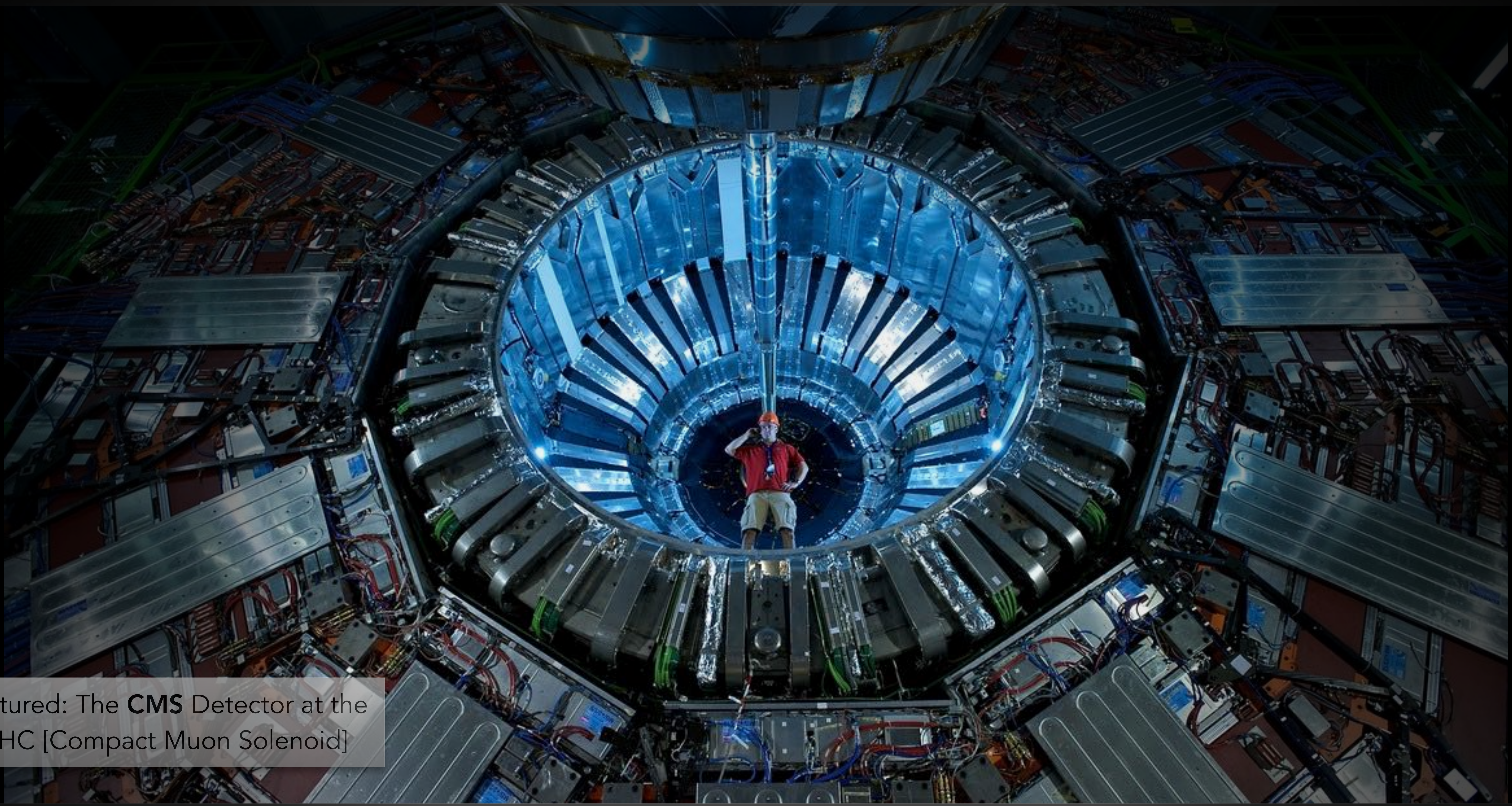
The Large Hadron Collider



Pictured: The **CMS** Detector at the LHC [Compact Muon Solenoid]

Dr. Peter Skands
School of Physics and Astronomy - Monash University
& ARC Centre of Excellence for Particle Physics at the Terascale

Why do Science?

