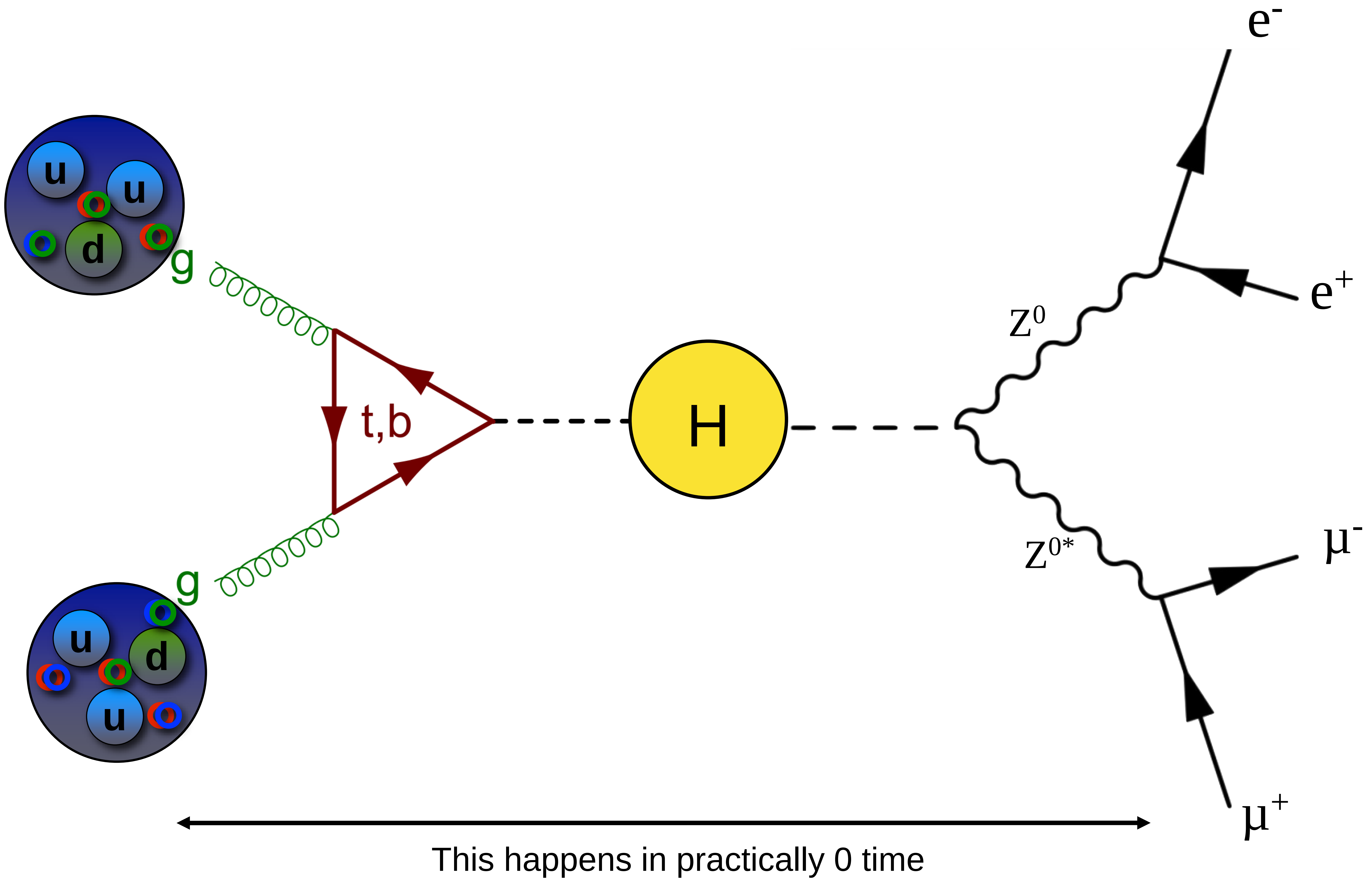


~ 60 individual proton-proton interactions

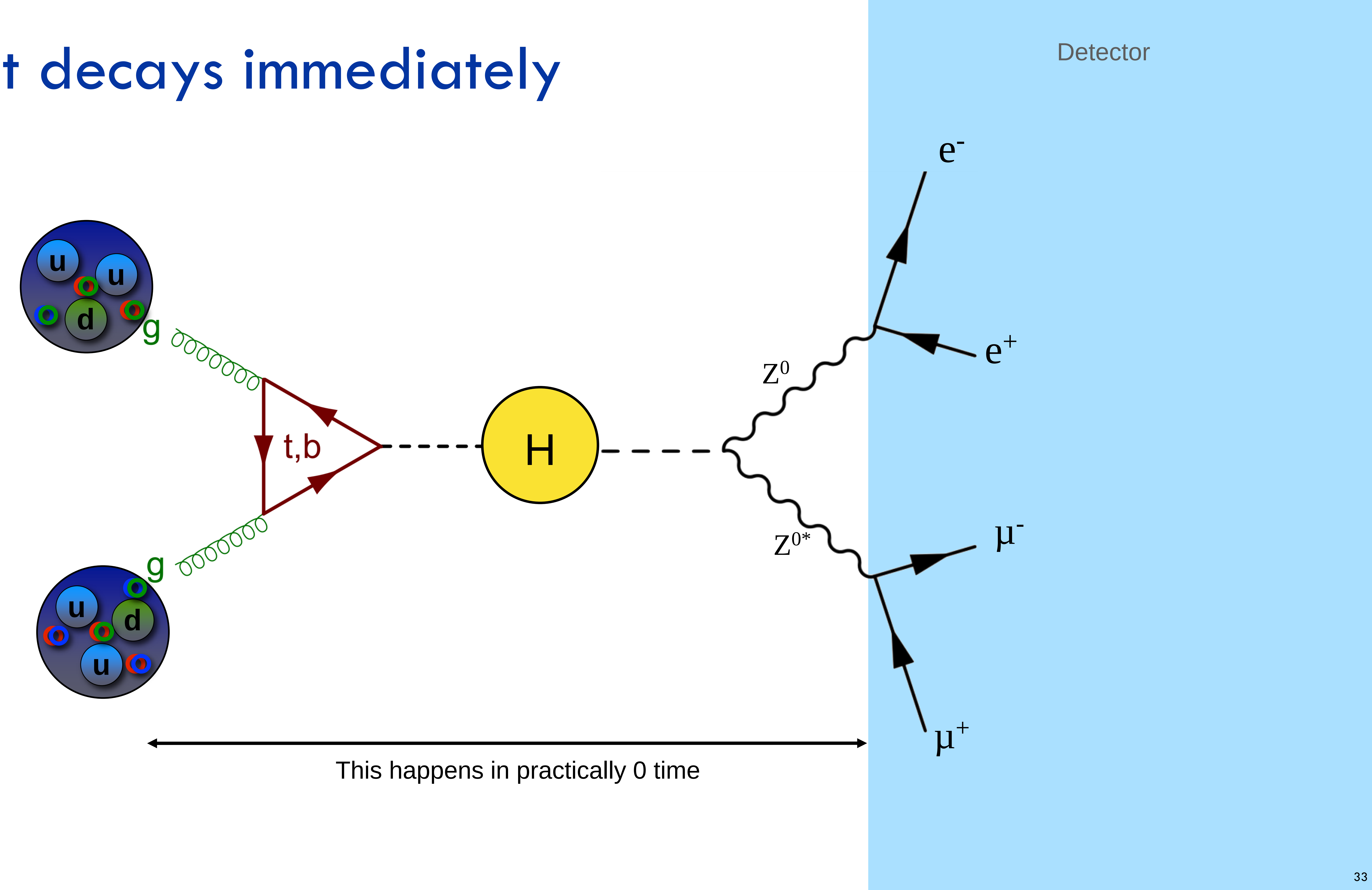
… and when it happens …



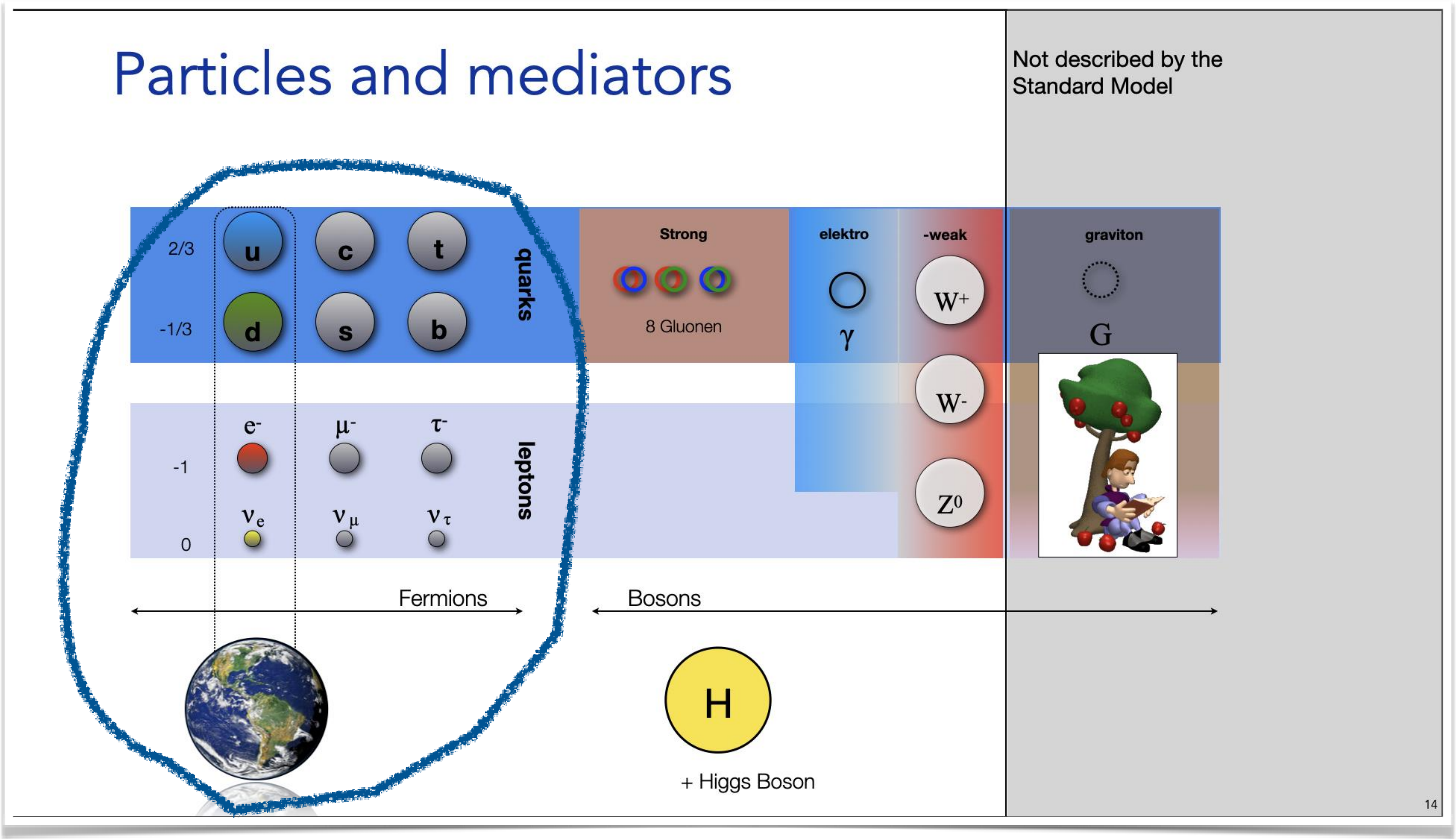
… it decays immediately



… it decays immediately

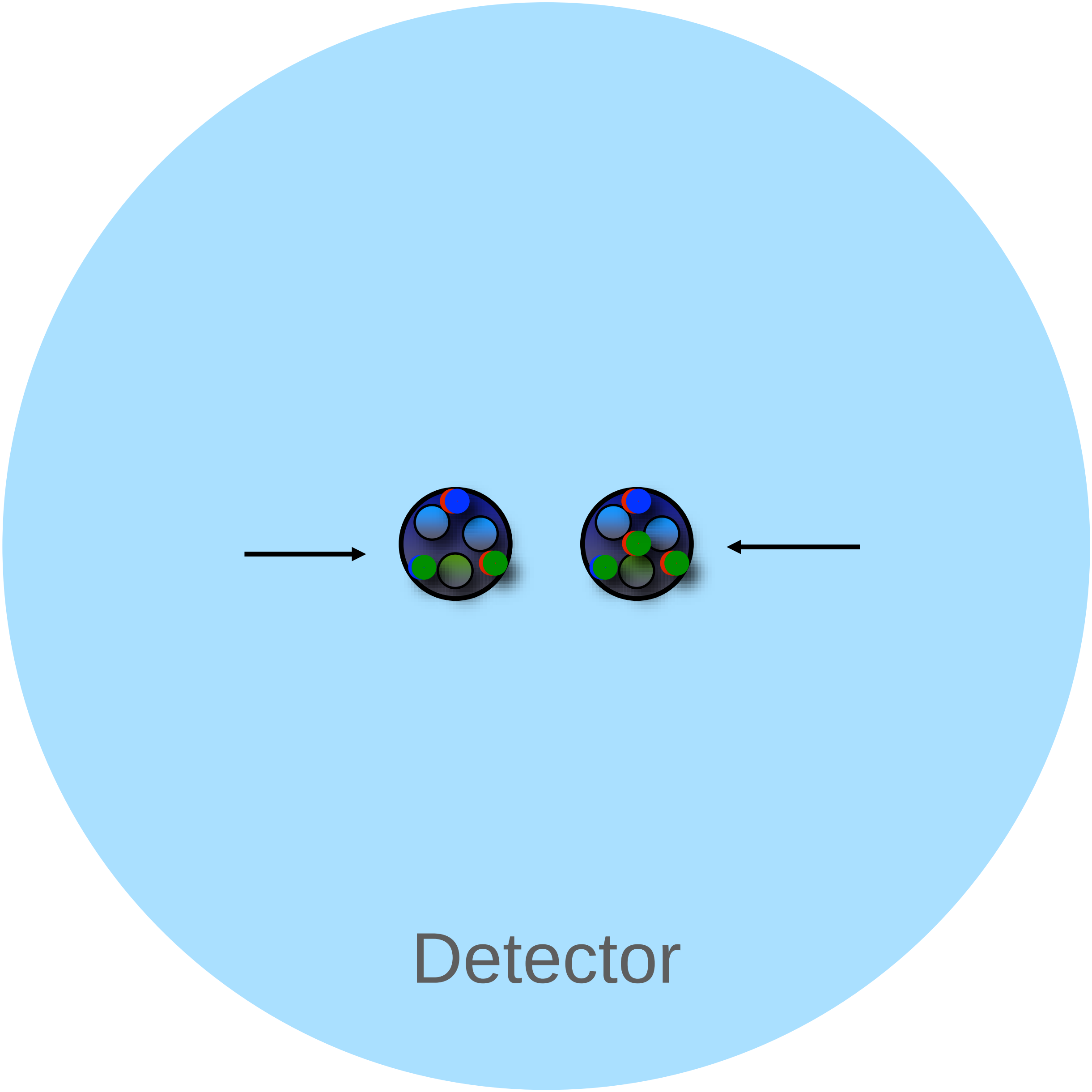


… anti-what?