Scientia potentia est - knowledge is power

We can improve our lives with it

We can build new things with it

We can solve problems with it

The Real Reasons:

Curiosity and **Fascination**

The Universe is vast, beautiful, and full of mysteries

I believe that science is a force for civilisation, without which …

“no knowledge of the face of the earth; no account of time, no arts, no letters, no society, and […] the life of man solitary, poor, nasty, brutish, and short.”

On mankind’s state without civilisation; Hobbes *Leviathan (1651)*

Superstition ain’t the way

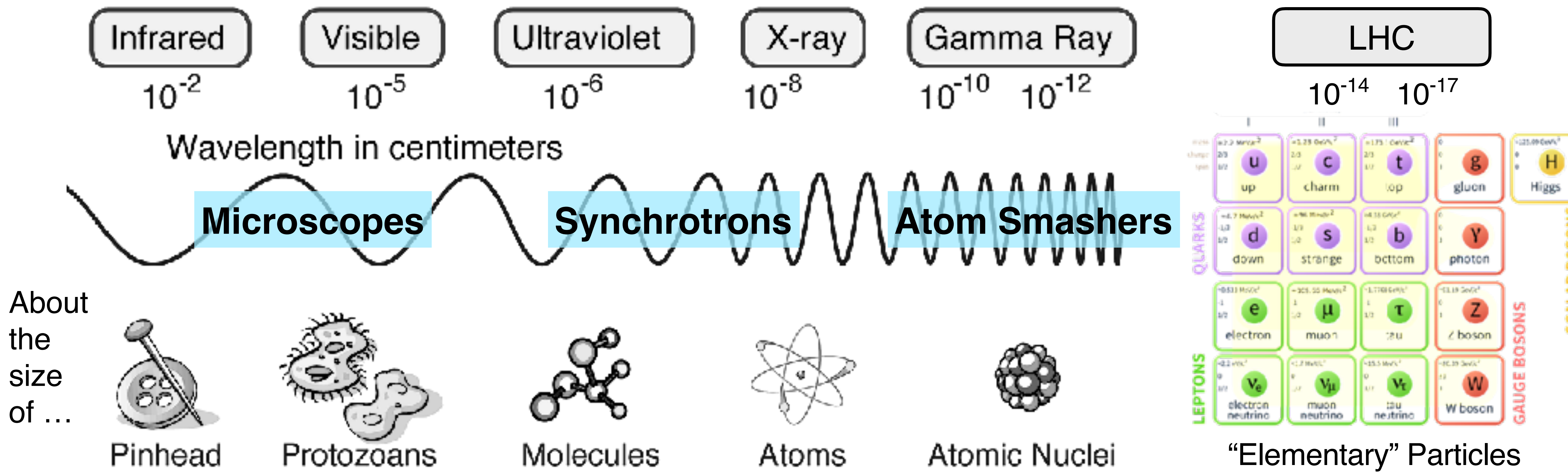
S. Wonder; *Superstition (1974)*

High Energy Physics

How do we see, in the quantum world?

To **see** something small, we need **short-wavelength probes**

NASA – MODIS



What do we need, to resolve a given wavelength with a single quantum (particle)?

"Planck-Einstein" relation

E: Energy

$$\mathbf{E} = h\nu = hc / \lambda$$

(The analogy of **E** = mc^2 for photons)