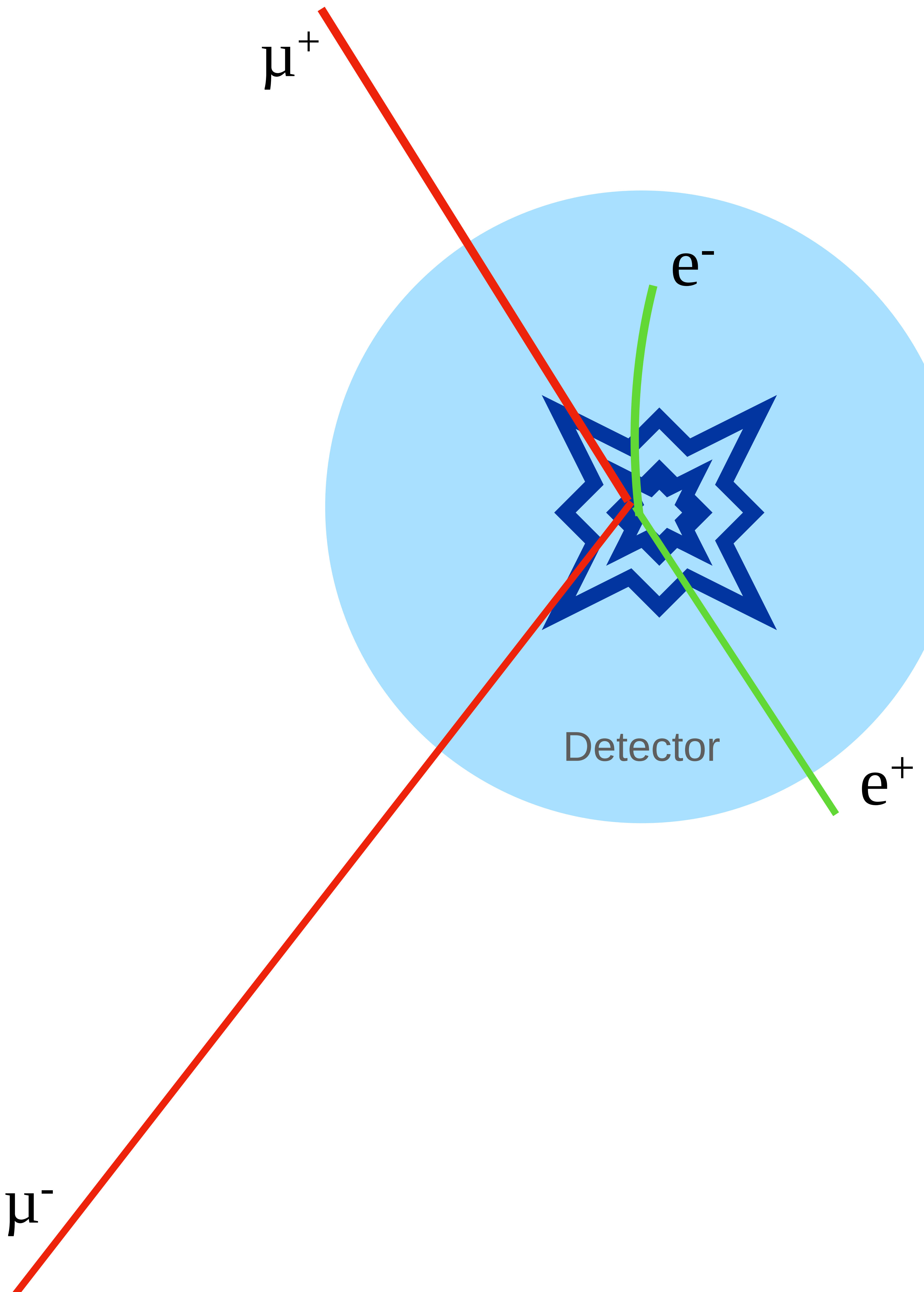


These particles also exist in their anti-matter form …

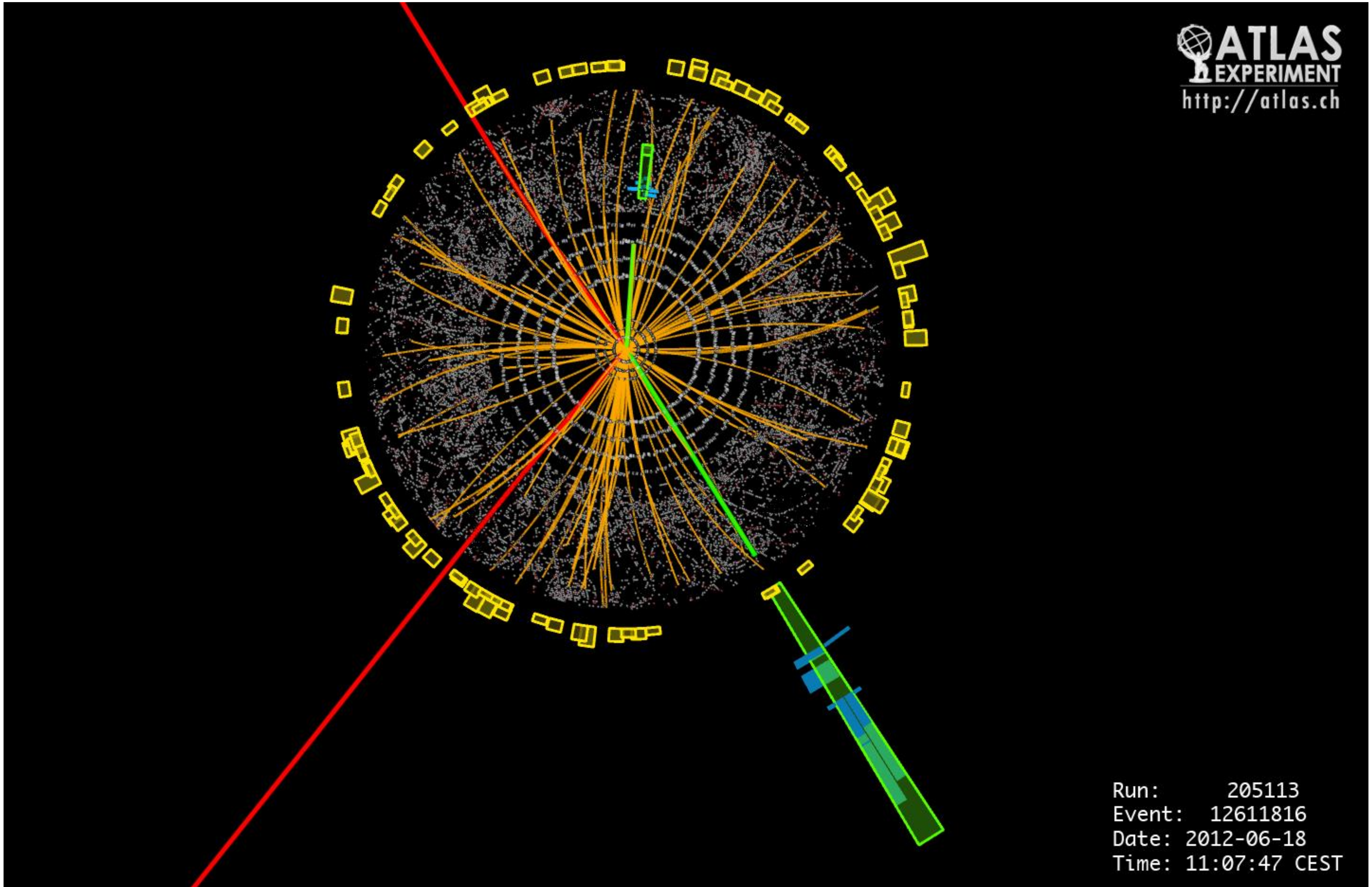
… in our world this looks like



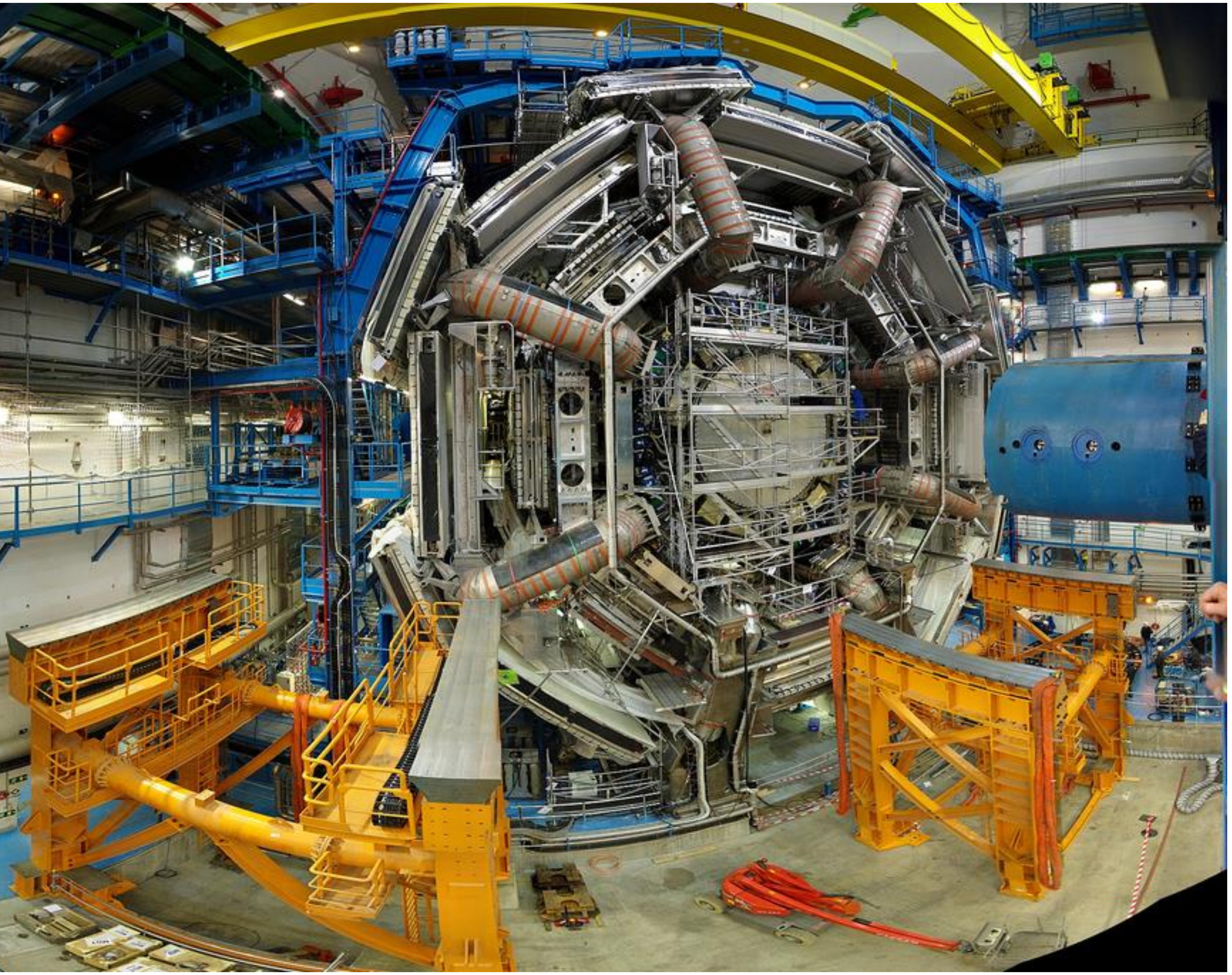
… in our world this looks like



… in our world this looks like

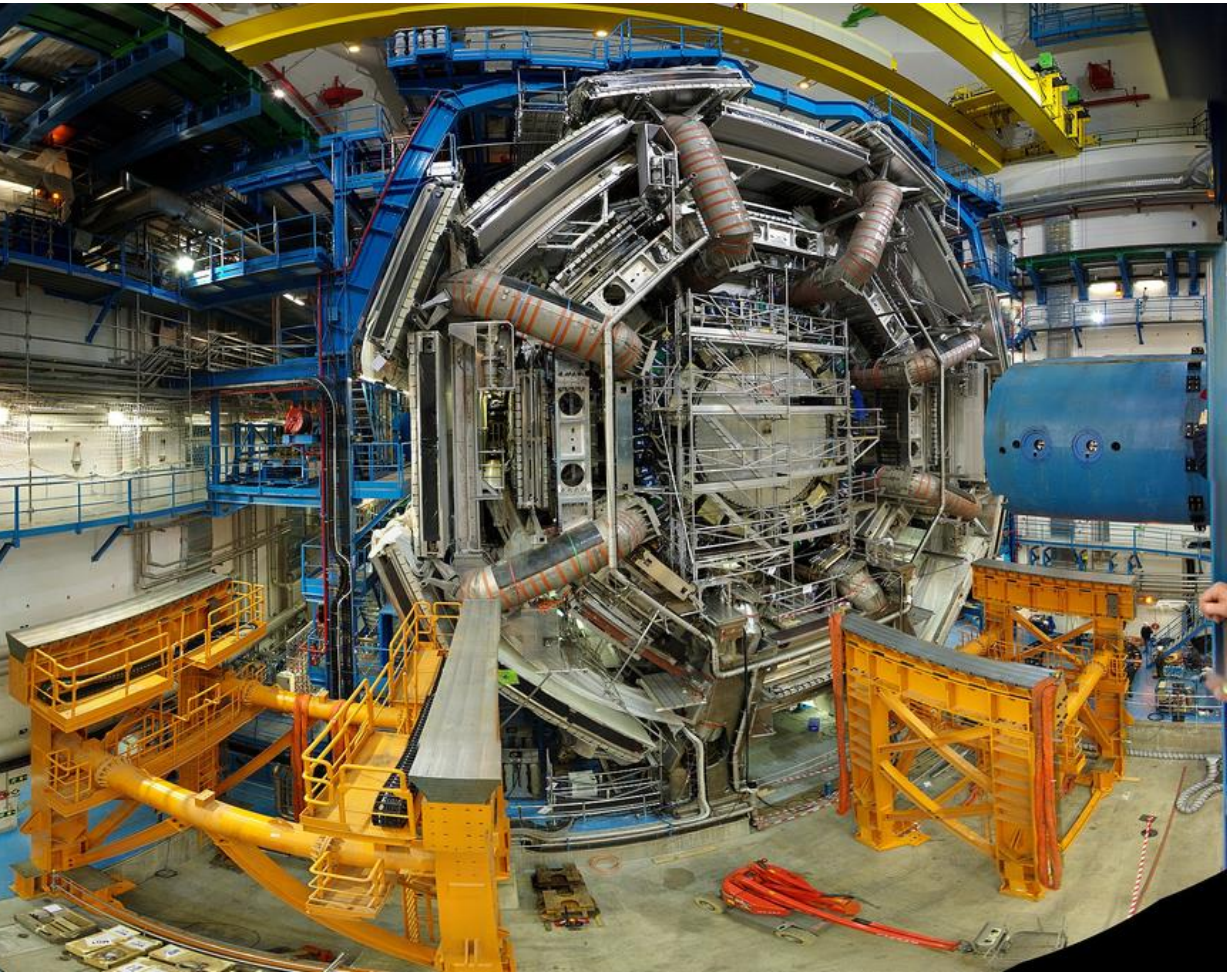


… does it though?

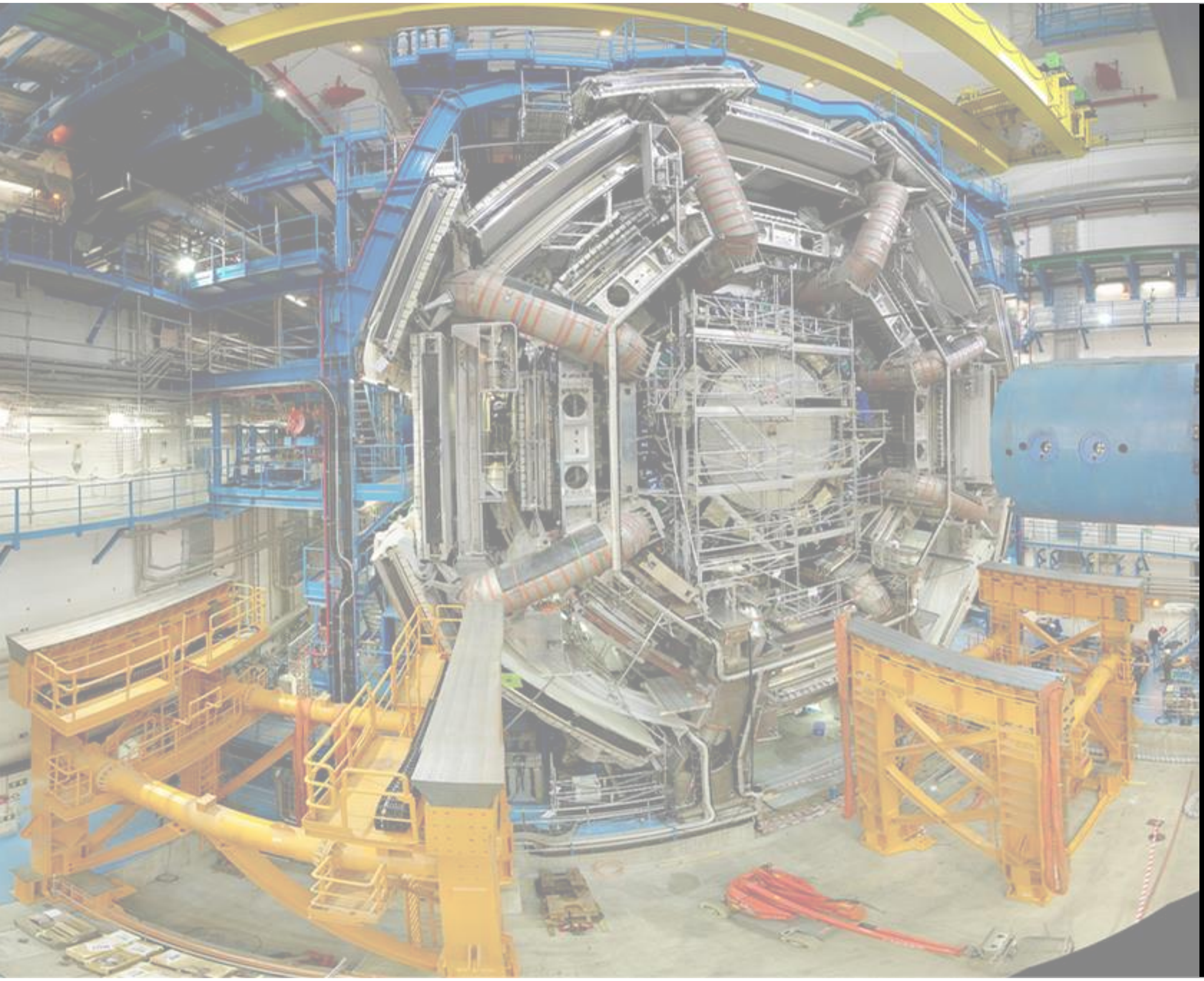


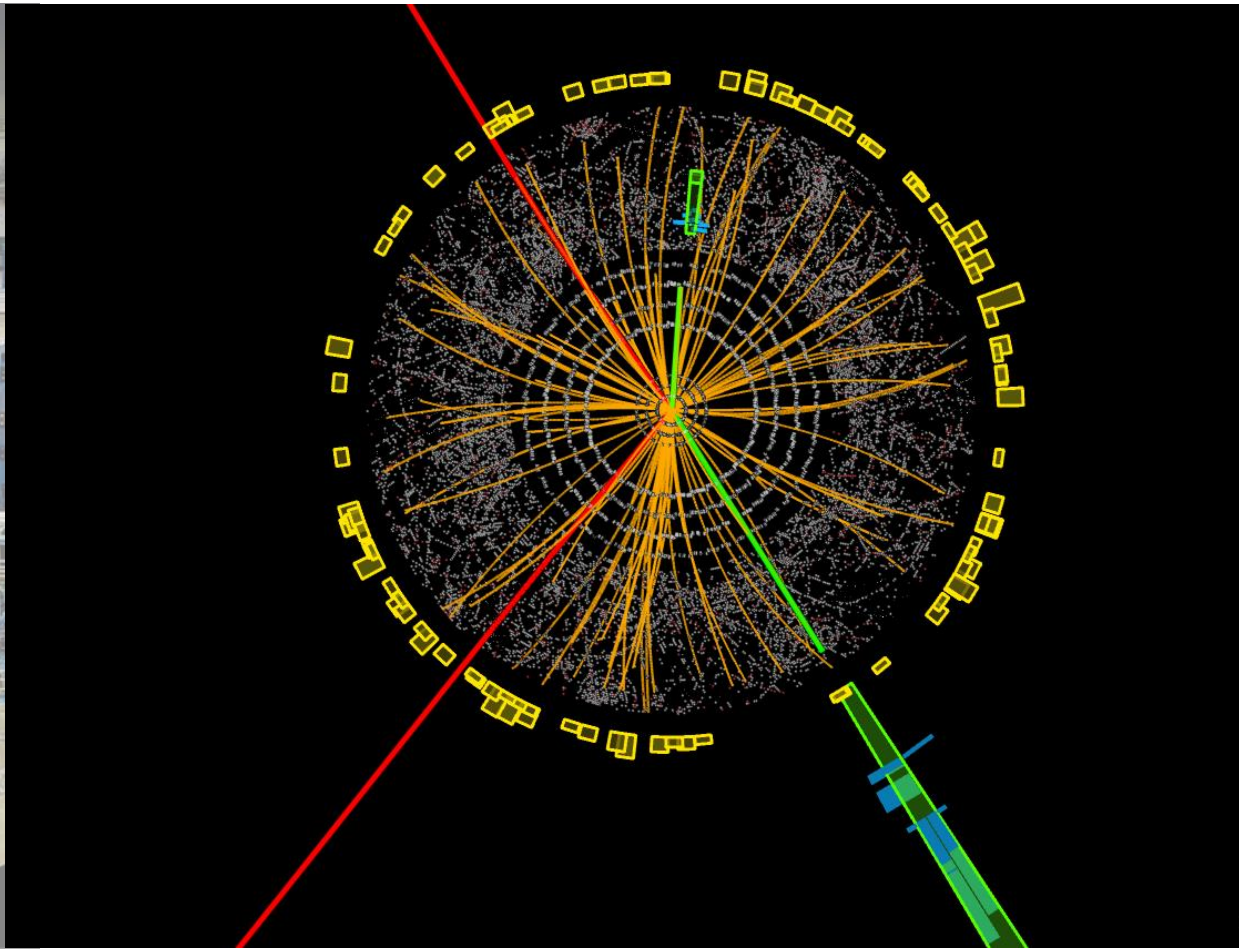
The ATLAS detector

How to get from here …



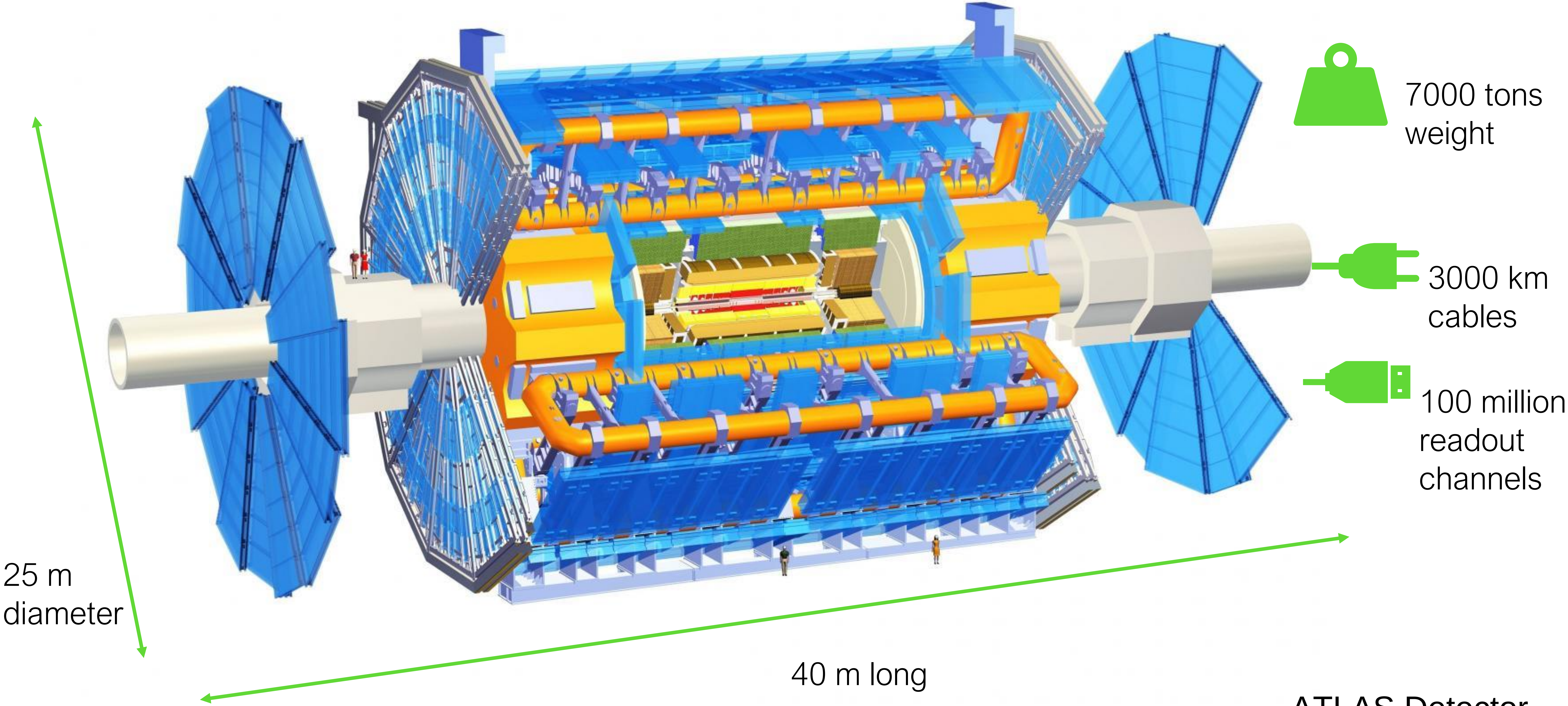
How to get from here …





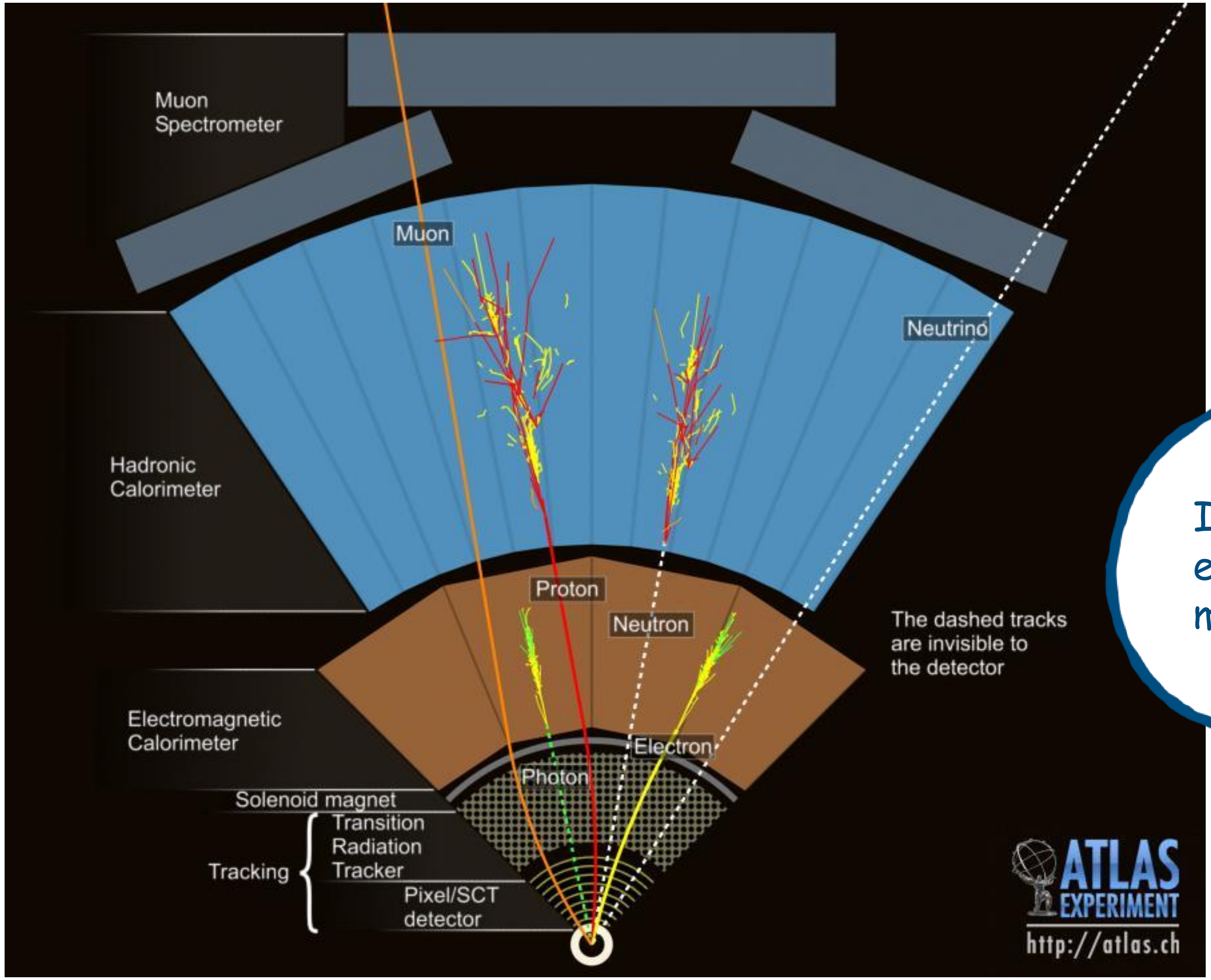
… to here ?

Detector

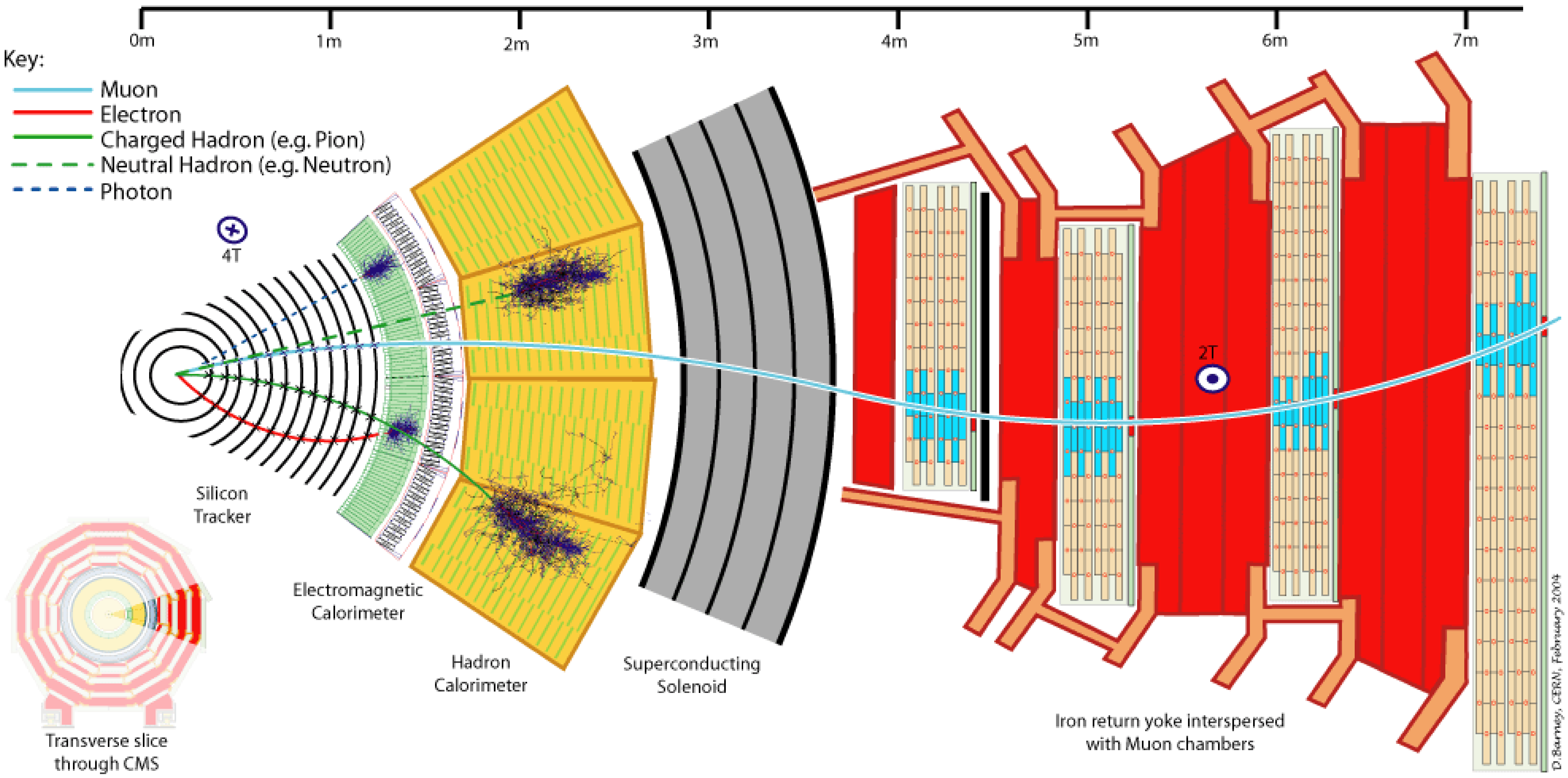


ATLAS Detector

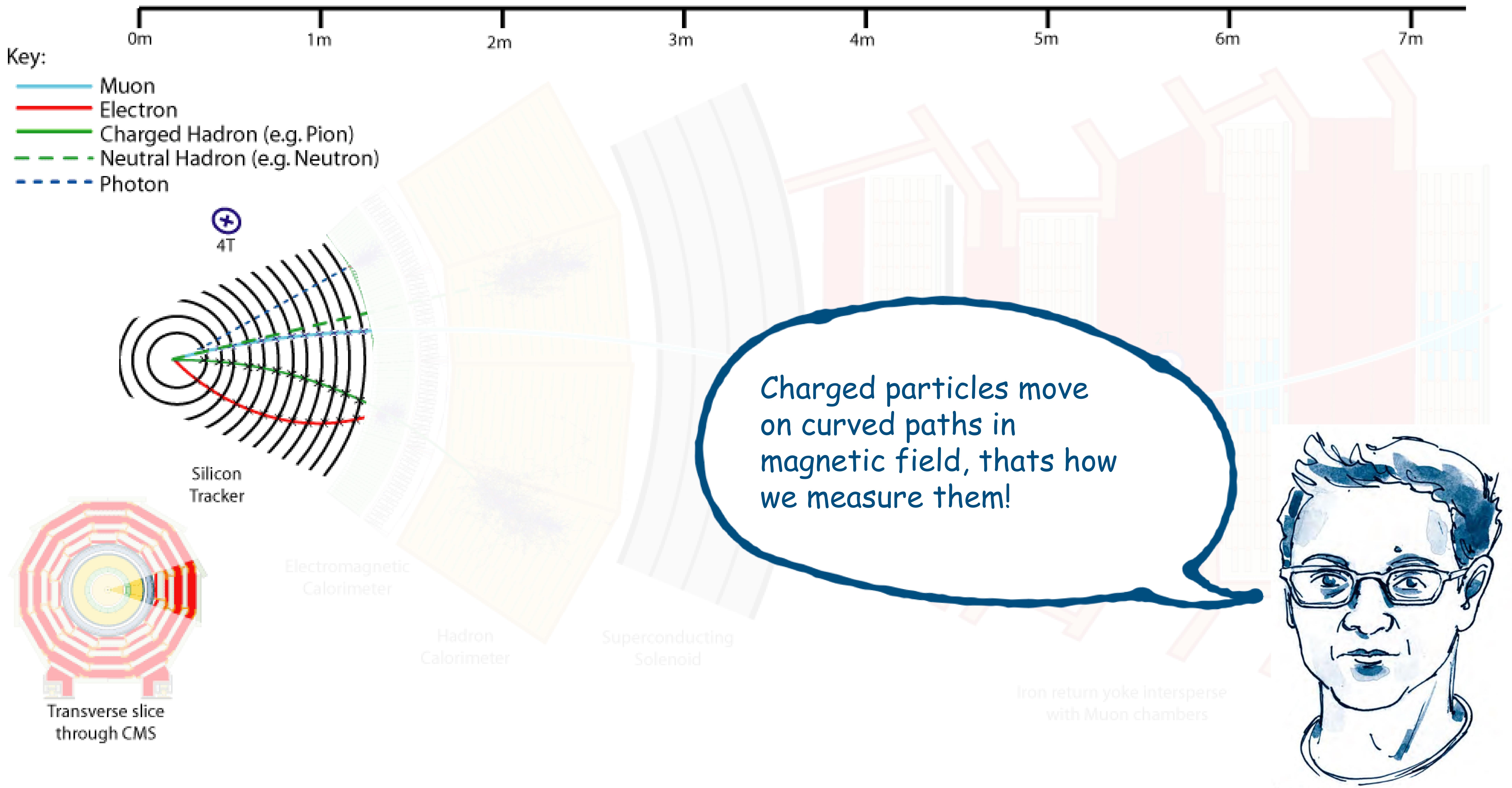
… and it's principle



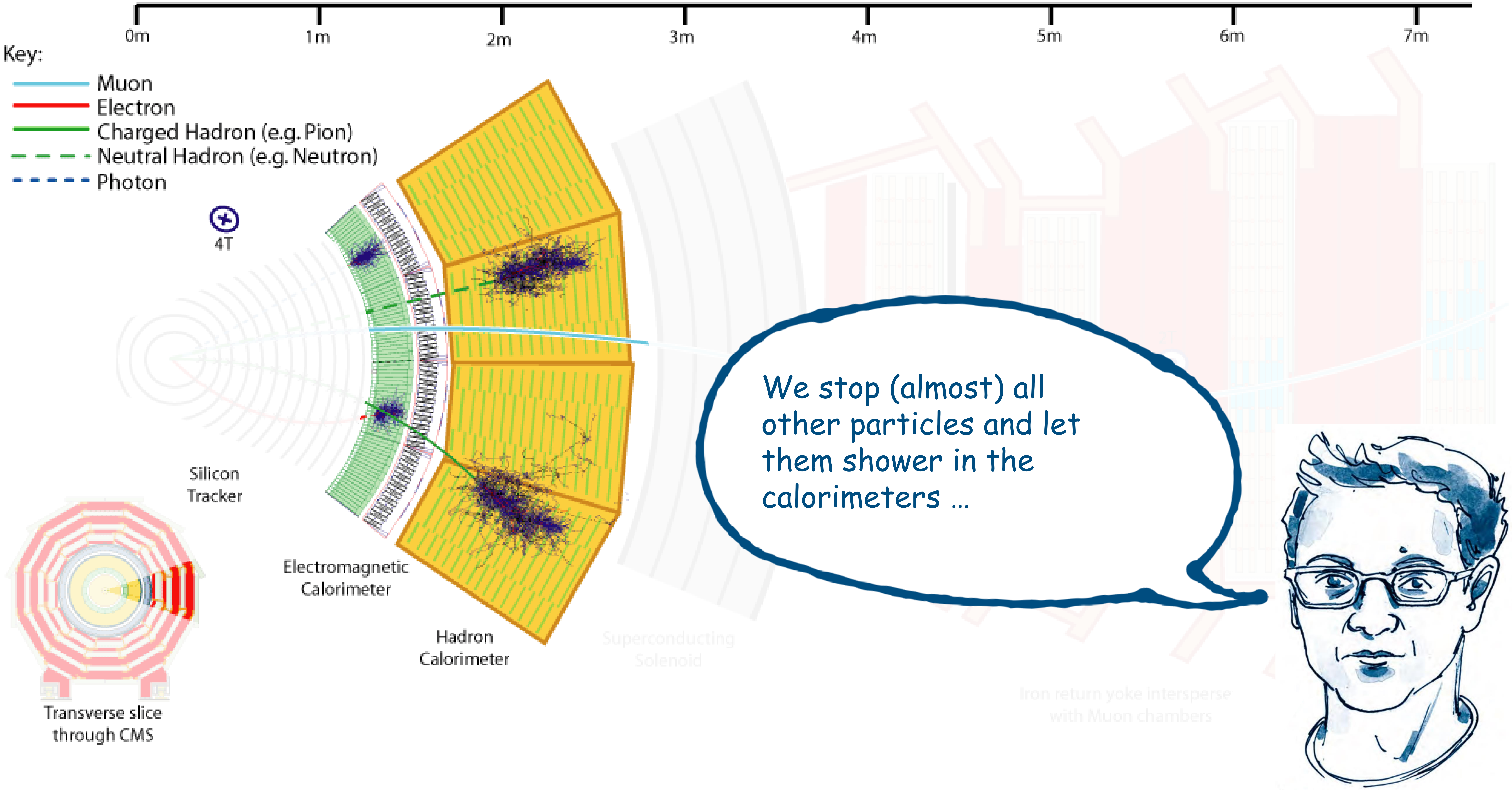
… and it's principle



Tracking

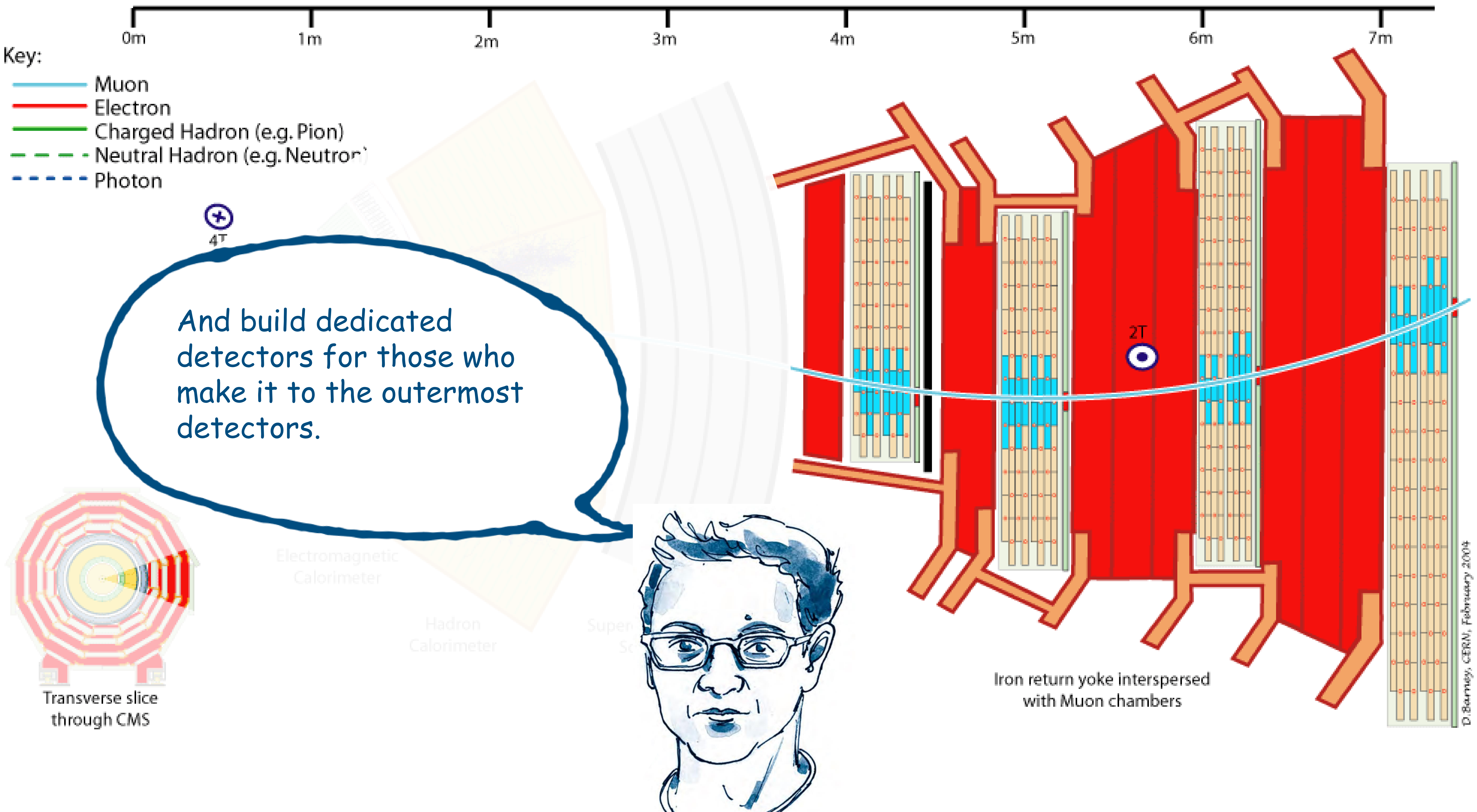

0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
Silicon Tracker
Transverse slice through CMS
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Charged particles move on curved paths in magnetic field, thats how we measure them!

Calorimetery



We stop (almost) all other particles and let them shower in the calorimeters …

Muon System



0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
And build dedicated detectors for those who make it to the outermost detectors.
Transverse slice through CMS
Iron return yoke interspersed with Muon chambers
D.Barney, CERN, February 2004

Let’s skip back one step …

Unfortunately … this does not happen often.

The boring regime:
“probability” of
any interaction

10^{10}

The exciting regime:
“probability” of
a Higgs boson
production

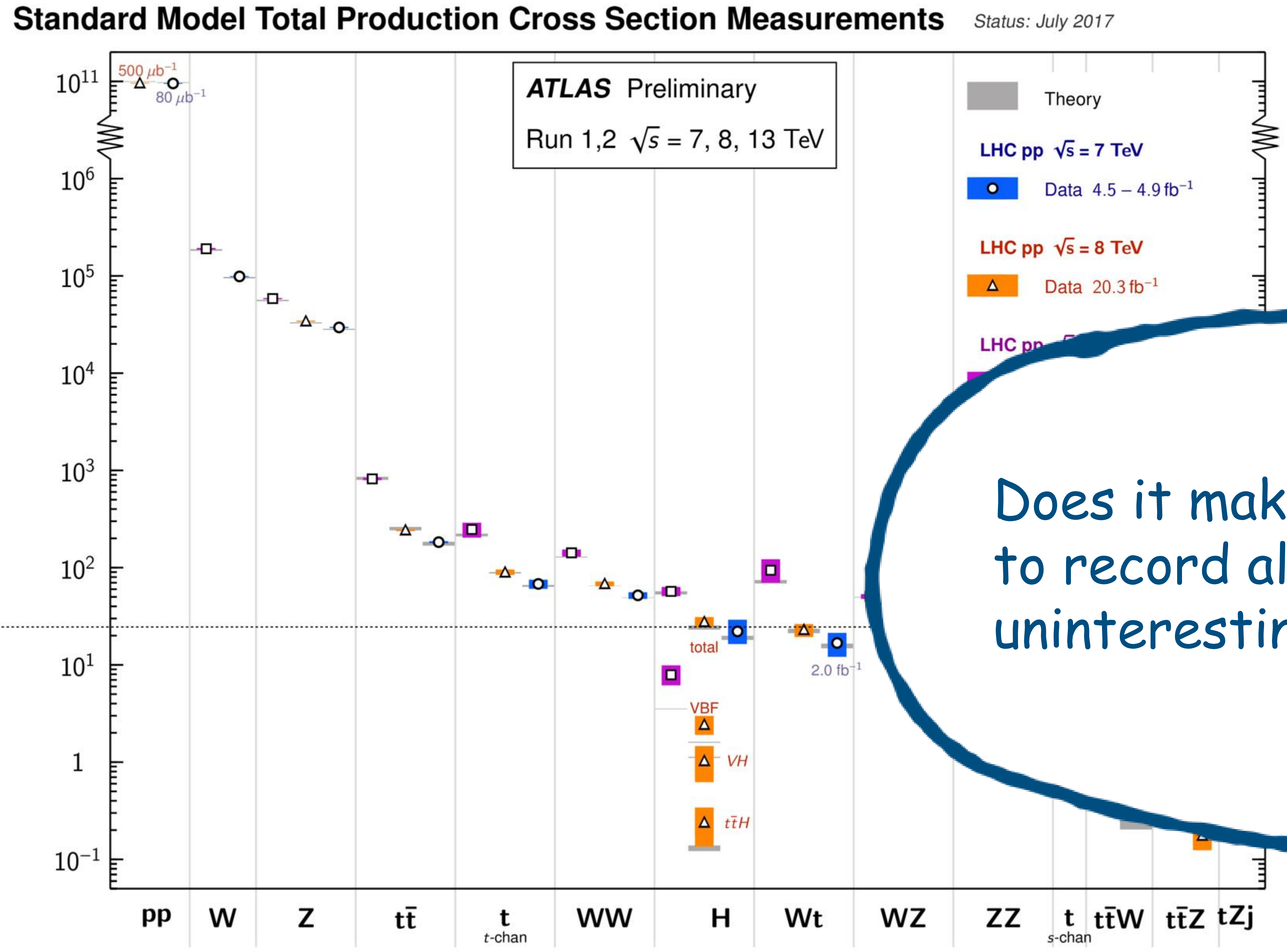
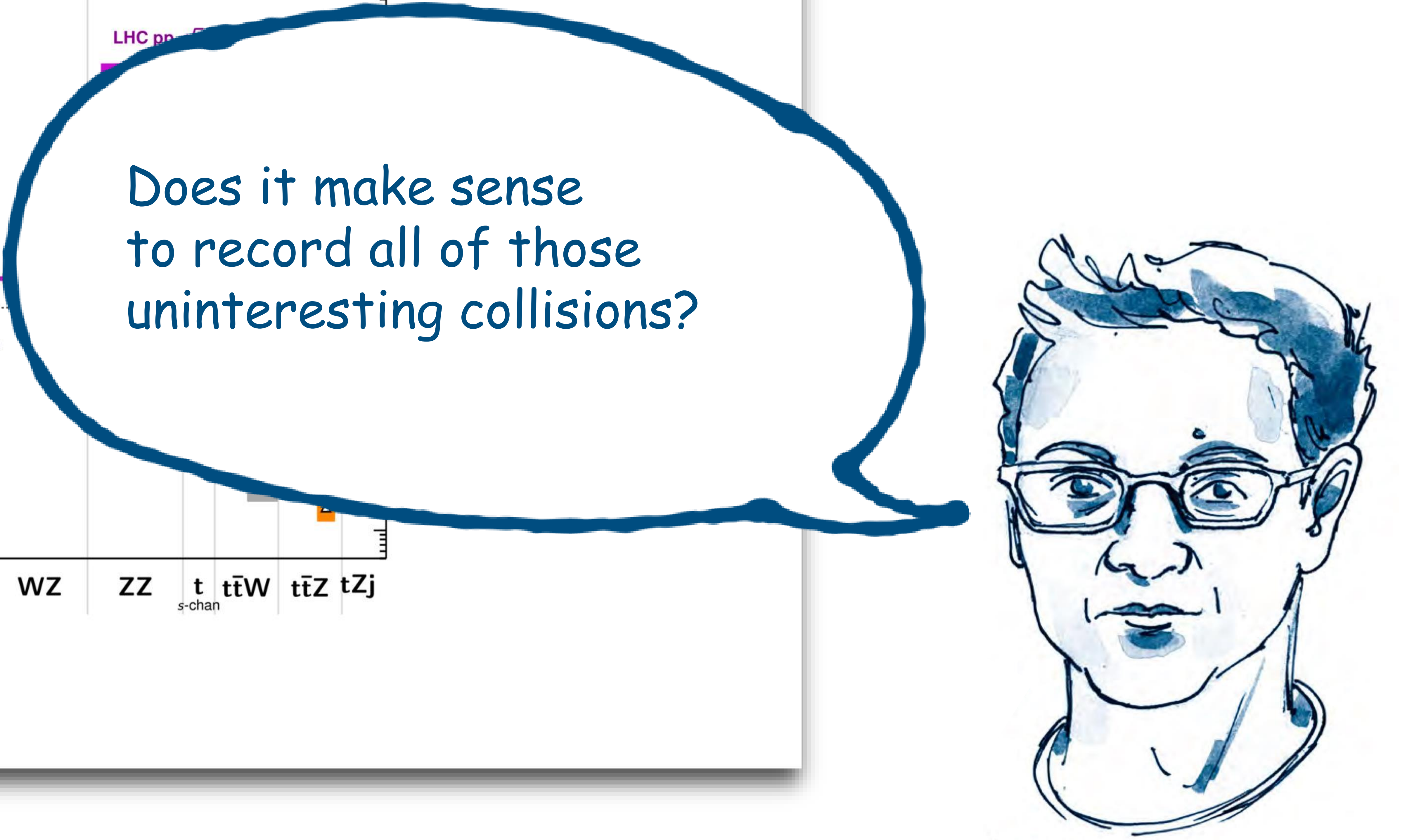
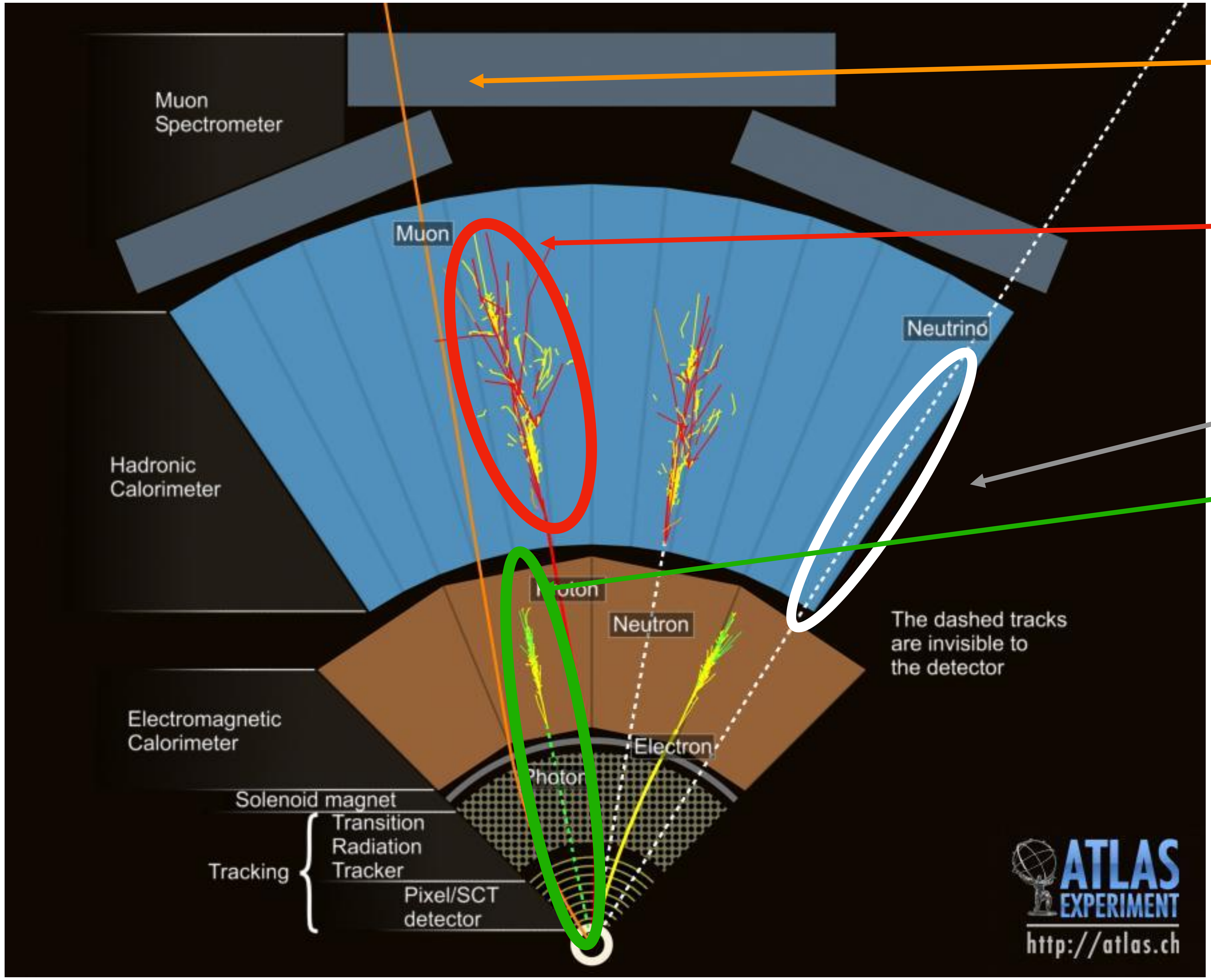


Figure:
Standard Model cross sections measured with the ATLAS experiment and compared to theoretical predictions, July 2017



We need a selection …

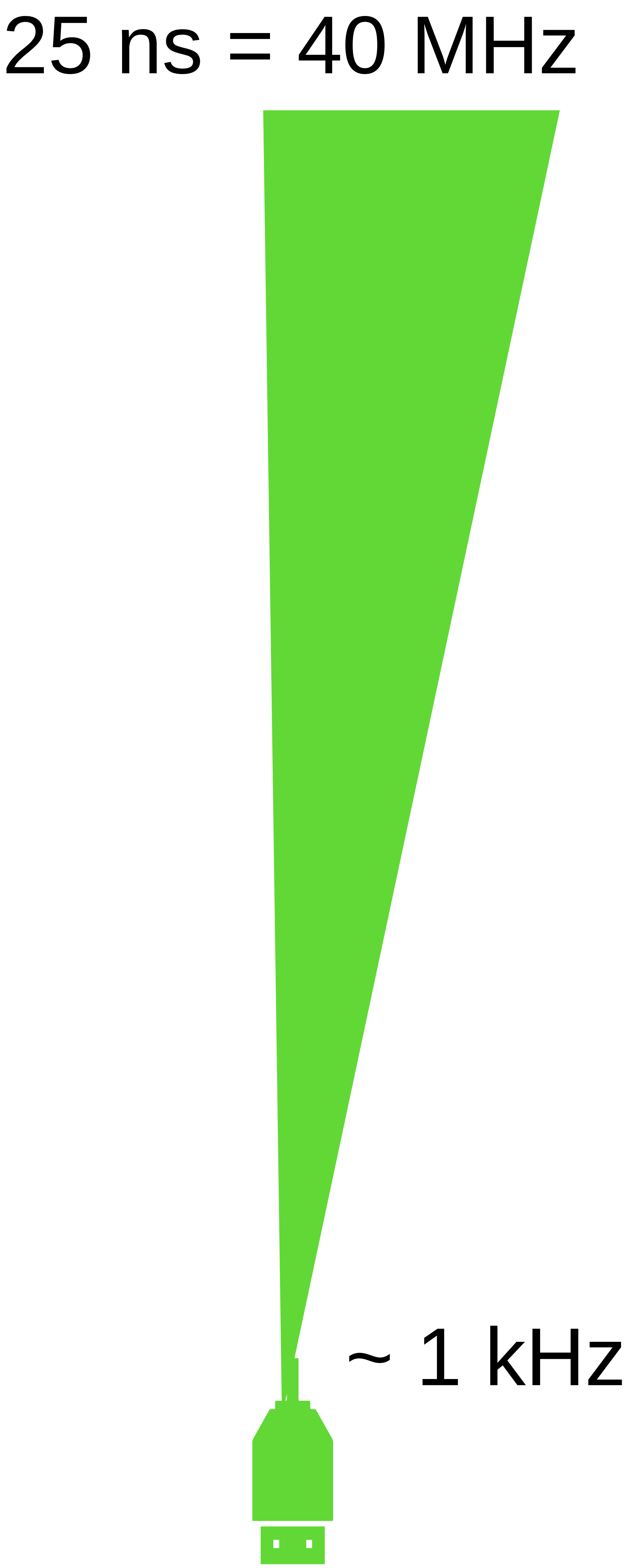


coincidence !

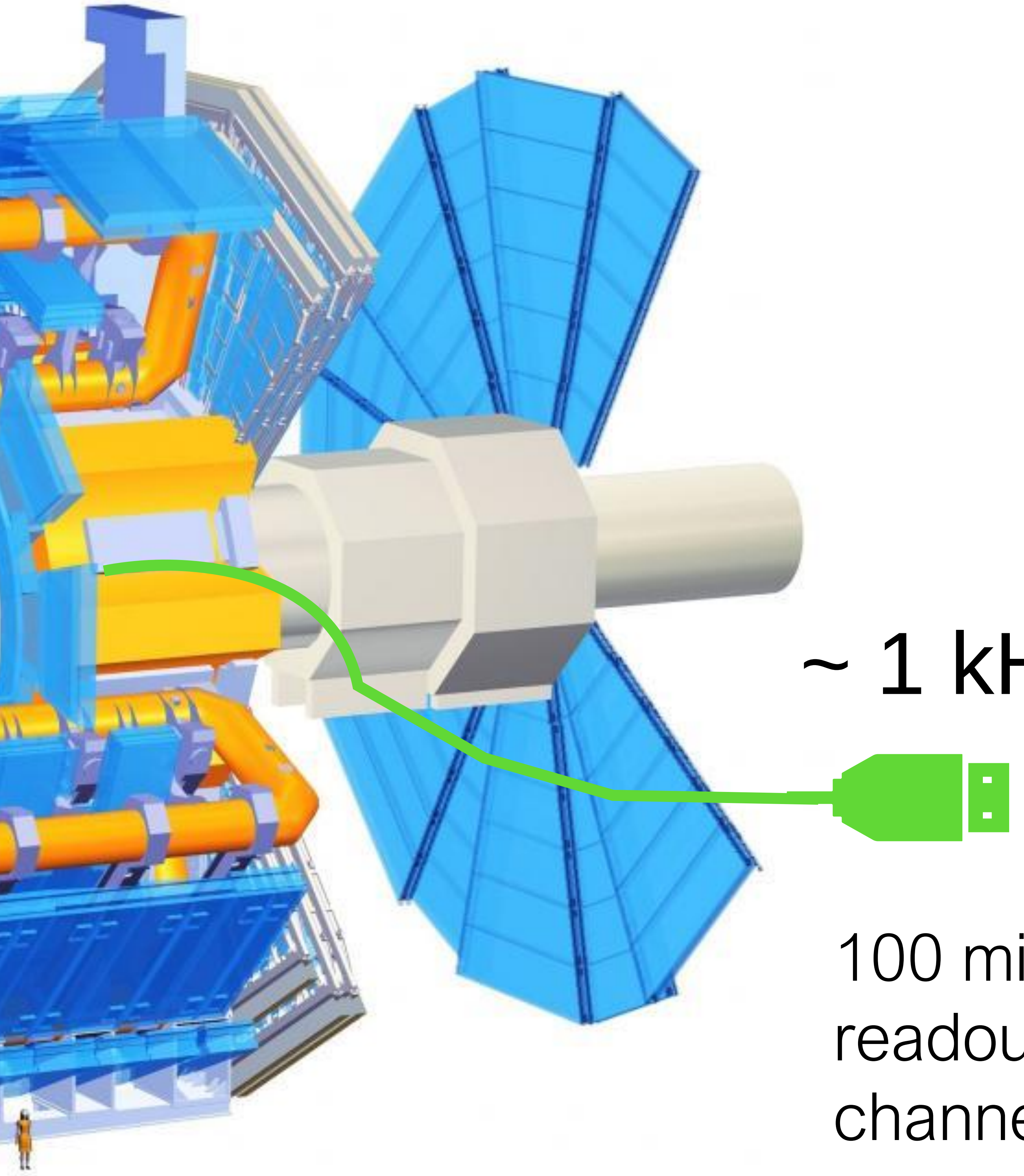
energy !

no energy !

energy!