h: Planck's constant
c: speed of light
ν: frequency
λ: wavelength

Short Wavelengths ➜ **High** Energies

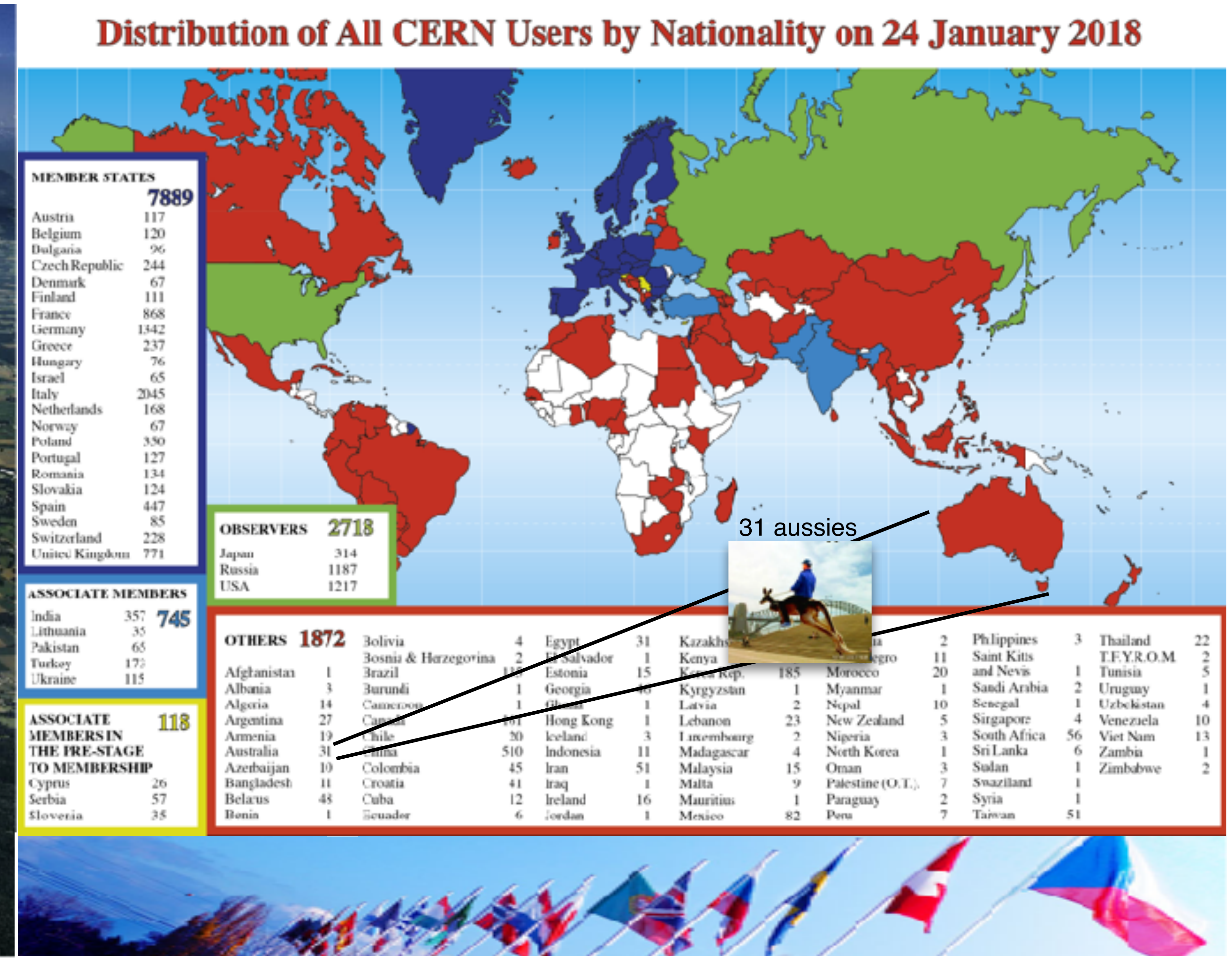
To resolve "a point" (truly fundamental particle?), we would need **infinitely** short wavelengths