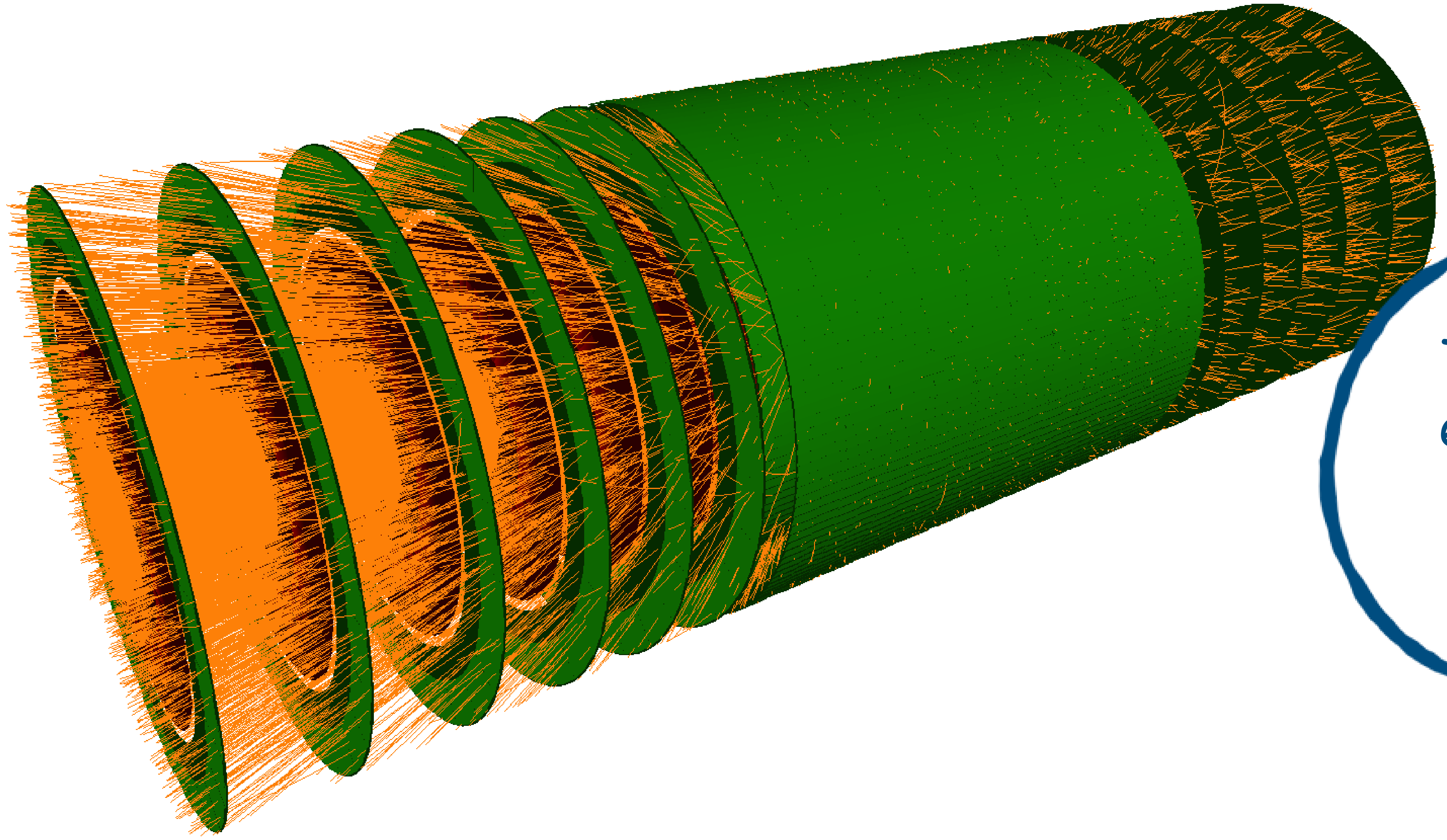
And then read it out …



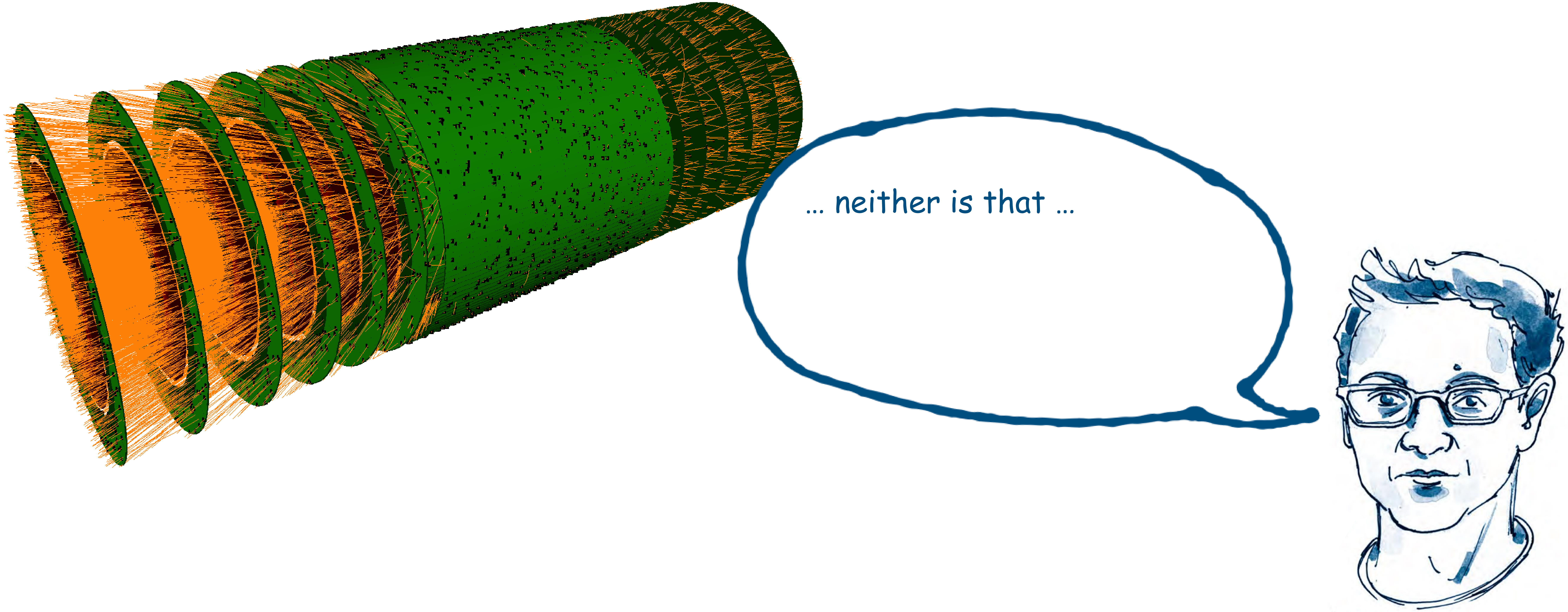
~ 1 kHz

100 million readout channels

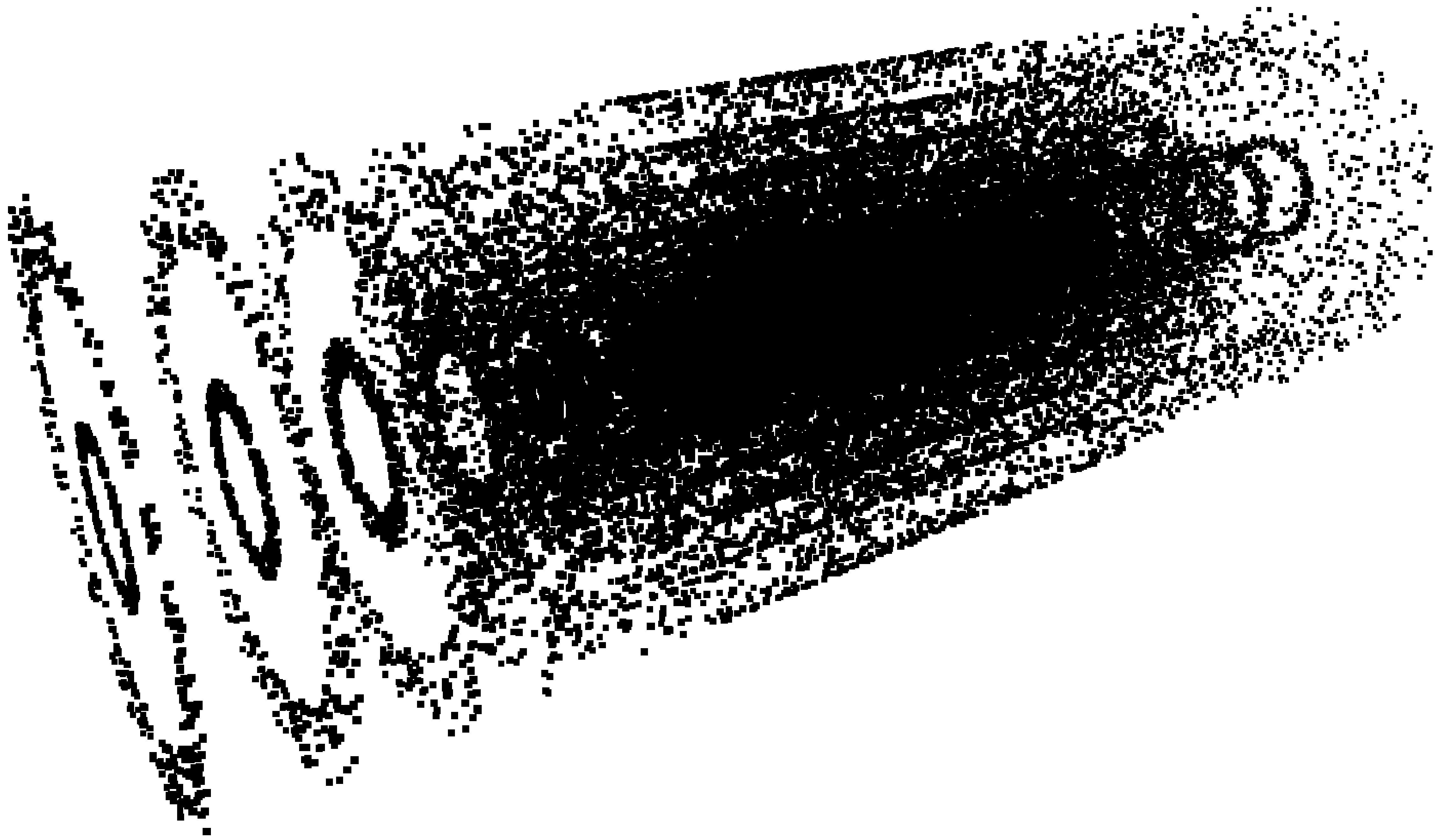
Reconstruct and analyse



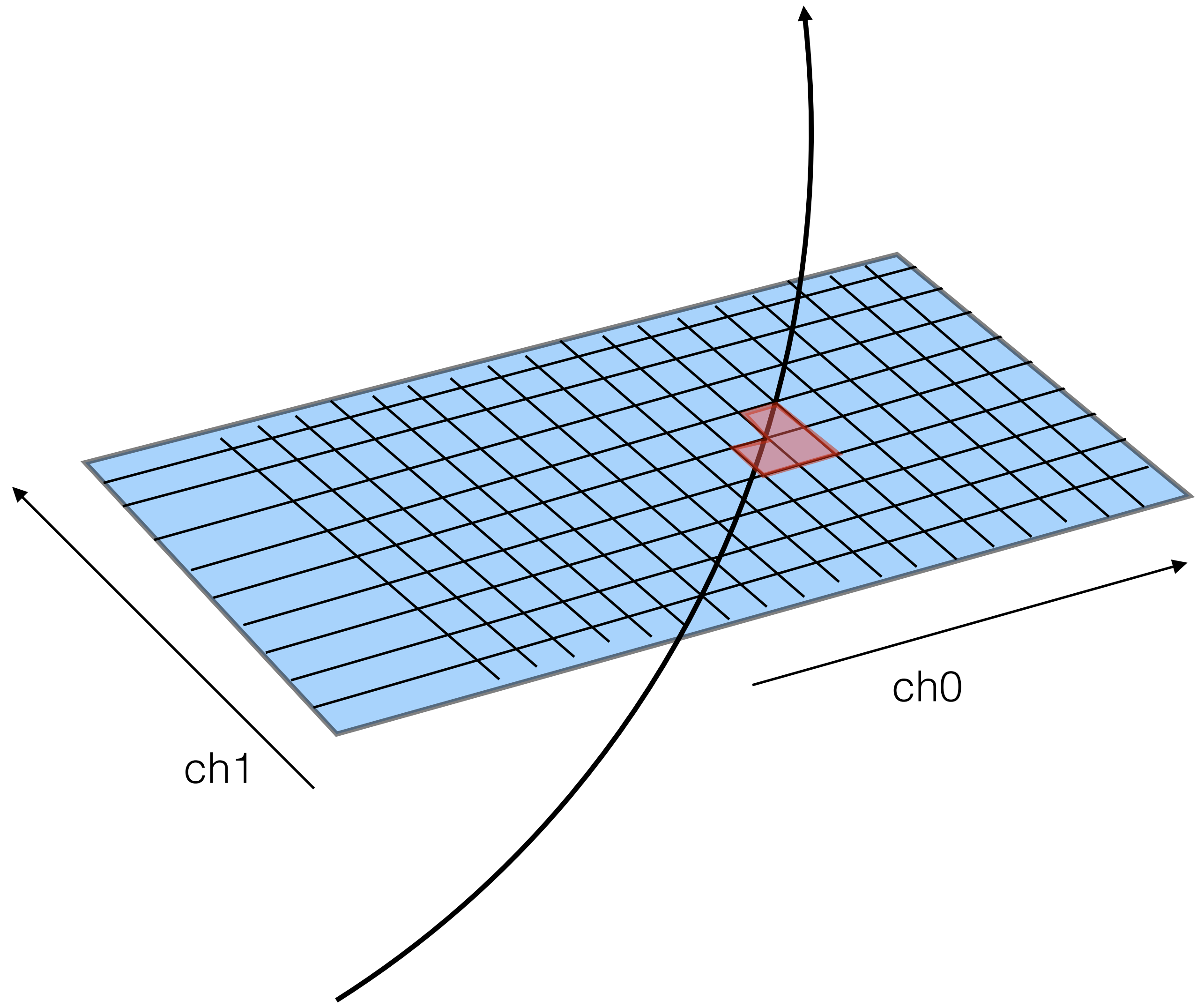
Reconstruct and analyse



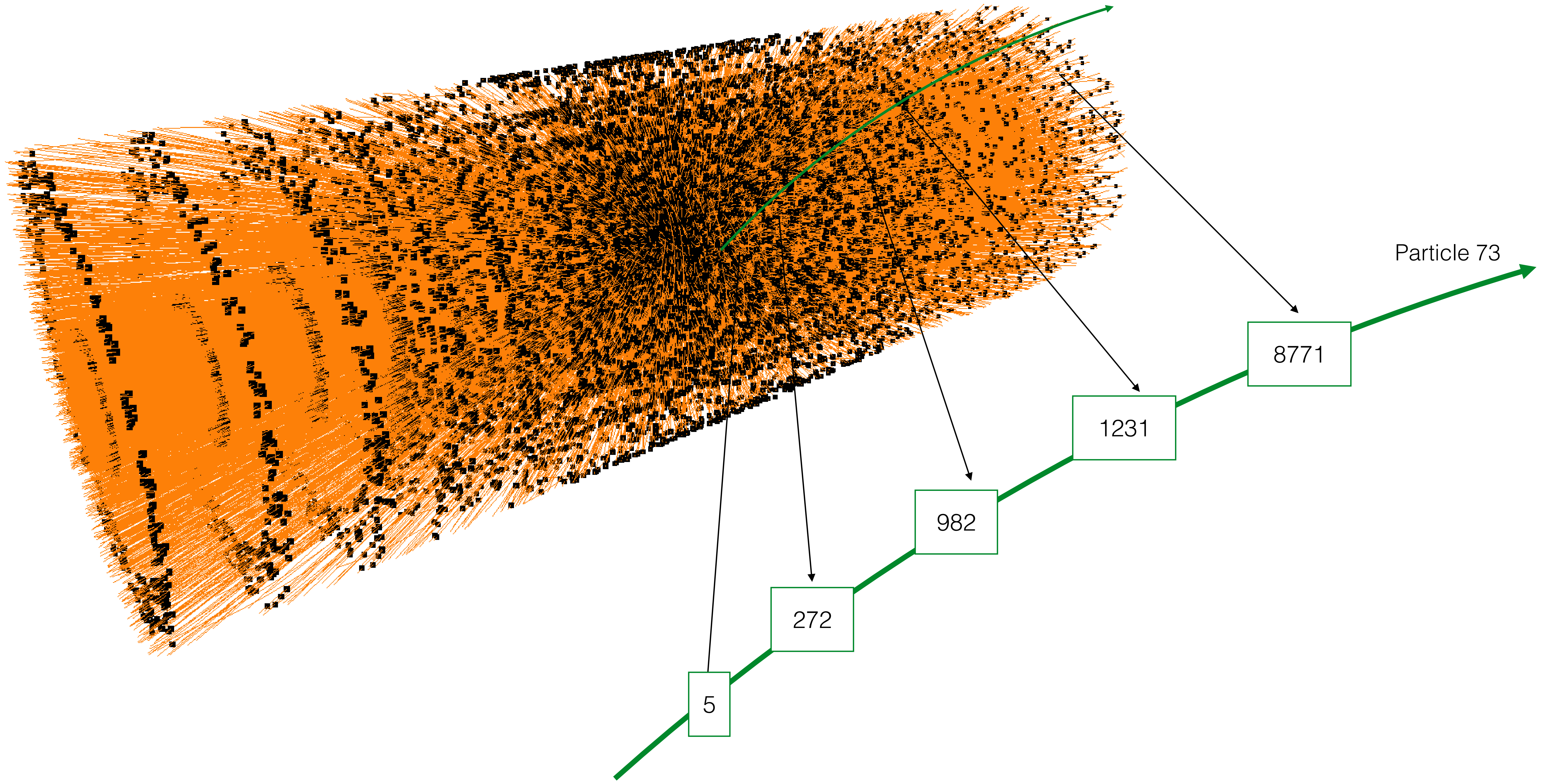
Reconstruct and analyse

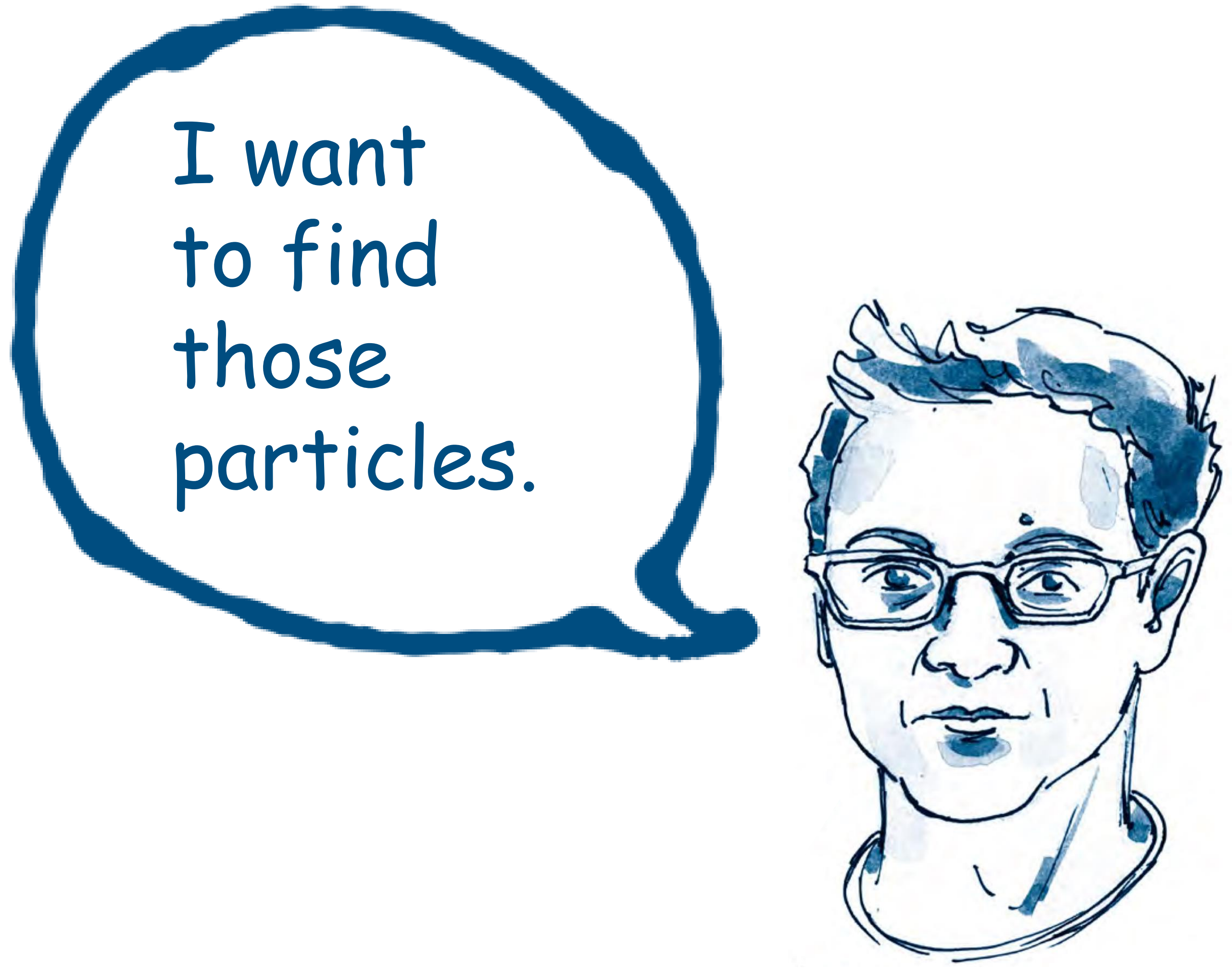


Detection devices measure the particle with a given resolution.

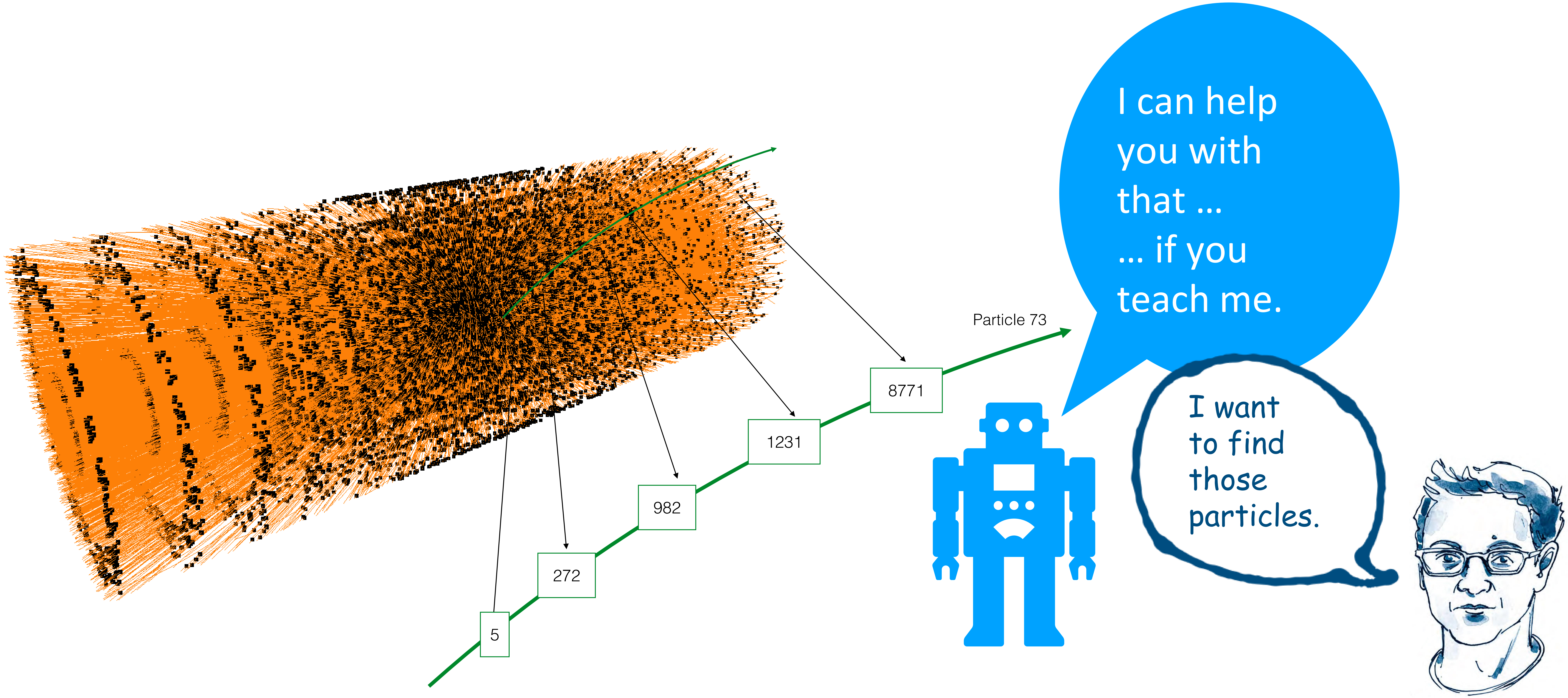


Reconstruct and analyse





Reconstruct and analyse

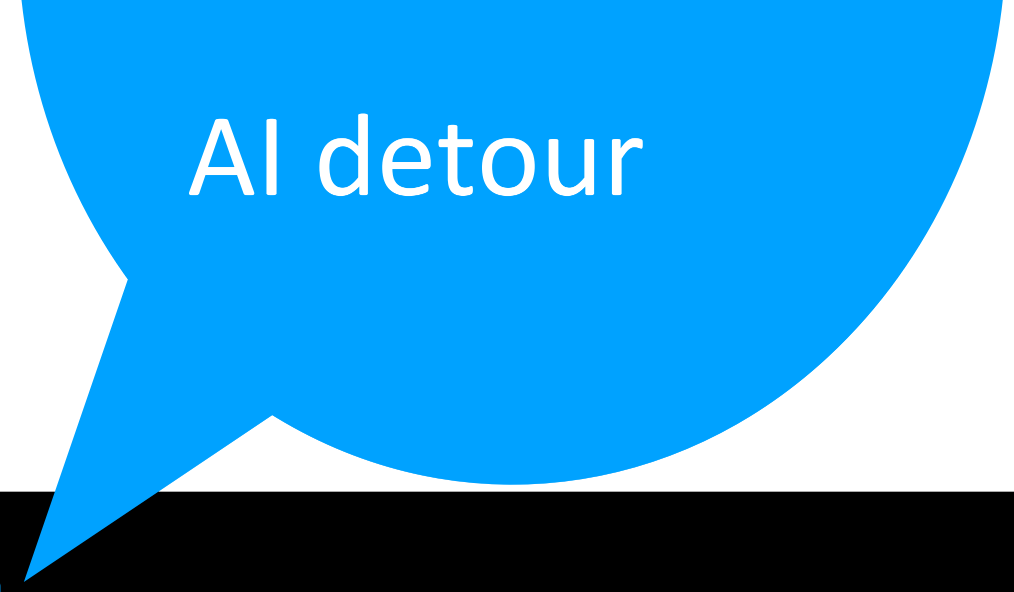


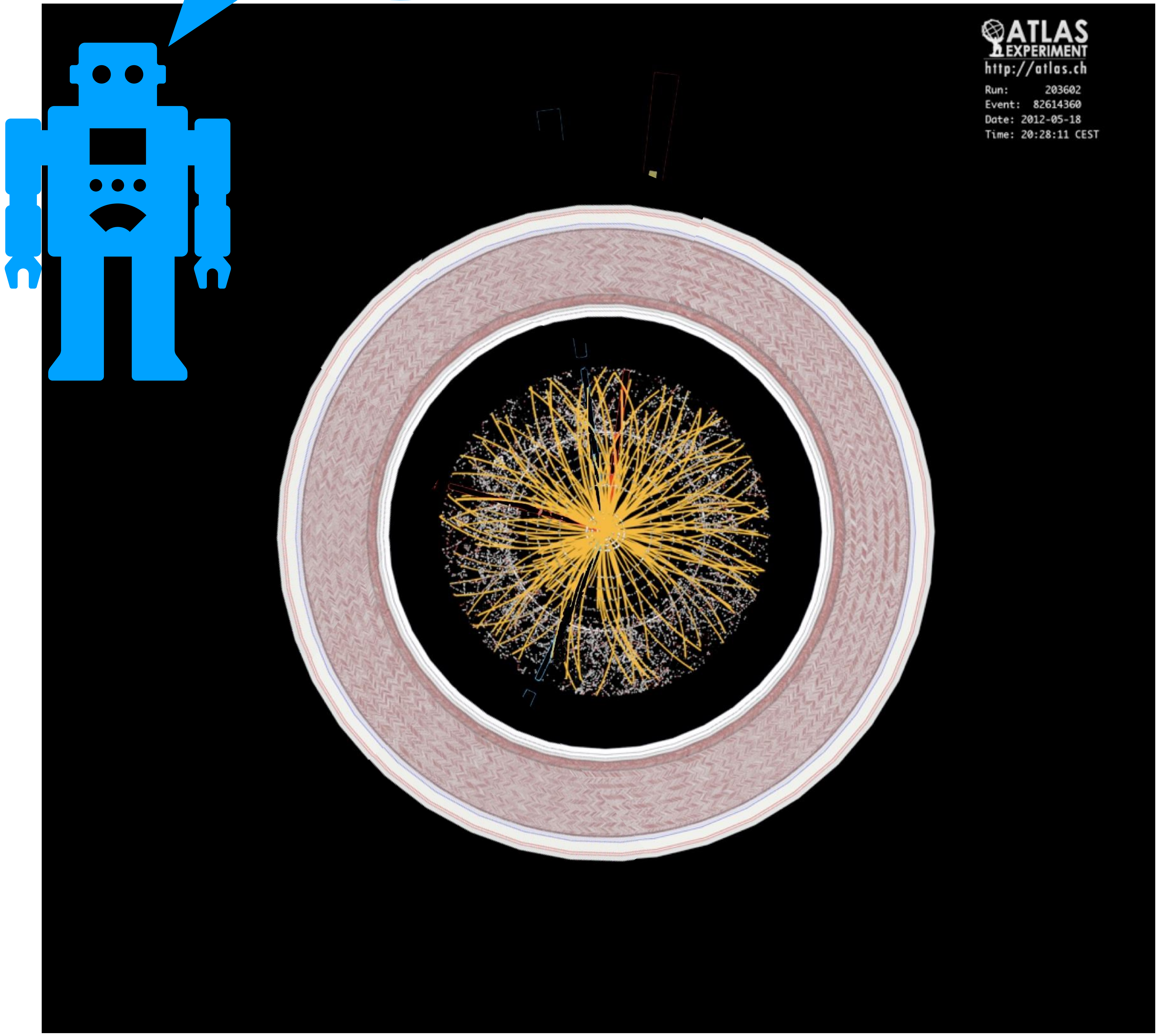
AI detour

Object detection and recognition is a AI standard problem

- big advances achieved in the last years
- Both in object detection & object calssification
- Can we use this for HEP?

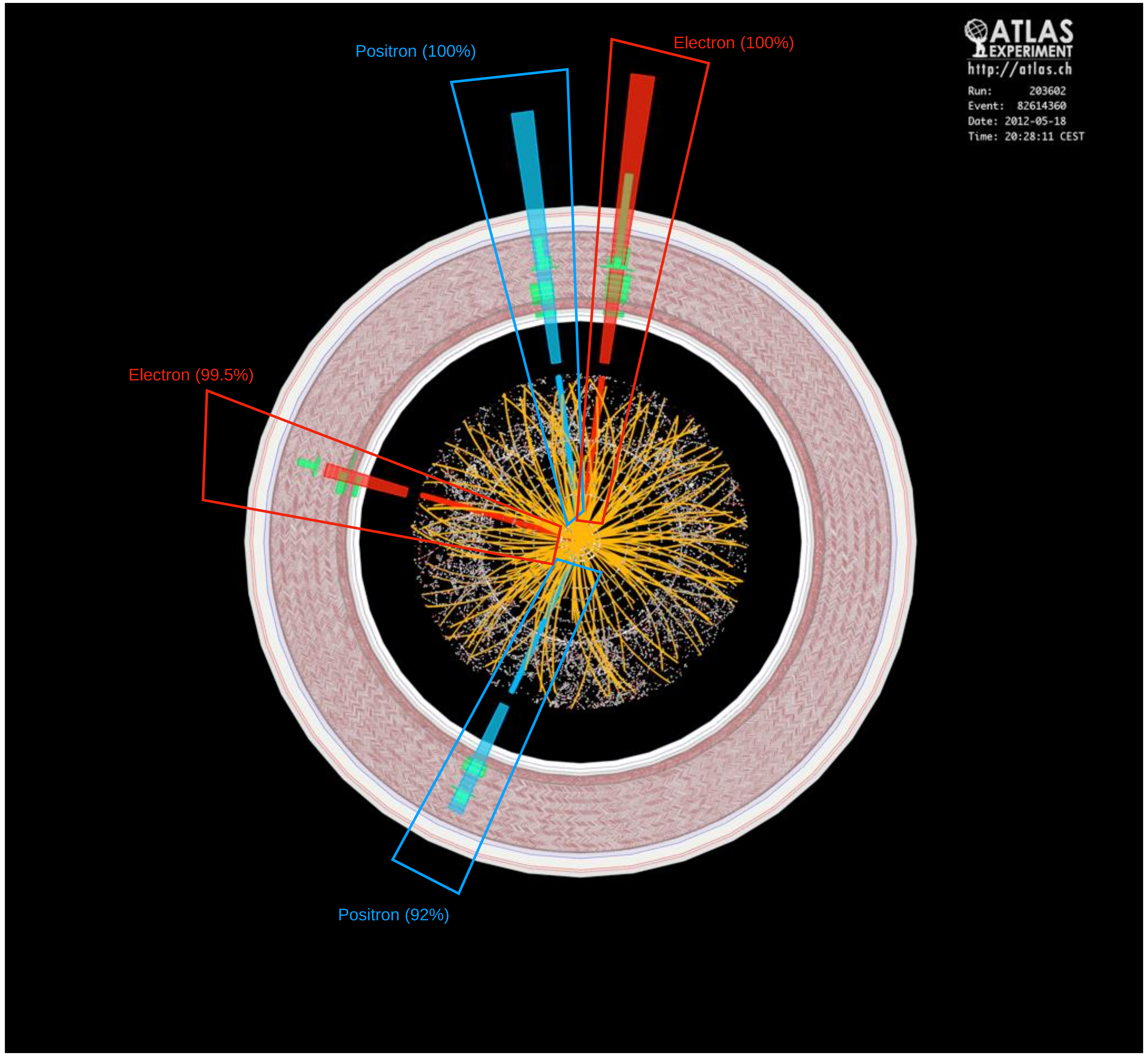
The Beatles, Abbey Road


AI detour

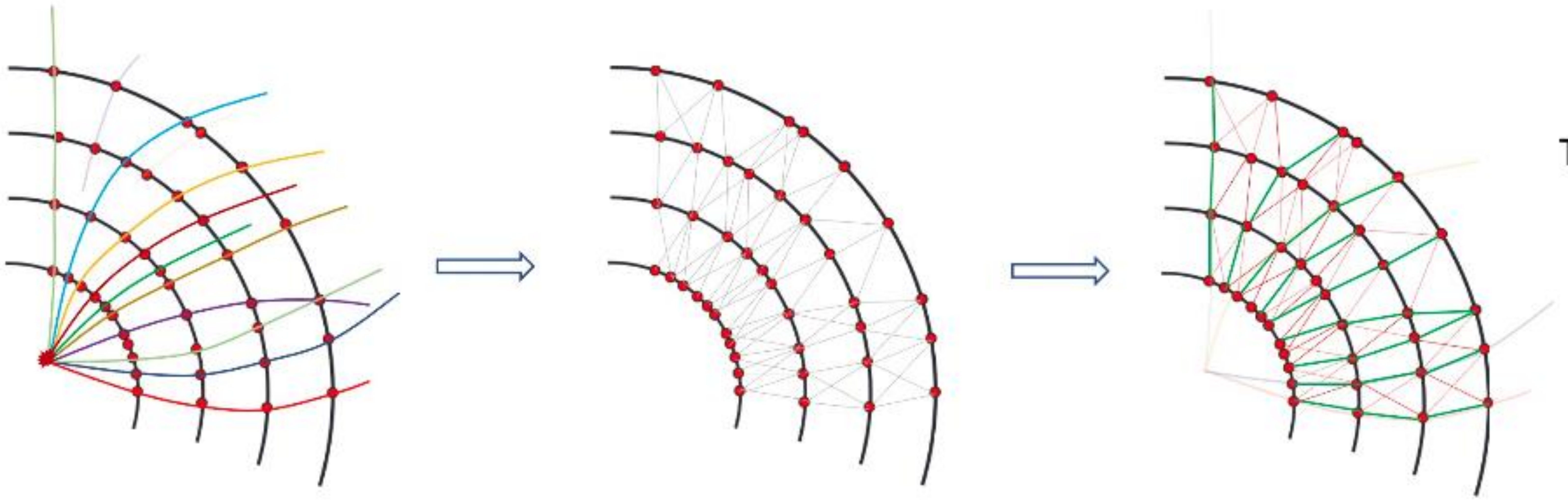

ATLAS
EXPERIMENT
http://atlas.ch
Run: 203602
Event: 82614360
Date: 2012-05-18
Time: 20:28:11 CEST

AI detour

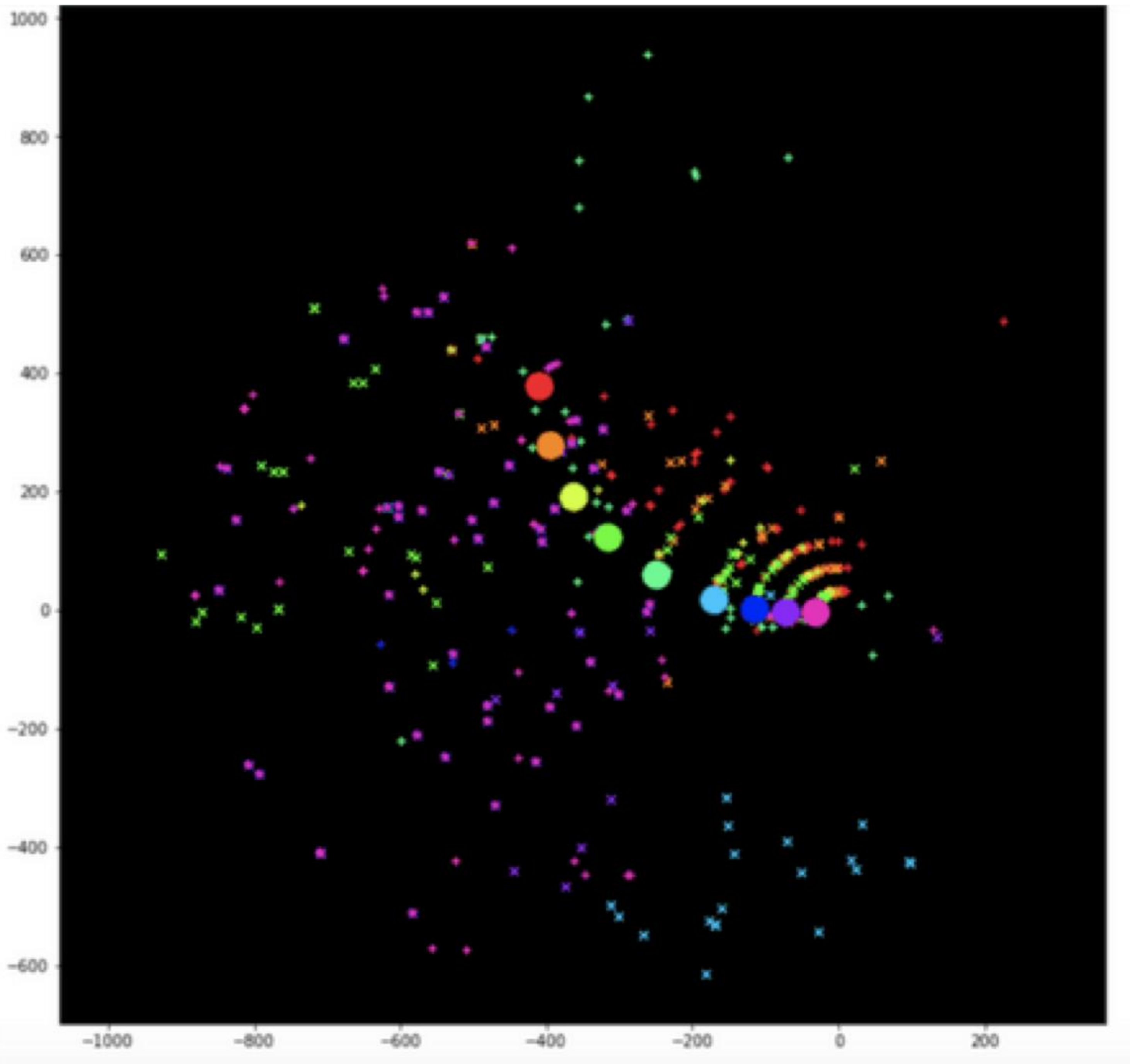

ATLAS EXPERIMENT
http://atlas.ch
Run: 203602
Event: 82614360
Date: 2012-05-18
Time: 20:28:11 CEST

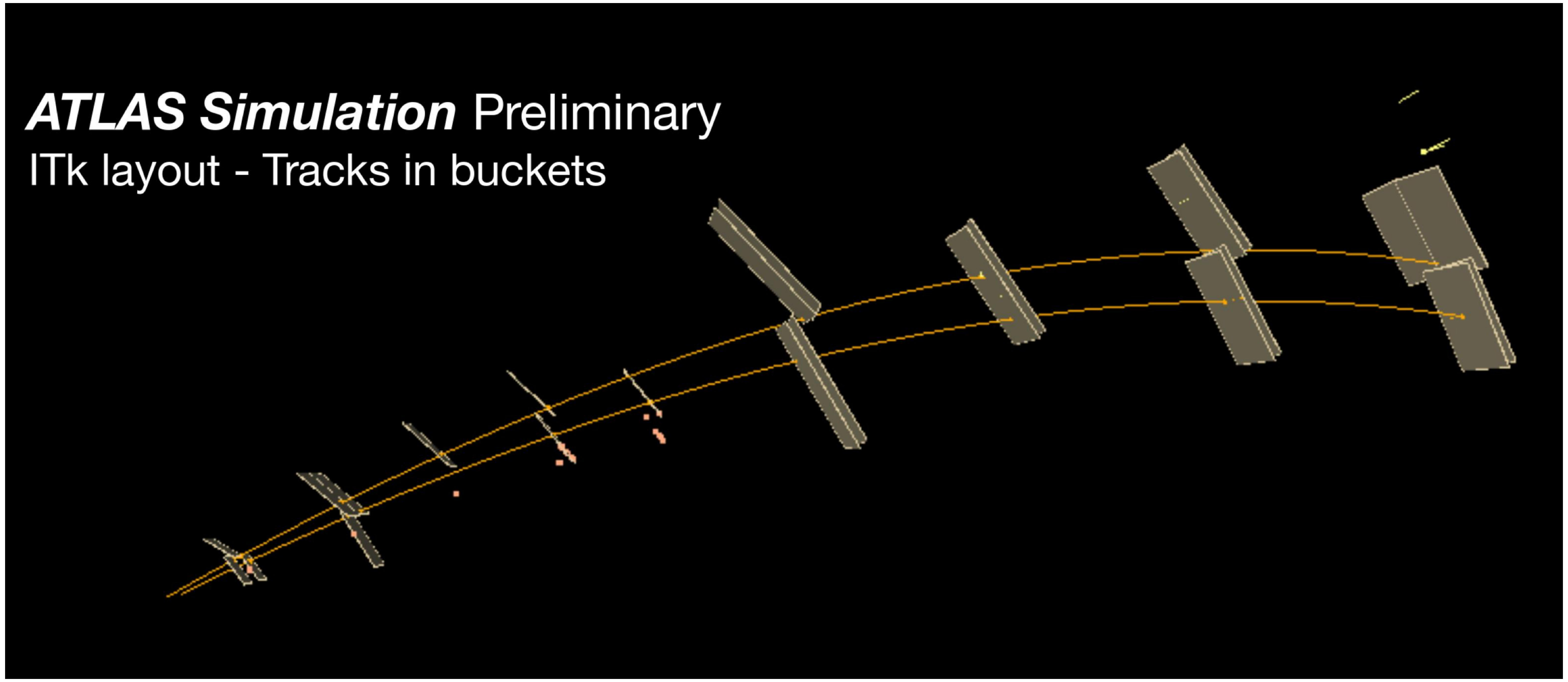

ATLAS EXPERIMENT
http://atlas.ch
Run: 203602
Event: 82614360
Date: 2012-05-18
Time: 20:28:11 CEST
Positron (100%)
Electron (100%)
Electron (99.5%)
Positron (92%)