In the real world: kick as hard as we can ➜ **accelerators**

CERN: European Organization for Nuclear Research

22 European Member States and around 60 other countries

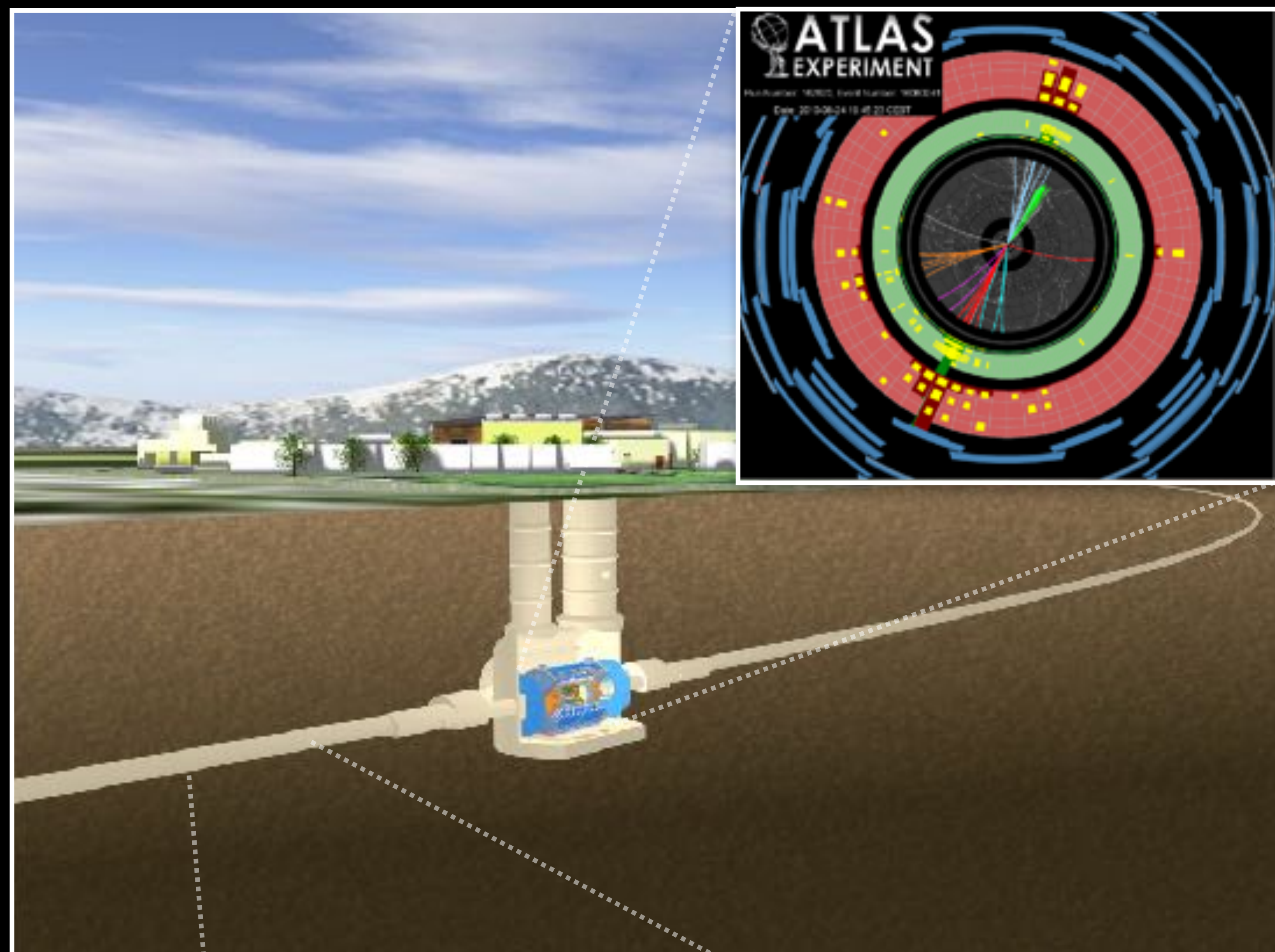
~ 13 000 scientists work at CERN



Founded in **1954** as one of Europe's first joint ventures

Yearly budget ~ 1 billion CHF ~ 1.4 billion AUD

What goes on at CERN?



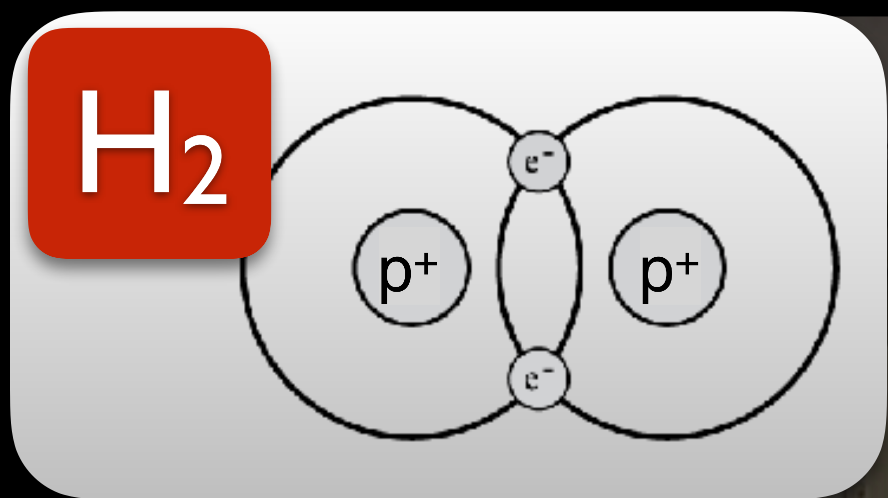
The LHC is housed in a tunnel
~ 100m underground and 27km long.