AI detour



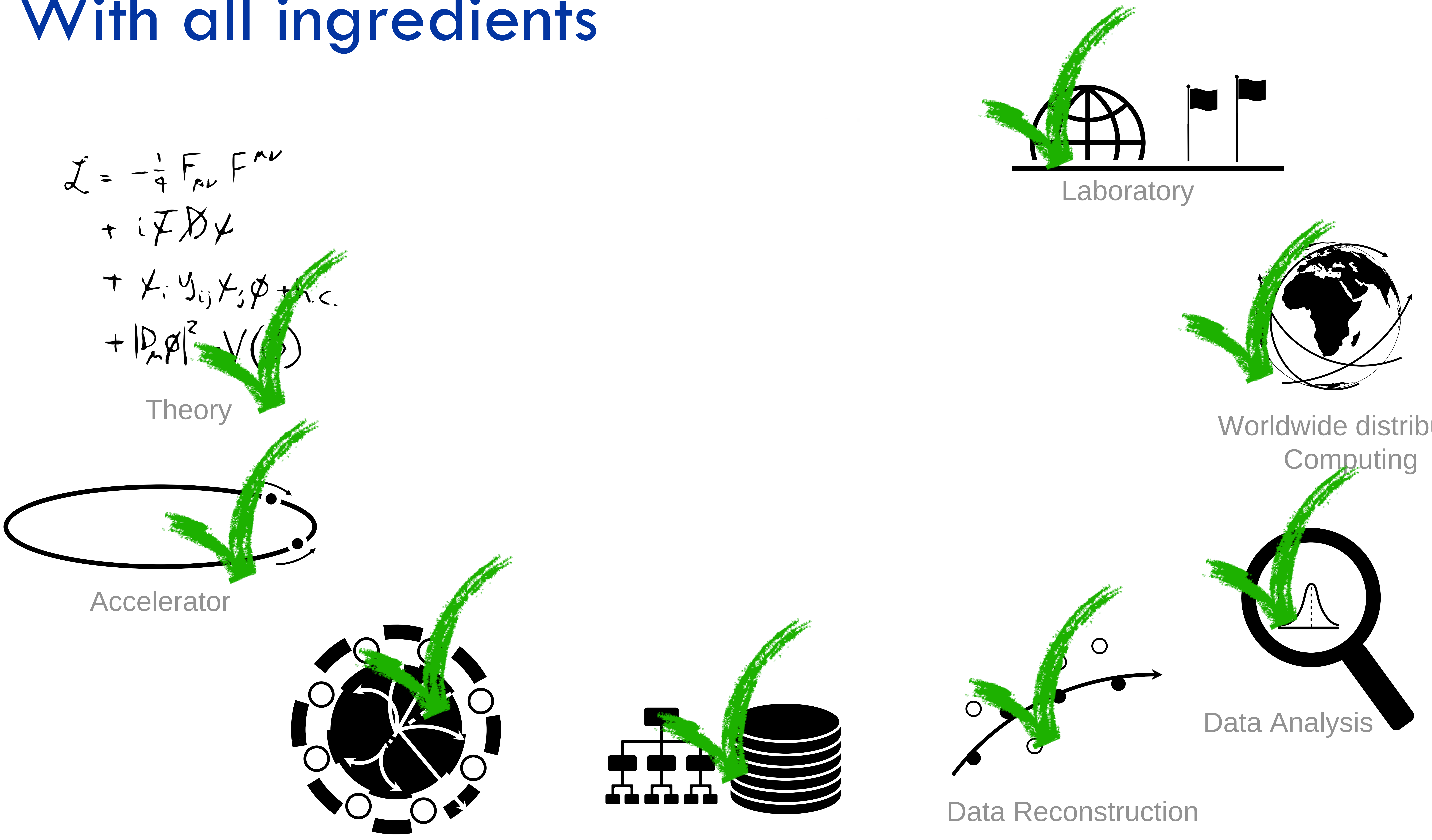
Track candidates



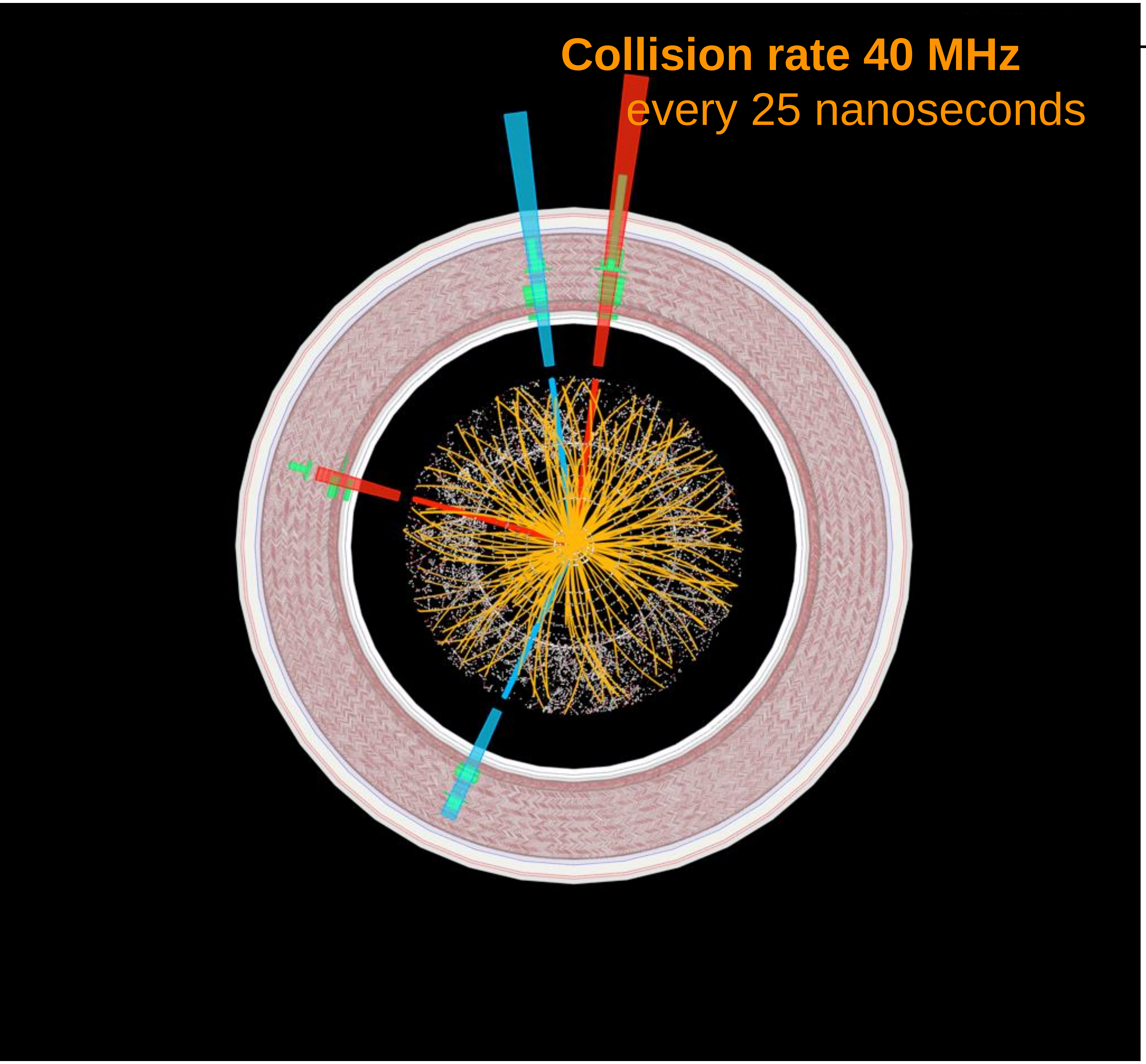


With all ingredients

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$



Let us run the experiment



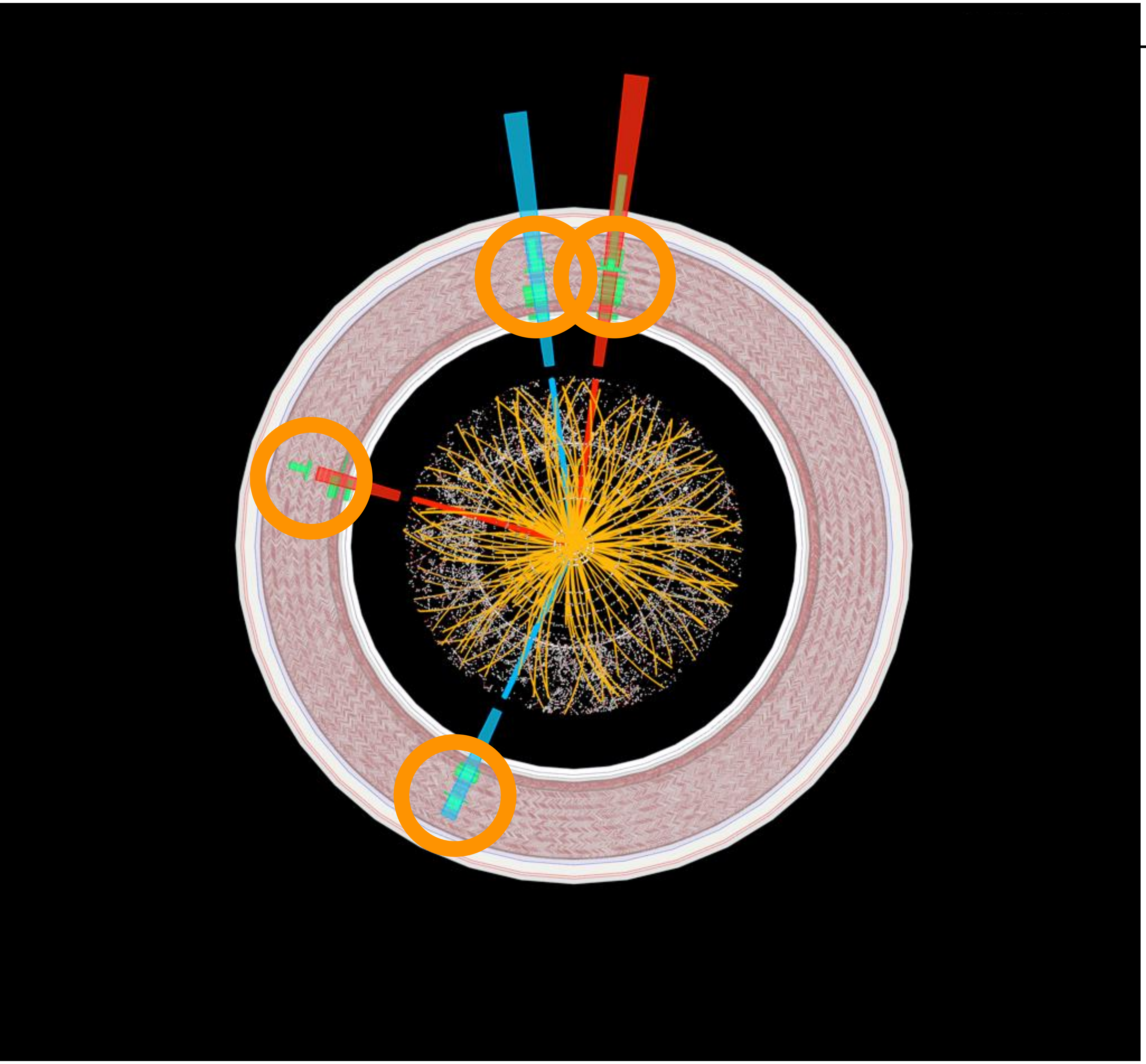
Level 1 Trigger to 100 kHz
on detector electronics

High level trigger ~1kHz
close-by computer farm

Full processing of events
1000 events/second

Data Analysis & publication

Let us run the experiment



Level 1 Trigger to 100 kHz
on detector electronics

4 lepton signals

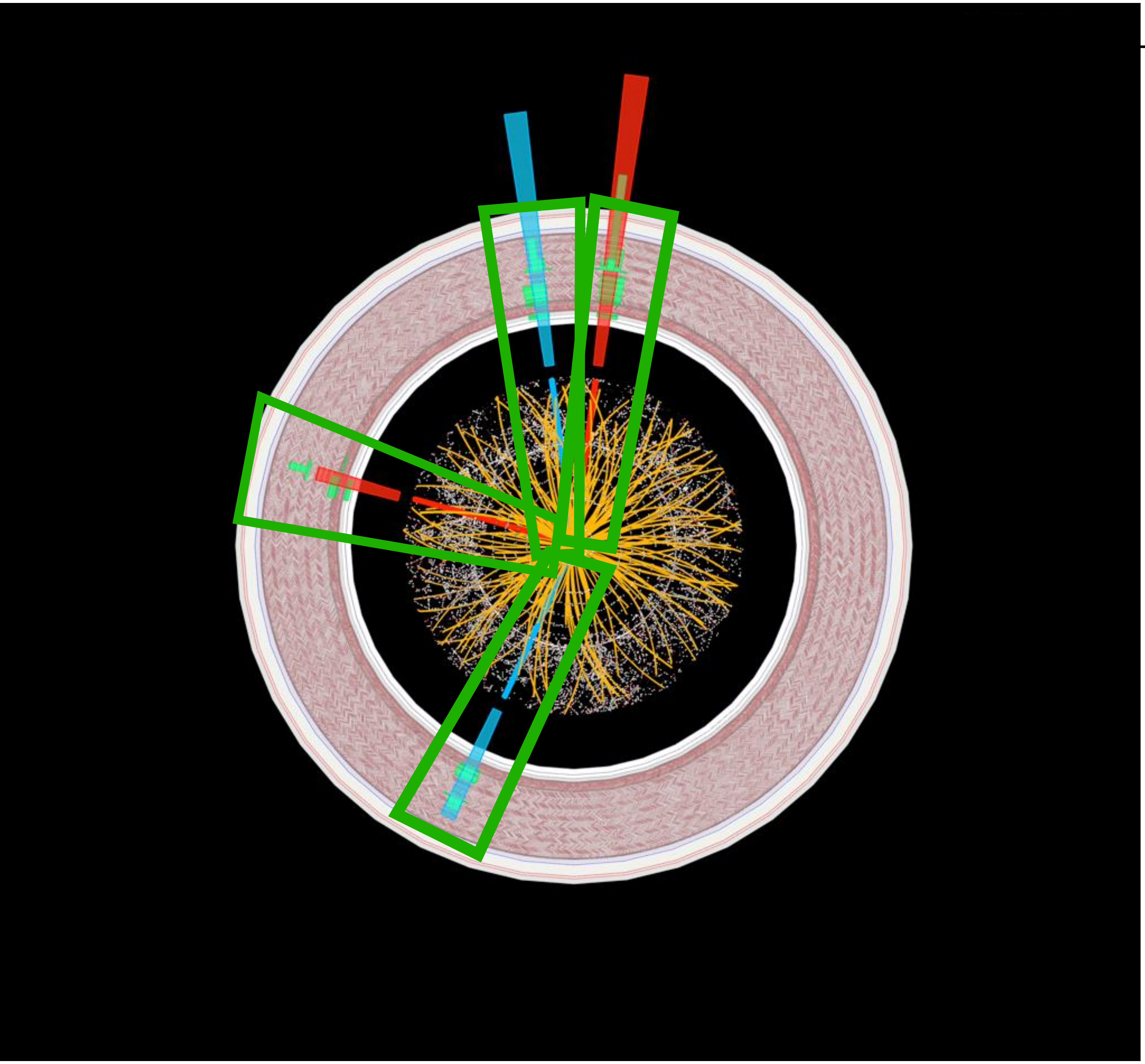
High level trigger ~1kHz
close-by computer farm

Full processing of events
1000 events/second

Data Analysis & publication

Nobel prize

Let us run the experiment



Level 1 Trigger to 100 kHz
on detector electronics

4 lepton signals

High level trigger ~1kHz
close-by computer farm

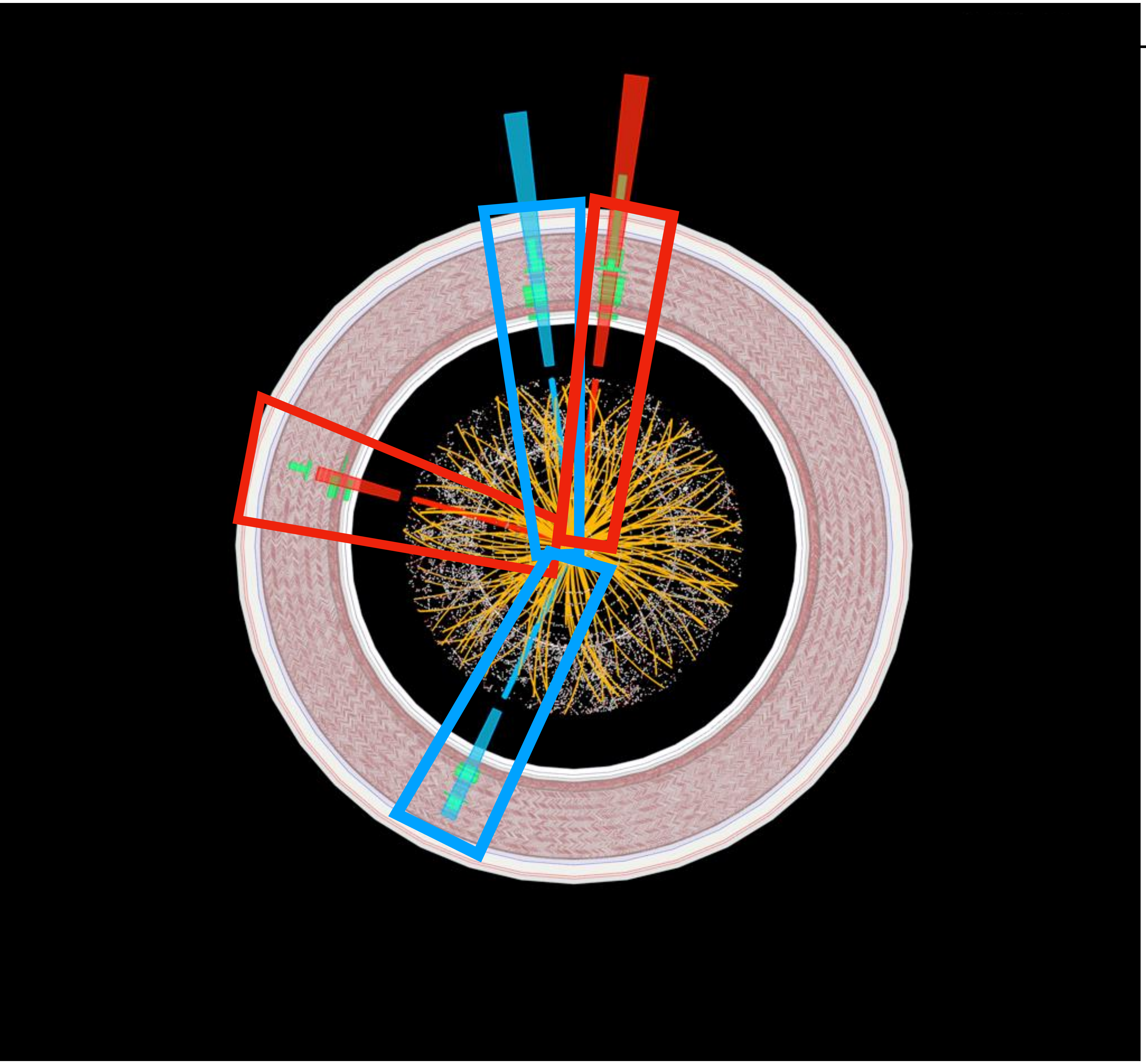
4 lepton signals confirmed

Full processing of events
1000 events/second

Data Analysis & publication

Nobel prize

Let us run the experiment



Level 1 Trigger to 100 kHz
on detector electronics

4 lepton signals

High level trigger ~1kHz
close-by computer farm

4 lepton signals
confirmed

Full processing of events
1000 events/second

2 positive leptons
2 negative leptons
and measured

Data Analysis & publication

Nobel prize

Let us run the experiment

Lesson 1 - Minkowski arithmetic

$p_\mu = (E, p_x, p_y, p_z)$

energy — momentum

Invariant mass:

$M^2 = E^2 - p_x^2 - p_y^2 - p_z^2$

Level 1 Trigger to 100 kHz
on detector electronics

4 lepton signals

High level trigger ~1kHz
close-by computer farm

4 lepton signals confirmed

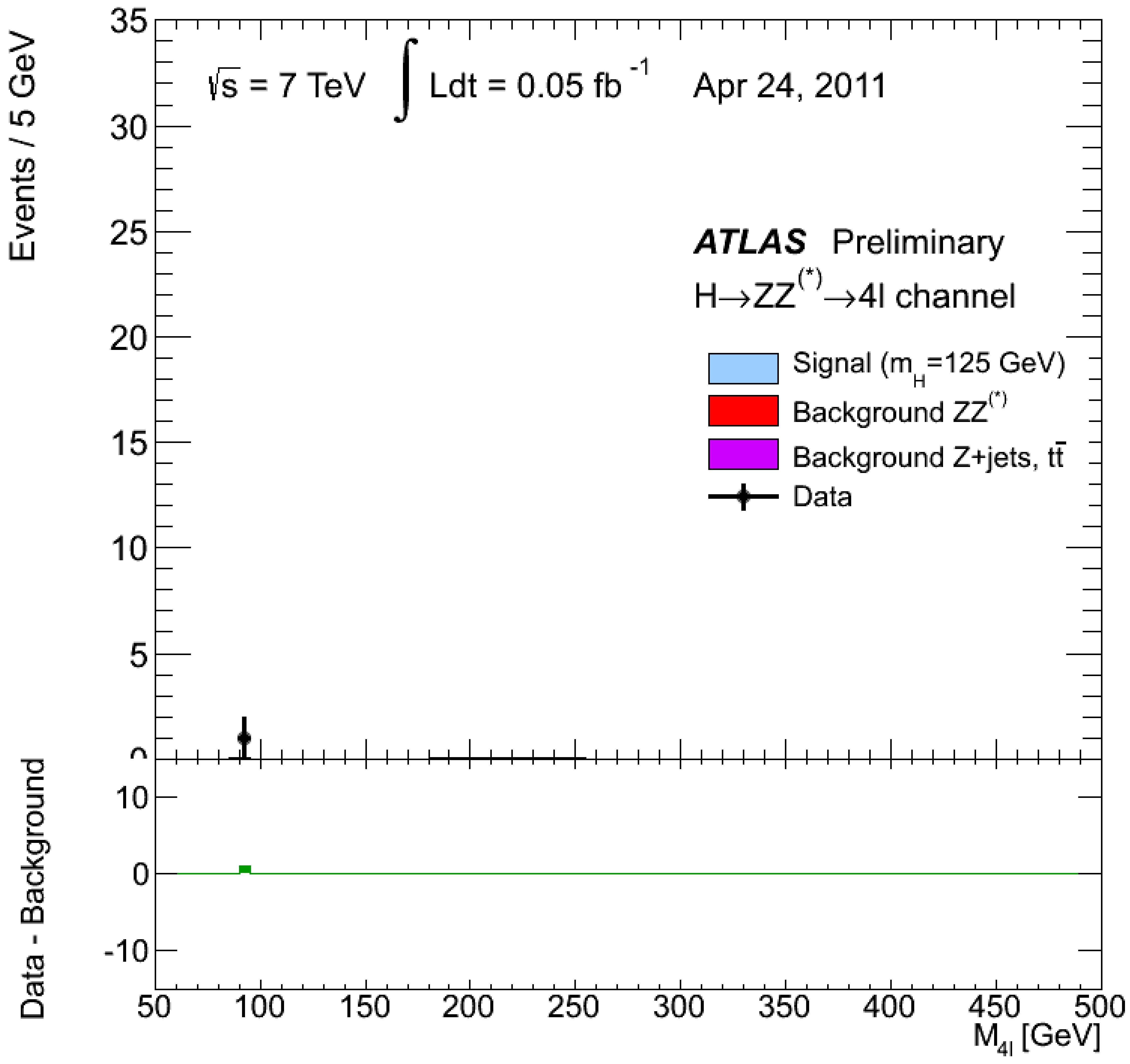
Full processing of events
1000 events/second

2 positive leptons
2 negative leptons
and measured

Data Analysis & publication

Nobel prize

Let us run the experiment … for real



Level 1 Trigger to 100 kHz
on detector electronics

High level trigger ~1kHz
close-by computer farm

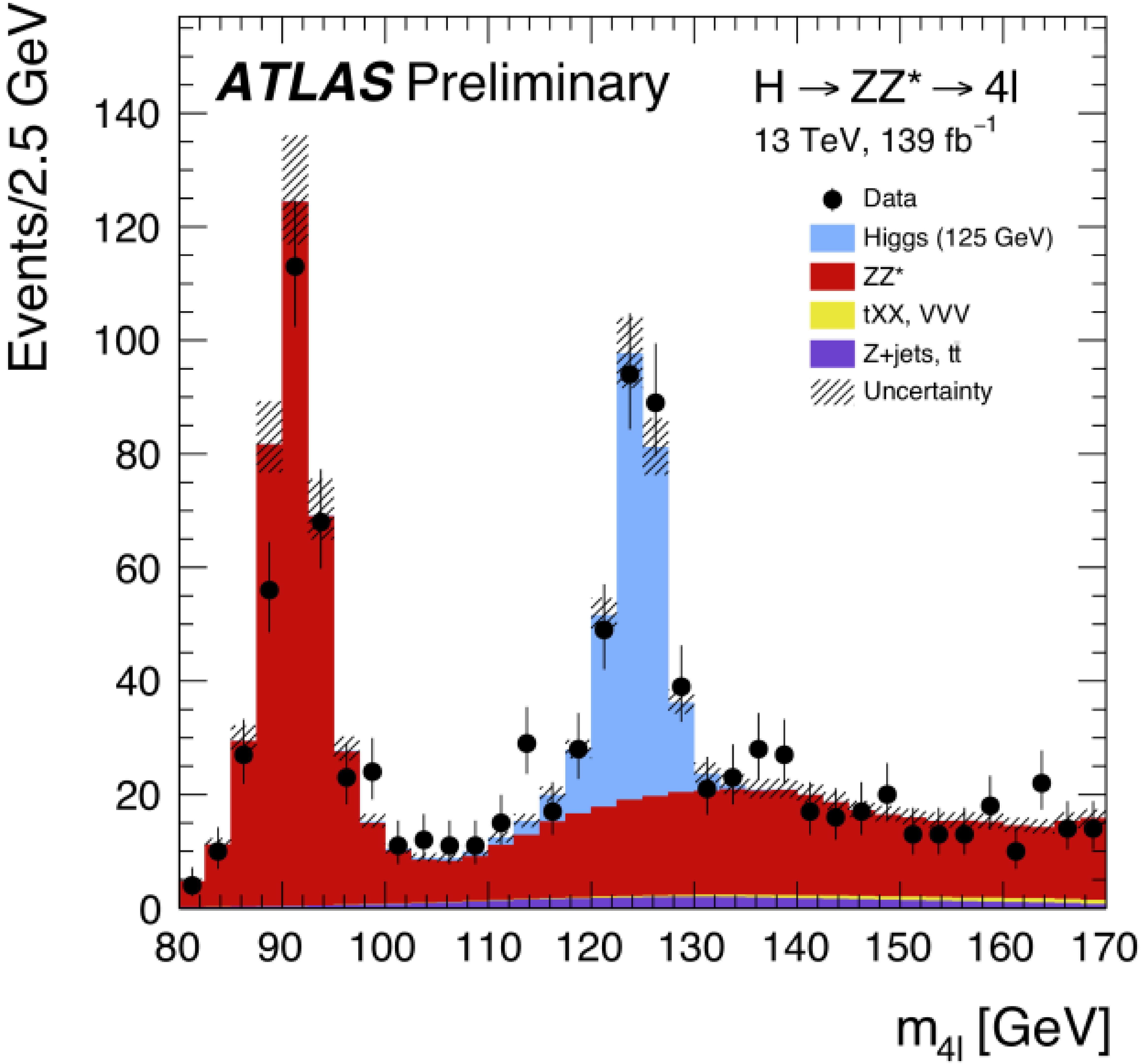
Full processing of events
1000 events/second

Data Analysis **& publication**

Nobel prize

[Animation source]

Let us run the experiment … for real



Level 1 Trigger to 100 kHz
on detector electronics

High level trigger ~1kHz
close-by computer farm

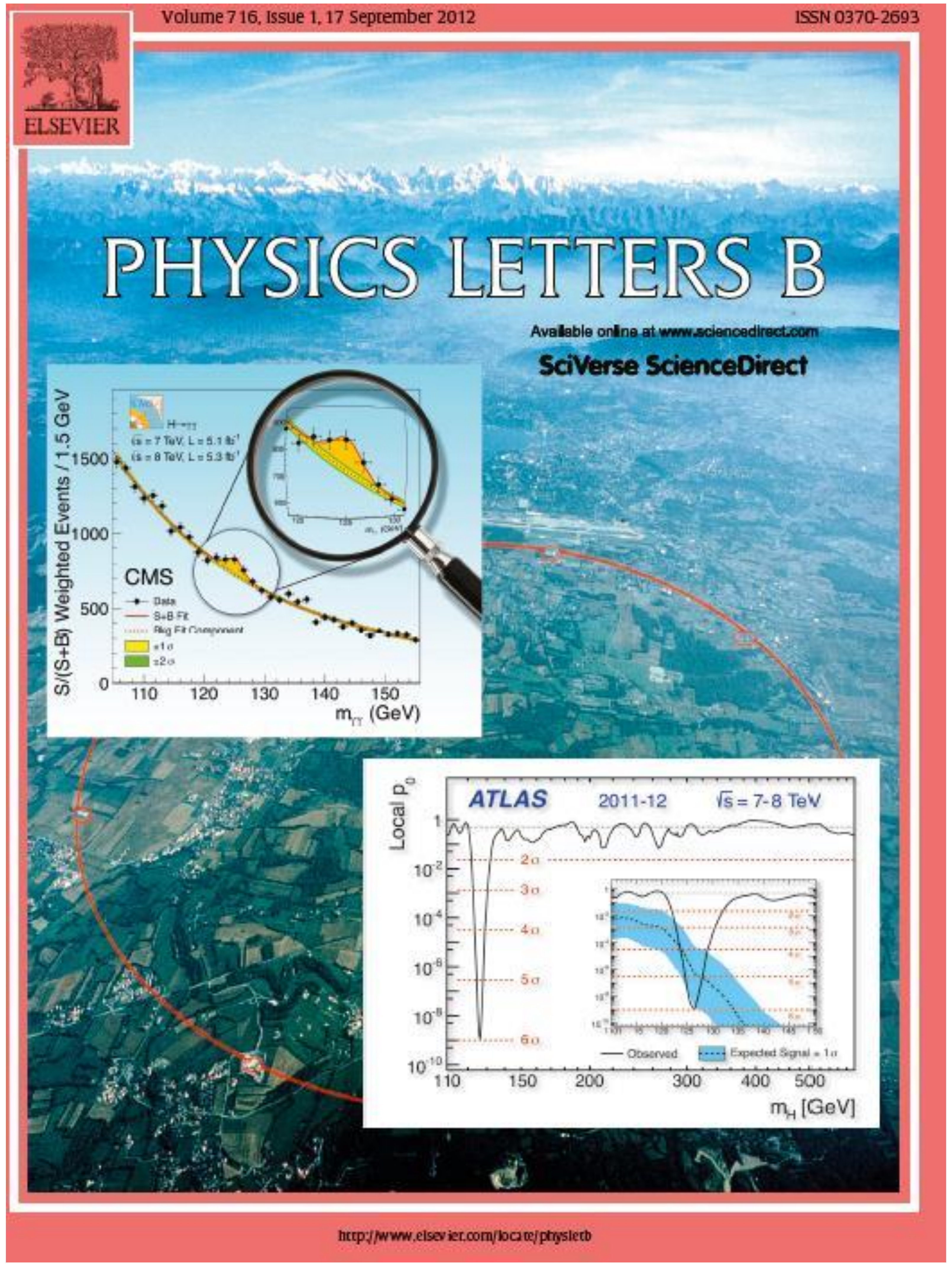
Full processing of events
1000 events/second

Data Analysis & publication

Nobel prize

[Animation source]

And so it went …



Level 1 Trigger to 100 kHz
on detector electronics

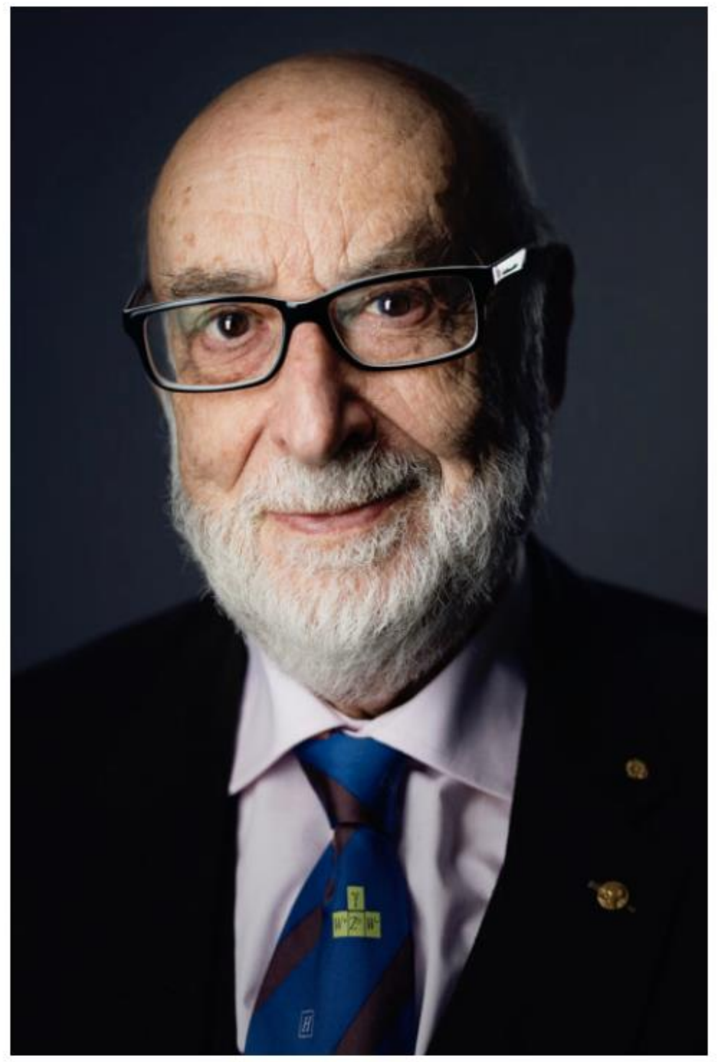
High level trigger ~1kHz
close-by computer farm

Full processing of events
1000 events/second

Data Analysis & publication

… and of course the right guys got it.

The Nobel Prize in Physics 2013



© Nobel Media AB. Photo: A. Mahmoud

François Englert

Prize share: 1/2

© Nobel Media AB. Photo: A. Mahmoud

Peter W. Higgs

Prize share: 1/2

Level 1 Trigger to 100 kHz
on detector electronics

High level trigger ~1kHz
close-by computer farm

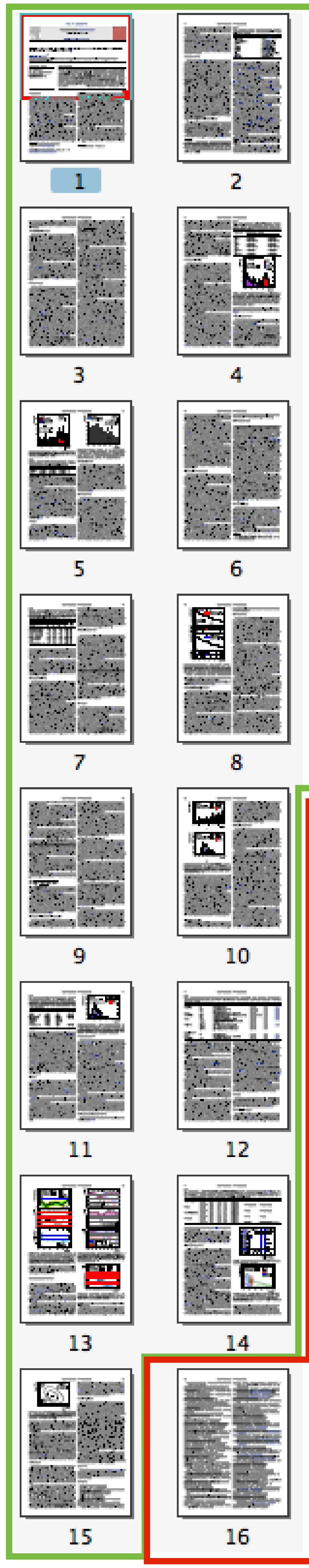
Full processing of events
1000 events/second

Data Analysis & publication

Nobel prize

[Animation source]

scientific information



Physics Letters B 716 (2012) 1–29

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Physics Letters B

www.elsevier.com/locate/physletb

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

ATLAS Collaboration *

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

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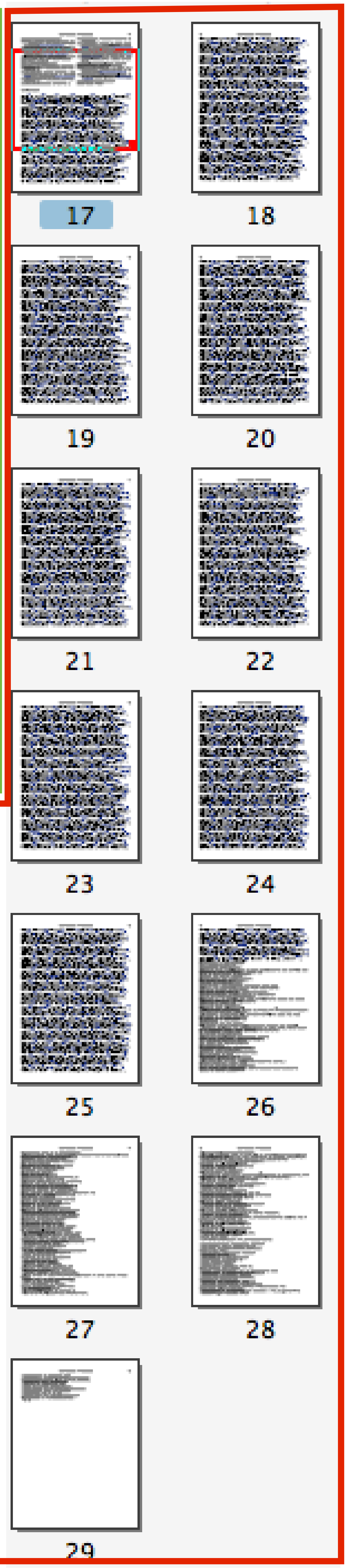
ABSTRACT

A search for the Standard Model Higgs boson in proton–proton collisions with the ATLAS detector at the LHC is presented. The datasets used correspond to integrated luminosities of approximately 4.8 fb^{-1} collected at $\sqrt{s} = 7$ TeV in 2011 and 5.8 fb^{-1} at $\sqrt{s} = 8$ TeV in 2012. Individual searches in the channels $H \to ZZ^{(*)} \to 4\ell$, $H \to \gamma\gamma$ and $H \to WW^{(*)} \to e\nu\mu\nu$ in the 8 TeV data are combined with previously published results of searches for $H \to ZZ^{(*)}$, $WW^{(*)}$, $b\bar{b}$ and $\tau^+\tau^-$ in the 7 TeV data and results from improved analyses of the $H \to ZZ^{(*)} \to 4\ell$ and $H \to \gamma\gamma$ channels in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of 126.0 ± 0.4 (stat) ± 0.4 (sys) GeV is presented. This observation, which has a significance of 5.9 standard deviations, corresponding to a background fluctuation probability of 1.7×10^{-9}, is compatible with the production and decay of the Standard Model Higgs boson.

author list information

L. Rumyantsev [64], Z. Rurikova [48], N.A. Rusakovich [64], J.P. Rutherfoord [7], P. Ruzicka [125], Y.F. Ryabov [121], M. Rybar [126], G. Rybkin [115], N.C. Ryder [118], A.F. Saavedra [150], I. Sadeh [153], H.F.-W. Sadrozinski [137], R. Sadykov [64], F. Safai Tehrani [132a], H. Sakamoto [155], G. Salamanna [75], A. Salamon [133a], M. Saleem [111], D. Salek [30], D. Salihagic [99], A. Salnikov [143], J. Salt [167], B.M. Salvachua Ferrando [6], D. Salvatore [37a,37b], F. Salvatore [149], A. Salvucci [104], A. Salzburger [30], D. Sampsonidis [154], B.H. Samset [117], A. Sanchez [102a,102b], V. Sanchez Martinez [167], H. Sandaker [14], H.G. Sander [81], M.P. Sanders [98], M. Sandhoff [175], T. Sandoval [28], C. Sandoval [162], R. Sandstroem [99], D.P.C. Sankey [129], A. Sansoni [47], C. Santamarina Rios [85], C. Santoni [34], R. Santonico [133a,133b], H. Santos [124a], J.G. Saraiva [124a], T. Sarangi [173], E. Sarkisyan-Grinbaum [8], F. Sarri [122a,122b], G. Sartisohn [175], O. Sasaki [65], Y. Sasaki [155], N. Sasao [67], I. Satsounkevitch [90], G. Sauvage [5,*], E. Sauvan [5], J.B. Sauvan [115], P. Savard [158,d], V. Savinov [123], D.O. Savu [30], L. Sawyer [25,m], D.H. Saxon [53], J. Saxon [120], C. Sbarra [20a], A. Sbrizzi [20a,20b], D.A. Scannicchio [163], M. Scarcella [150], J. Schaarschmidt [115], P. Schacht [99], D. Schaefer [120], U. Schäfer [81], A. Schaelicke [46], S. Schaepe [21], S. Schaetzel [58b], A.C. Schaffer [115], D. Schaile [98], R.D. Schamberger [148], A.G. Schamov [107], V. Scharf [58a], V.A. Schegelsky [121], D. Scheirich [87], M. Schernau [163], M.I. Scherzer [35], C. Schiavi [50a,50b], J. Schieck [98], M. Schioppa [37a,37b], S. Schlenker [30], P. Schmid [30], E. Schmidt [48], K. Schmieden [21], C. Schmitt [81], S. Schmitt [58b], M. Schmitz [21], B. Schneider [17], U. Schnoor [44], L. Schoeffel [136], A. Schoening [58b], A.L.S. Schorlemmer [54], M. Schott [30], D. Schouten [159a], J. Schovancova [125], M. Schram [85], C. Schroeder [81], N. Schroer [58c], M.J. Schultens [21], J. Schultes [175], H.-C. Schultz-Coulon [58a], H. Schulz [16], M. Schumacher [48], B.A. Schumm [137], Ph. Schune [136], C. Schwanenberger [82], A. Schwartzman [143], Ph. Schwegler [99],



15 pages scientific context

~ 3000 authors

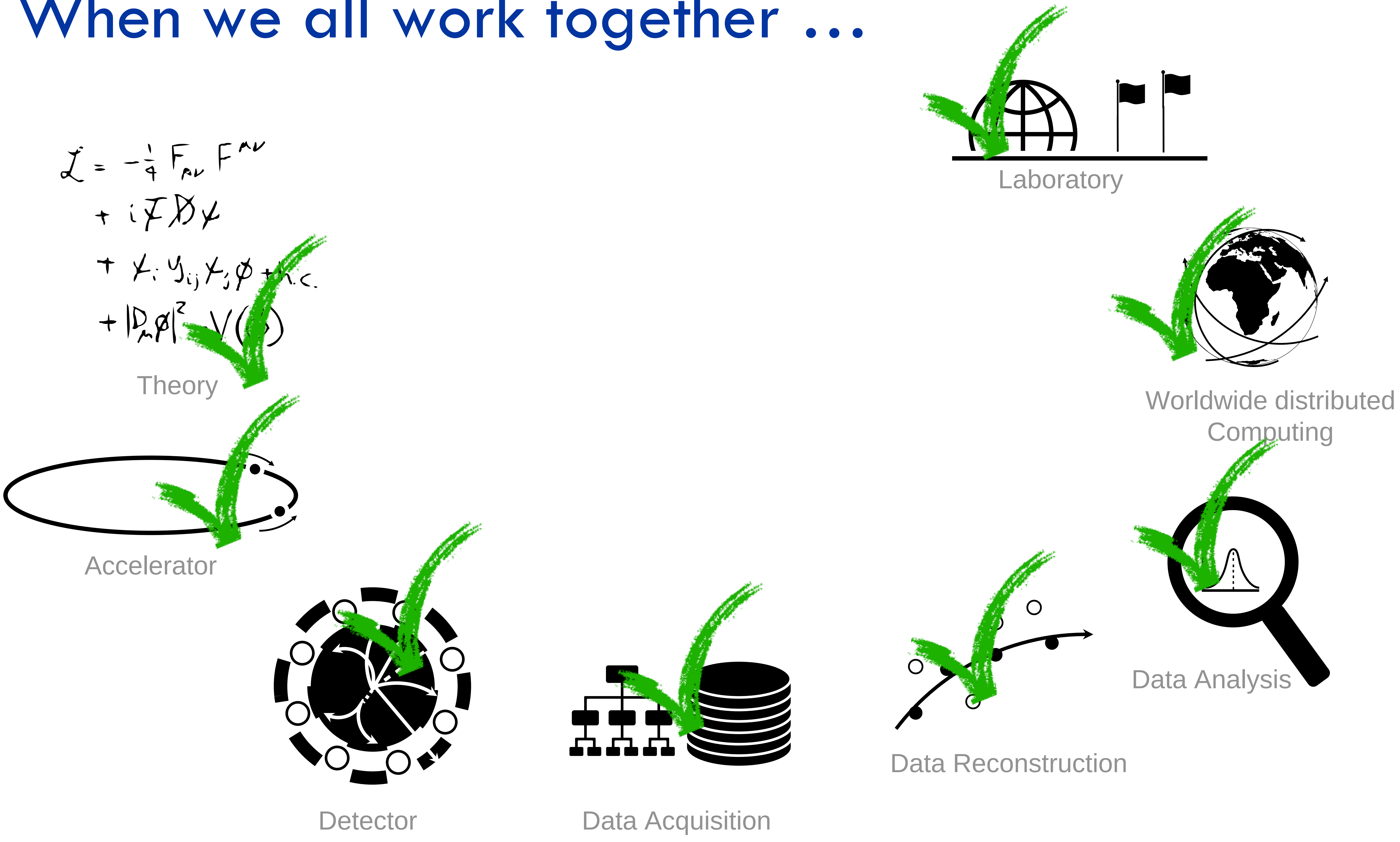
3000
Scientific authors

182
Institutions

42
Countries

1200
Doctoral students

When we all work together …



When we all work together …

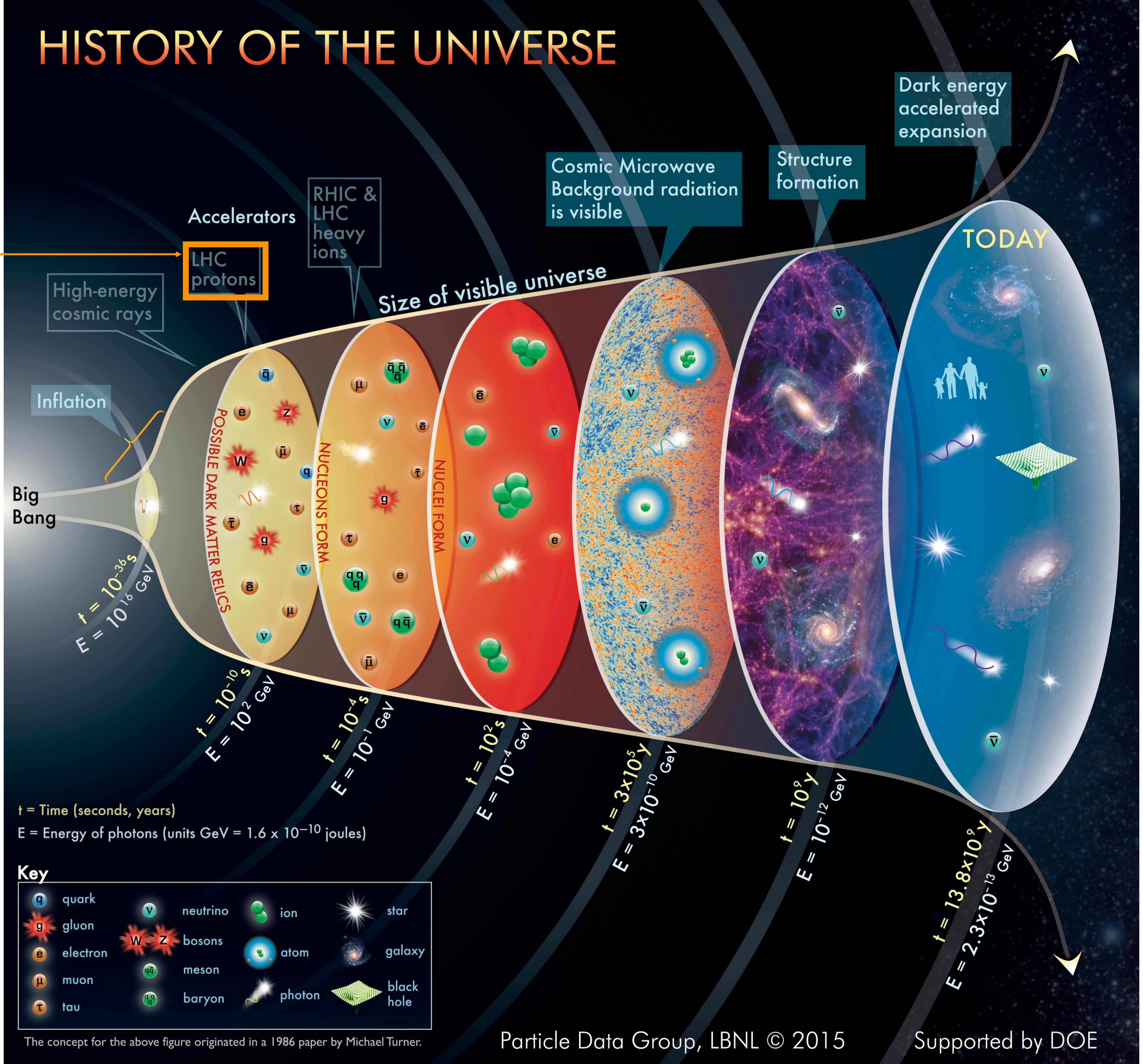
CERN

… we can achieve amazing things.

The why

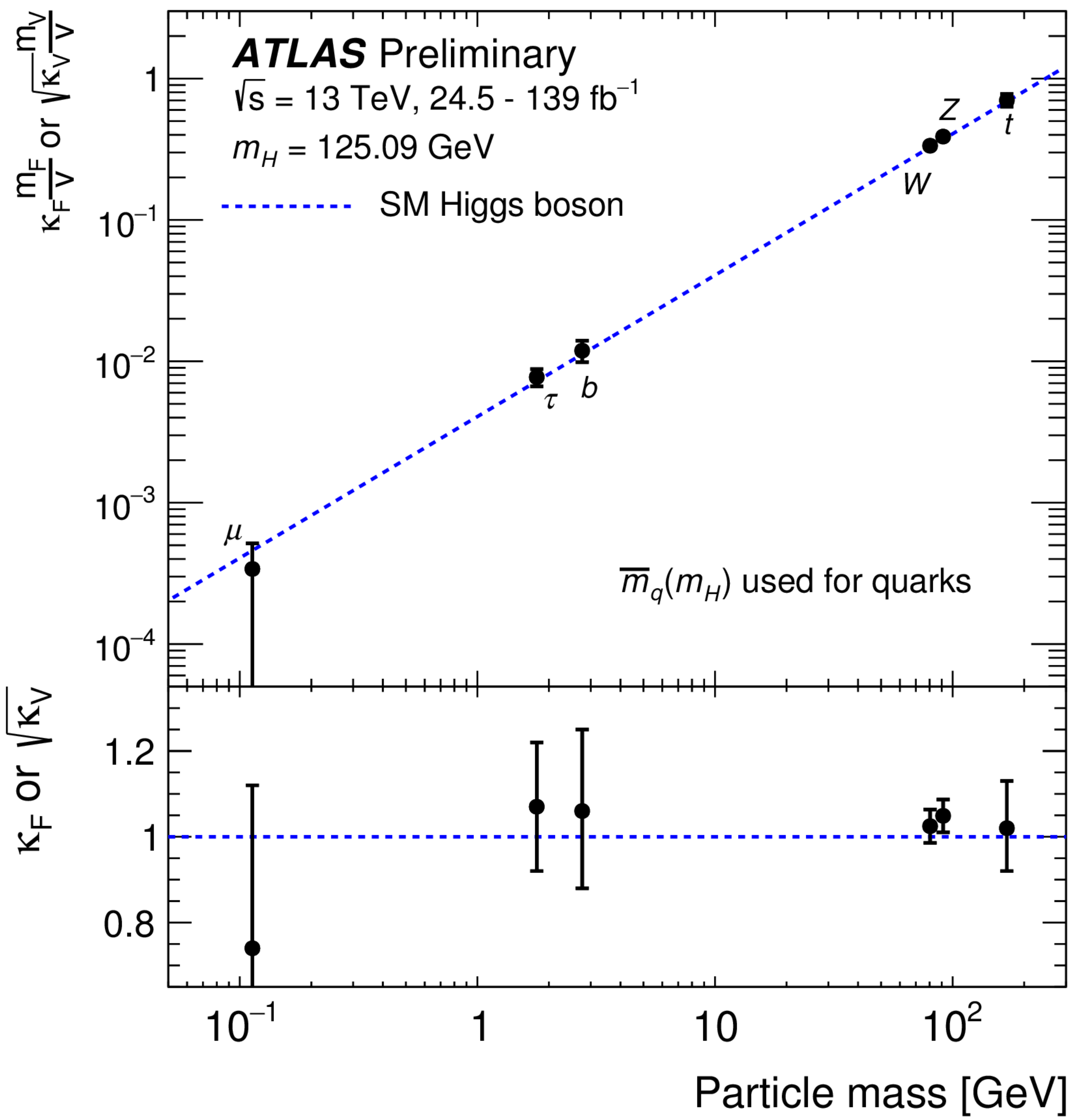
allows us to investigate universe at an age of