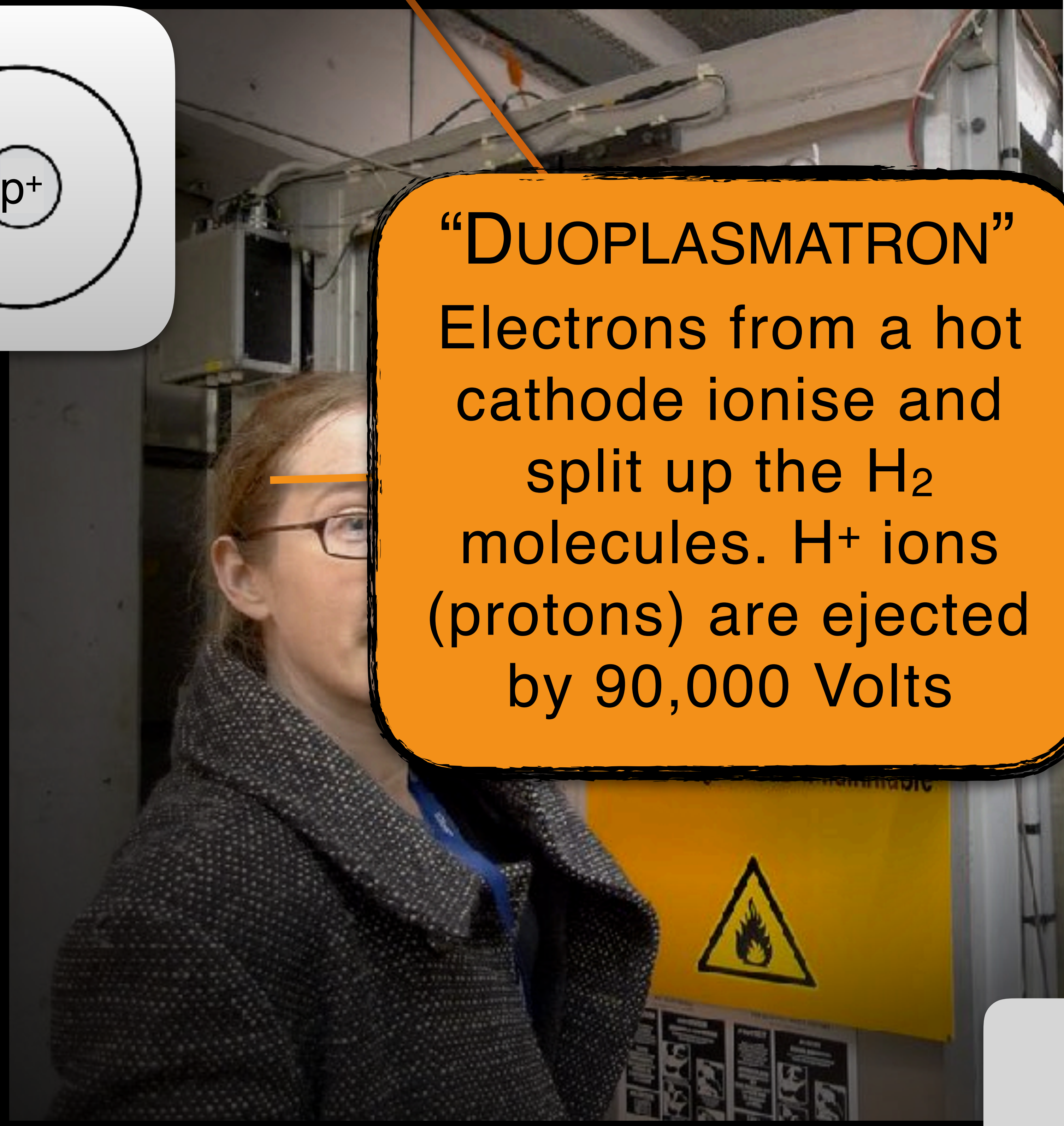
Two proton beams are brought into collision at four points on the ring

First collisions at 7 TeV in the ATLAS detector at LHC - March 2010

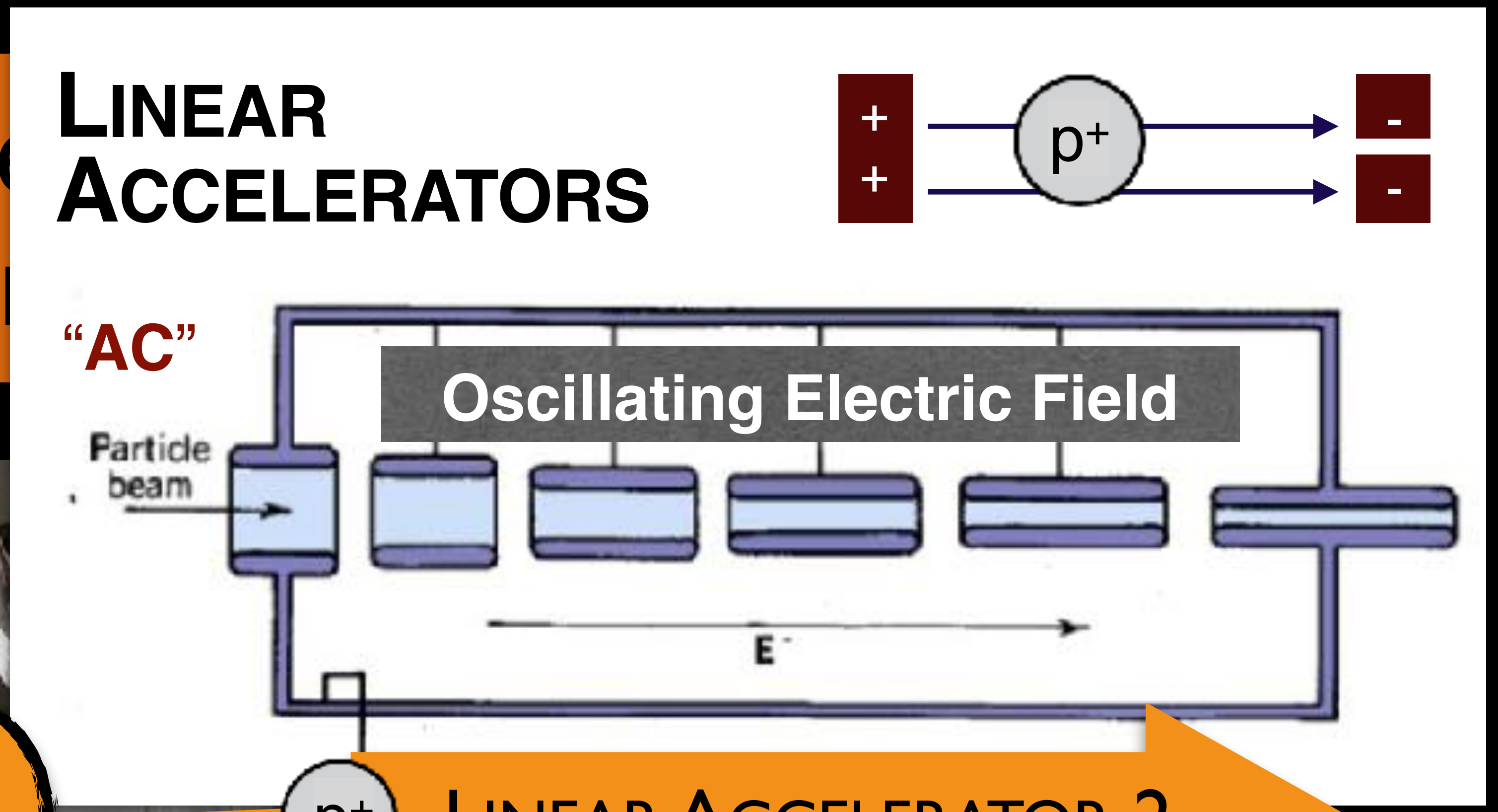
Colliding Protons

The **proton source** is a bottl
gas at one end of the acceler