10^{-10} s = 0.0000000001 s

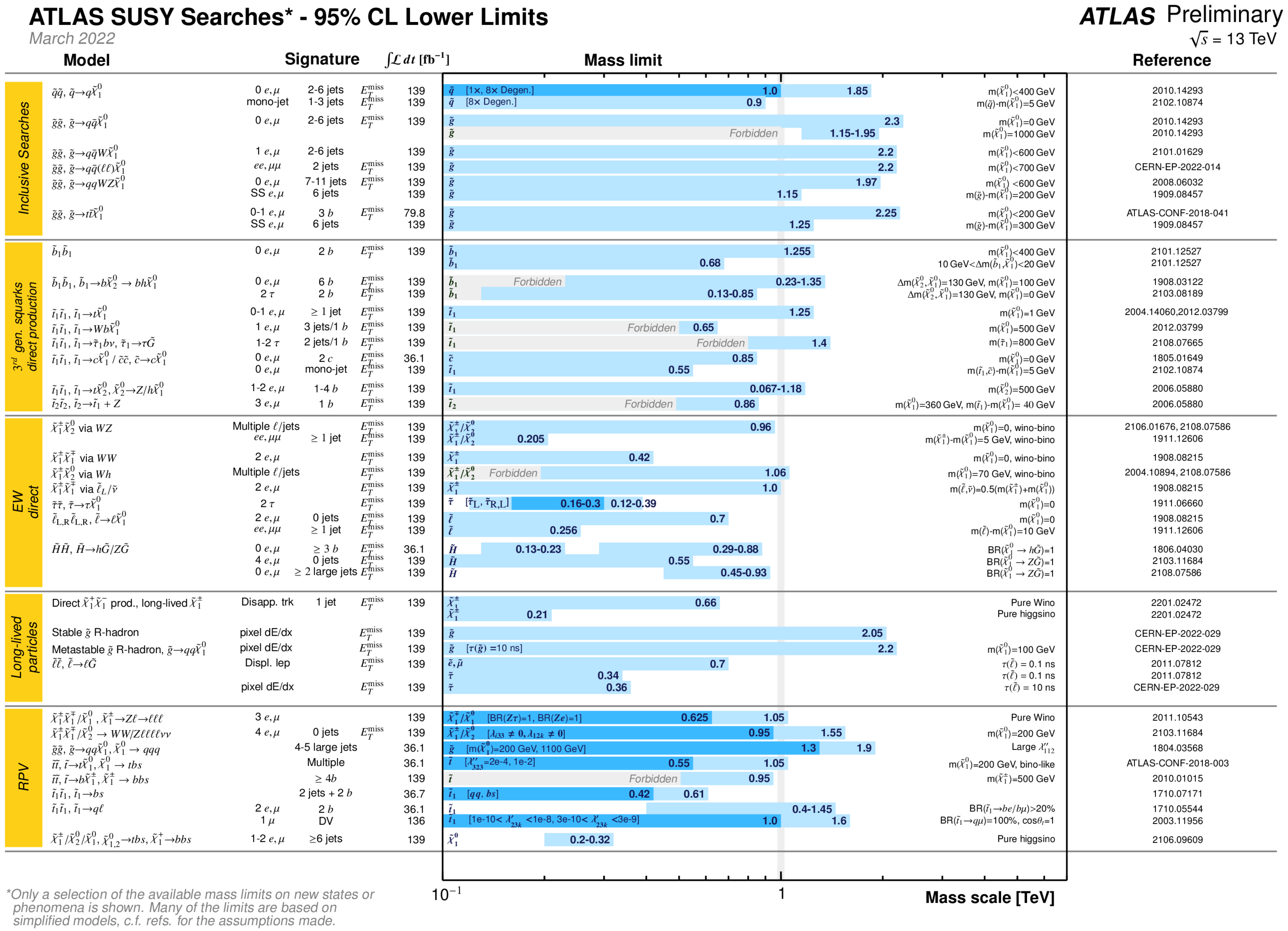


The duck & the wall

SM Higgs coupling to fermions & vector bosons

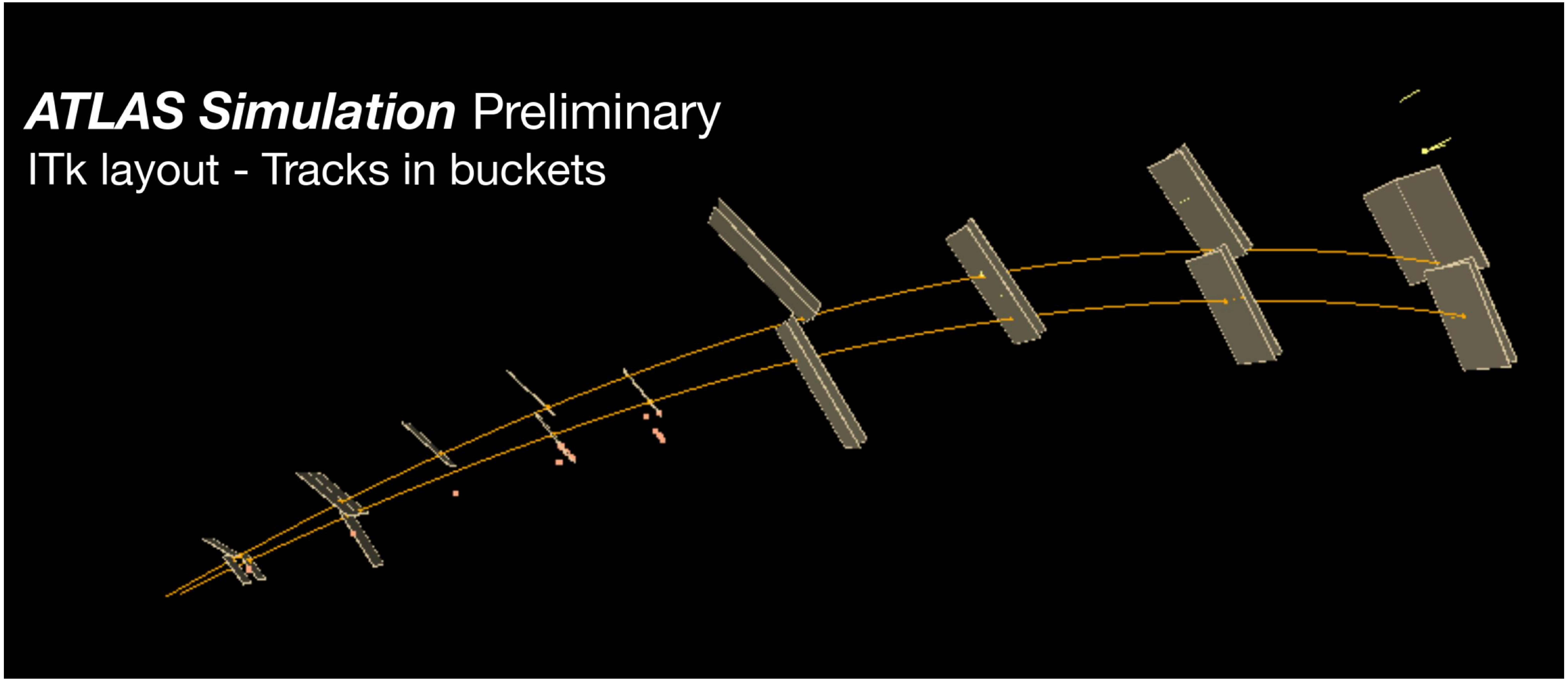


Exclusion limits for various SUSY particles



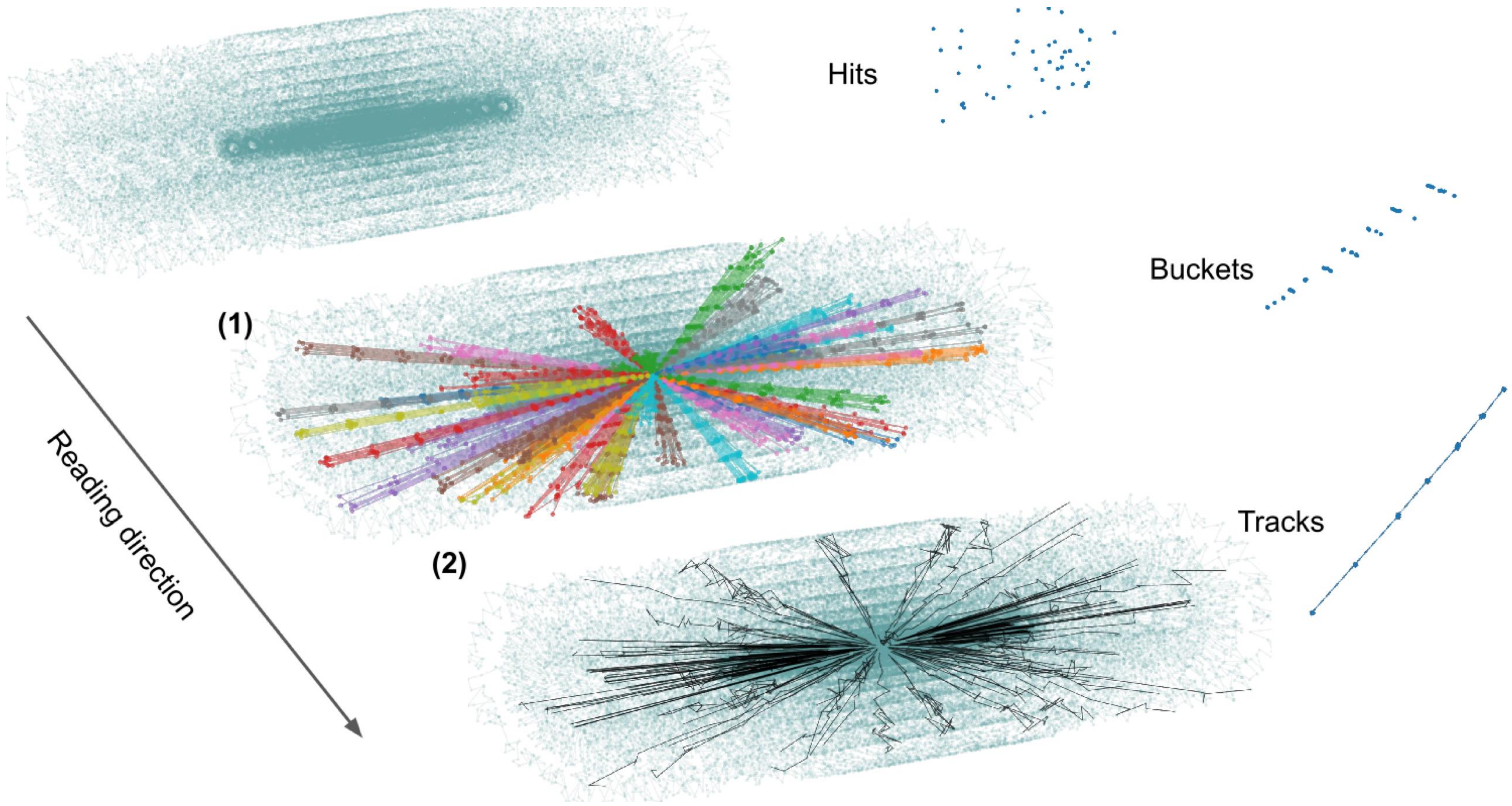
[ATLAS Public results]

Labelling: Music & Neighbours



Trajectories from simulated particles in the ATLAS upgrade tracker, **found** with (the help of) **Spotify**

Labelling: Music & Neighbours



[S. Amrouche, T. Golling, M. Kiehn, AS: Music, Neighbours & Tracking]
[S. Amrouche, N. Calace, T. Golling, M. Kiehm. AS : Hashing & similarity learning]

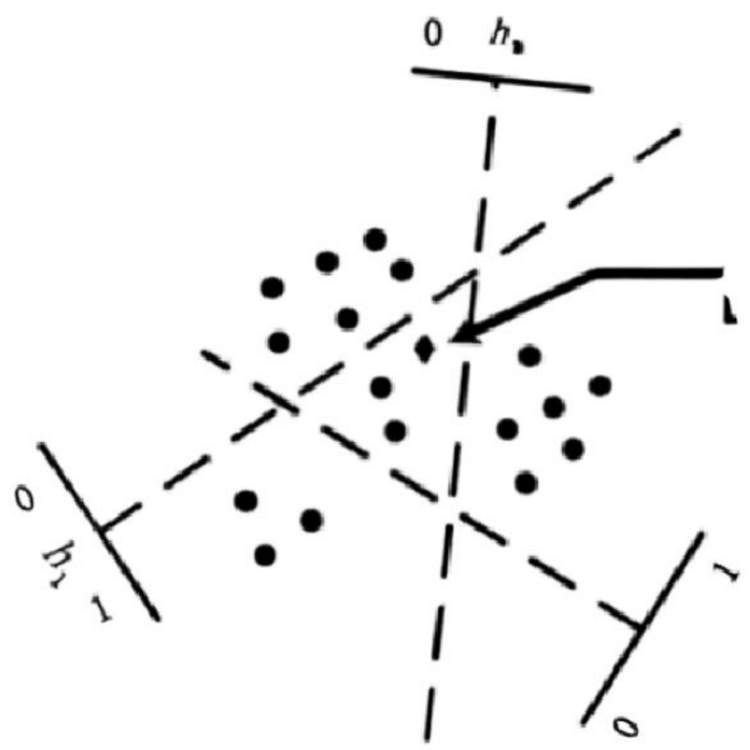
Labelling: Music & eighbours

Perfect hash function would solve the tracking problem

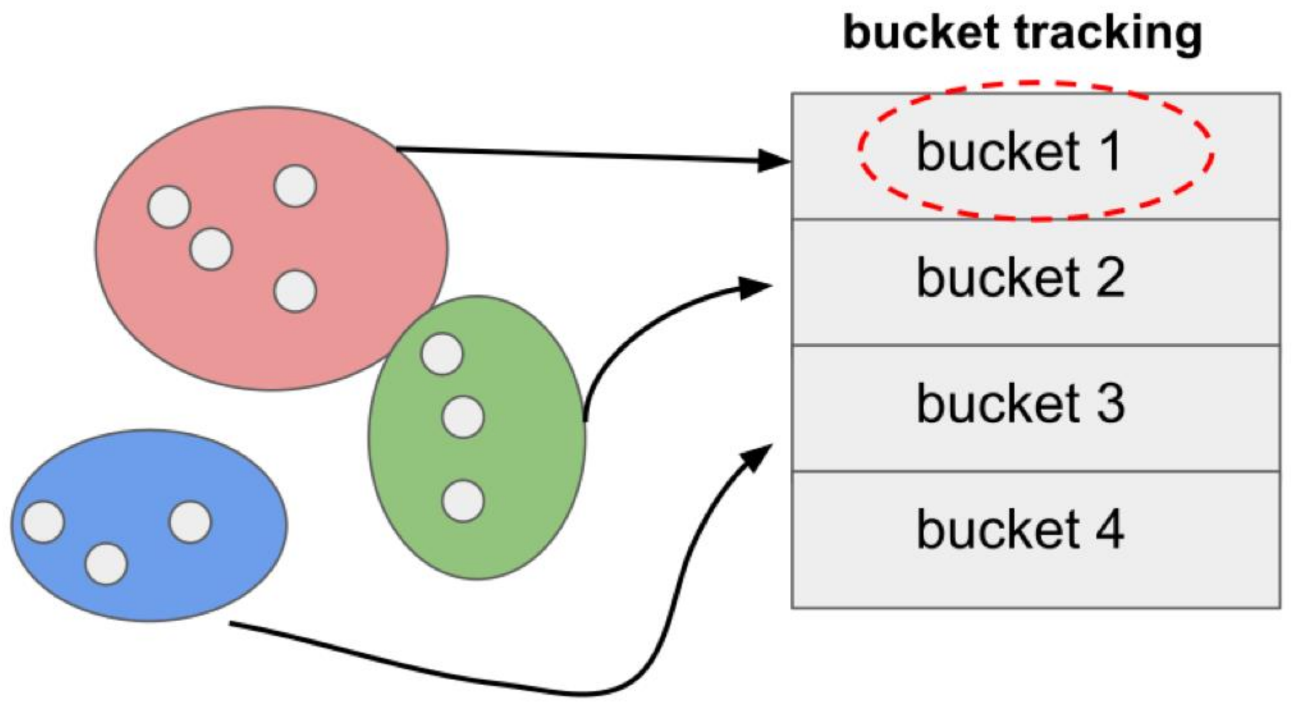
h(hit) = track number

Approximate hashing, however, can be done

h(track 1, hit 0) = group x
h(track 1, hit 1) = group x
h(track 0, hit 1) = group x



RADNOM PROJECTIONS

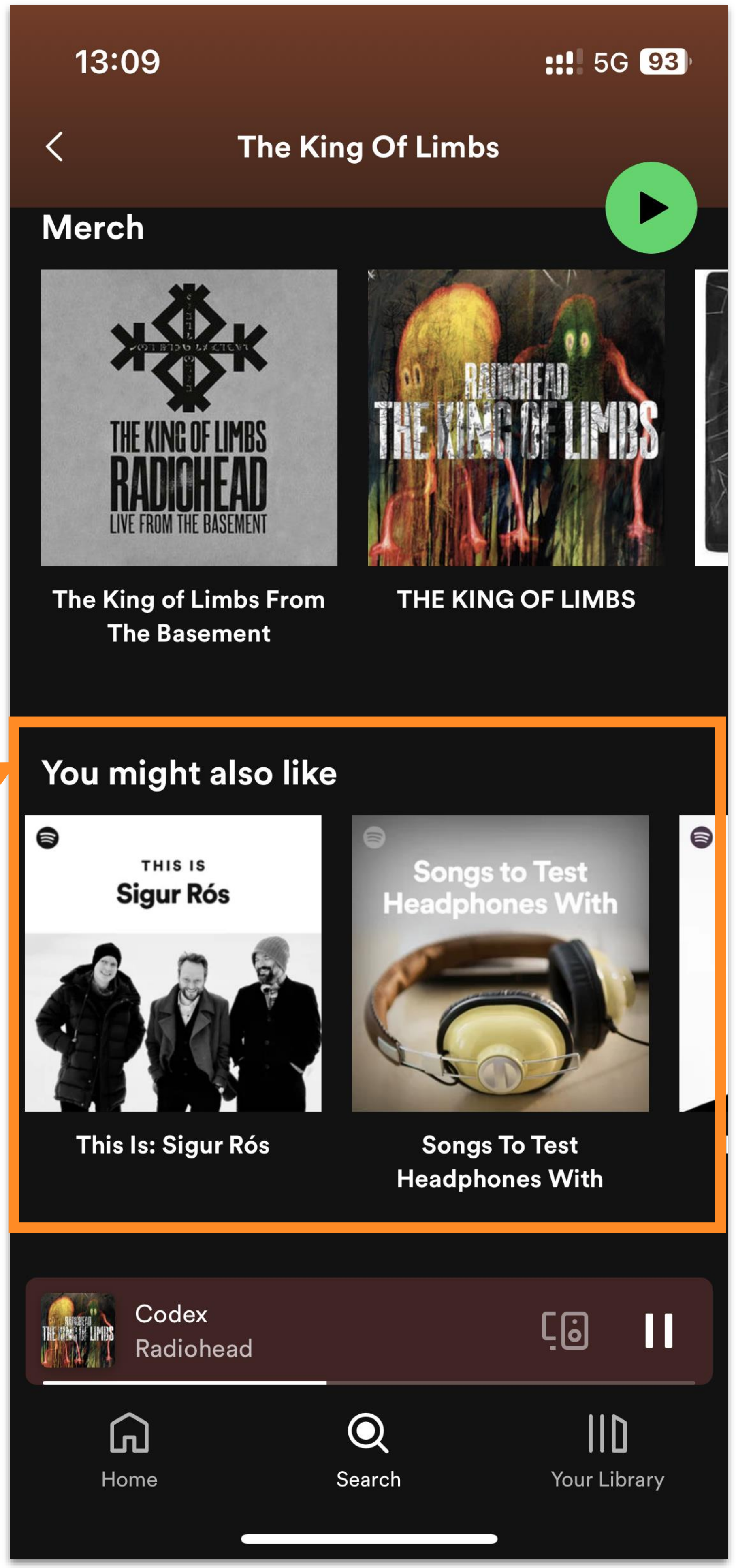


APPROXIMATE NEAREST NEIGHBOURS

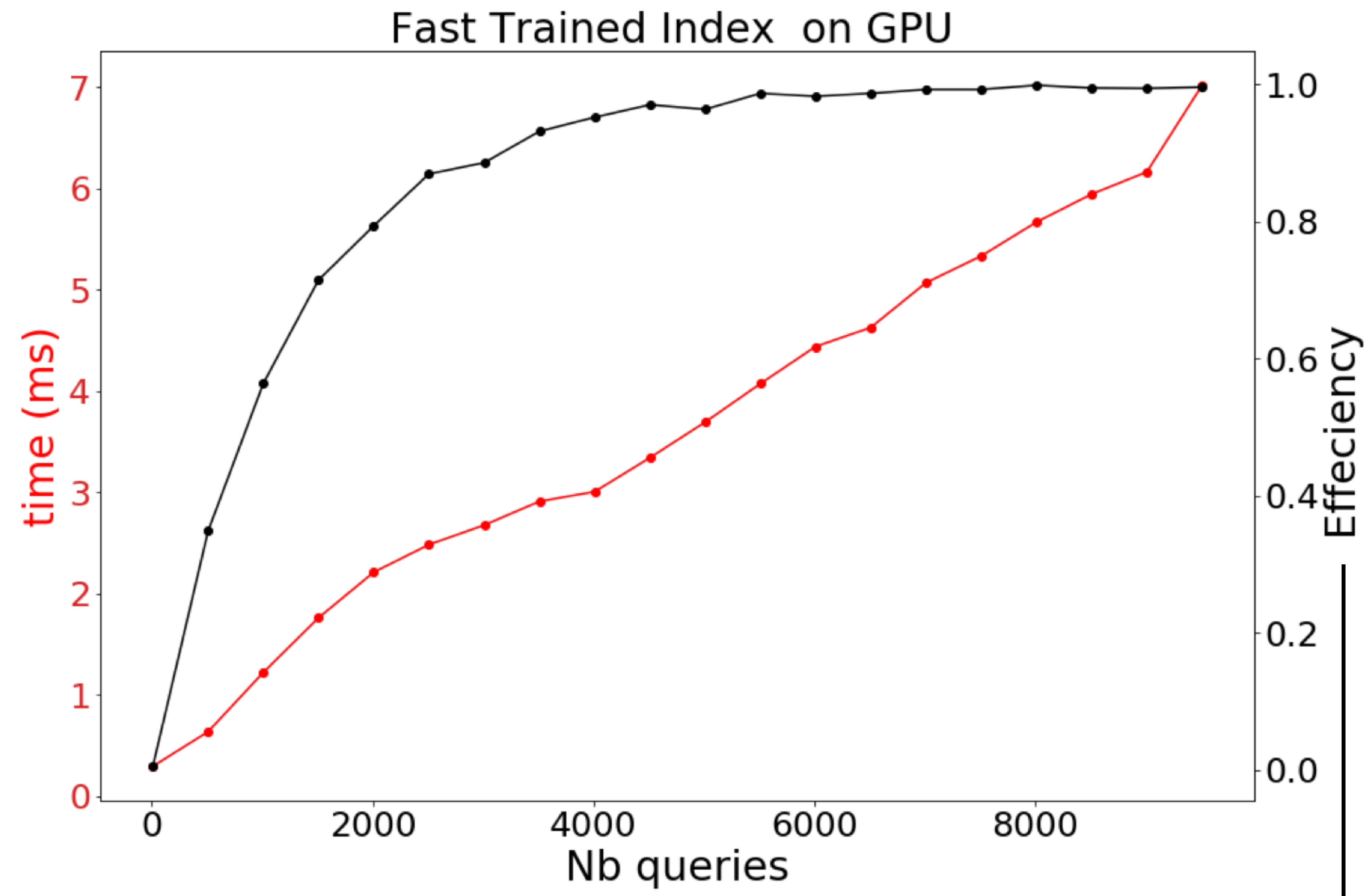
[S. Amrouche, T. Golling, M. Kiehn, AS: Music, Neighbours & Tracking]
[S. Amrouche, N. Calace, T. Golling, M. Kiehm. AS : Hashing & similarity learning]

Labelling: Music & eighbours

Spotify's approximate nearest neighbourhood library: [ANNOY]



Industry/open source libraries offer quite some potential also for science applications

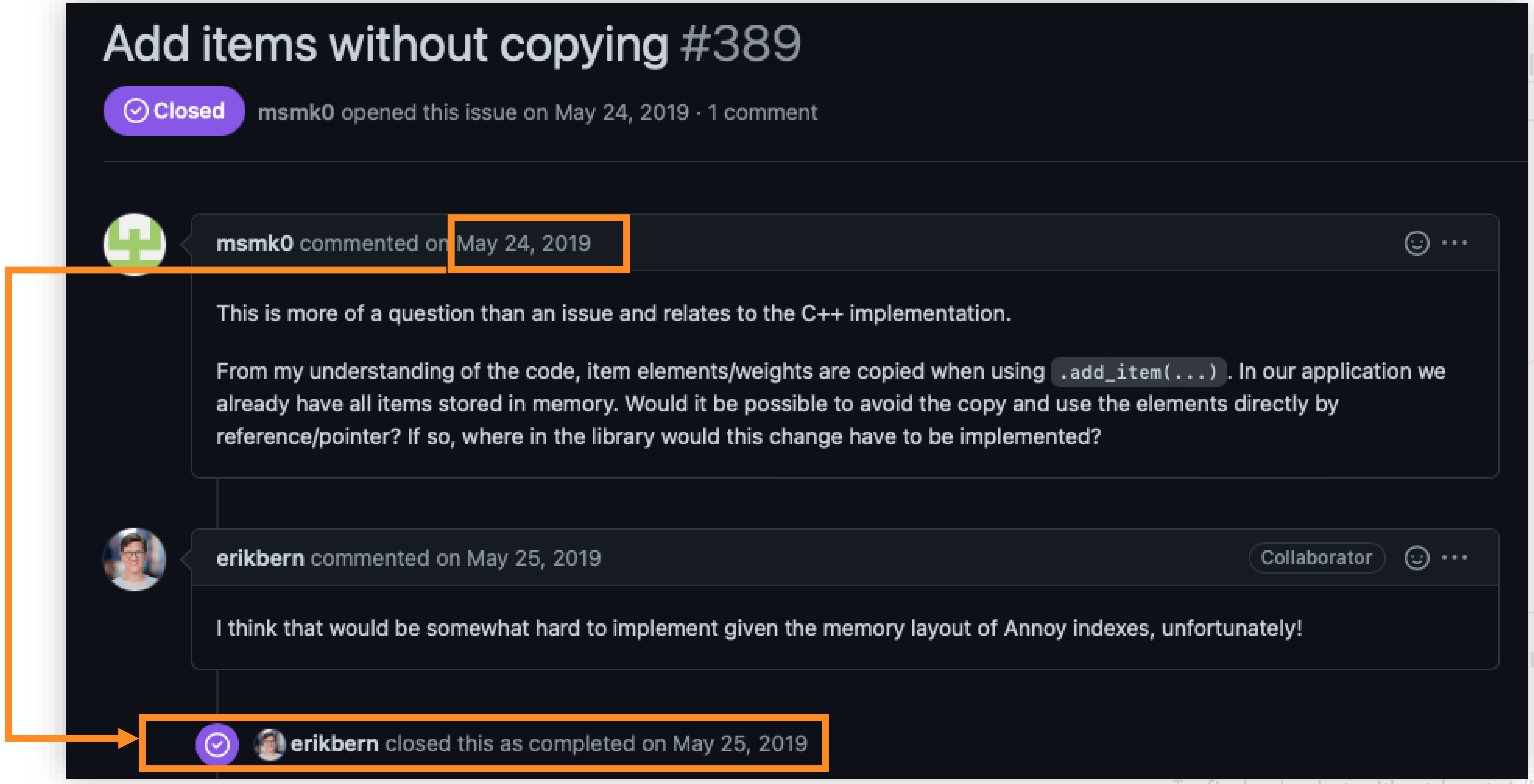


To find a bucket with at least 4/hits of the track contained (good enough for track seeding)

[S. Amrouche, T. Golling, M. Kiehn, AS: Music, Neighbours & Tracking]
[S. Amrouche, N. Calace, T. Golling, M. Kiehn. AS : Hashing & similarity learning]

Labelling: Music & Neighbours

Industry/open source libraries offer quite some potential also for science applications, but ...



.. no business model!

(In other words)

[S. Amrouche, T. Golling, M. Kiehn, AS: Music, Neighbours & Tracking]

[S. Amrouche, N. Calace, T. Golling, M. Kiehn. AS : Hashing & similarity learning]