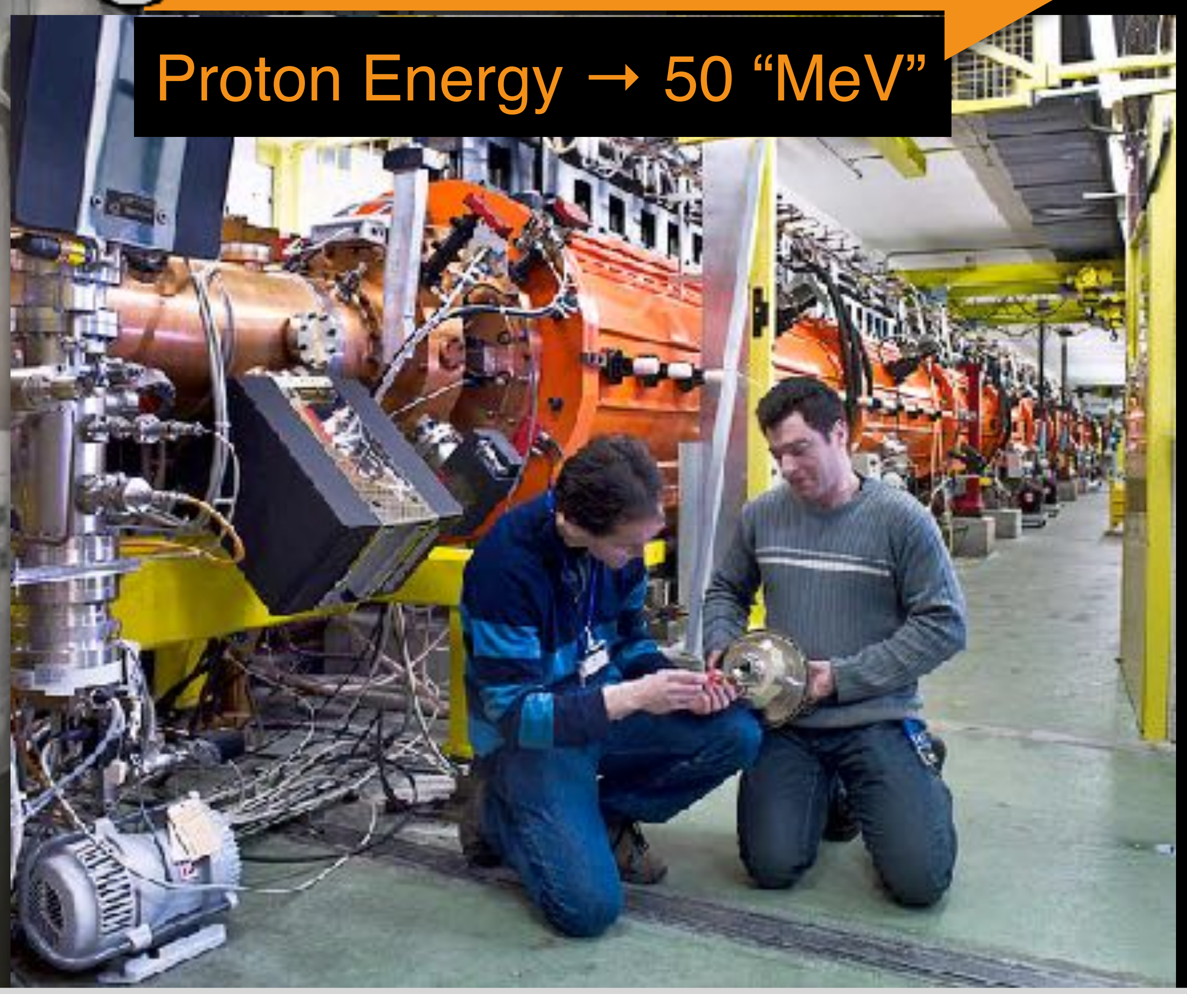


"DUOPLASMATRON"
Electrons from a hot cathode ionise and split up the H_2 molecules. H^+ ions (protons) are ejected by 90,000 Volts



p+ LINEAR ACCELERATOR 2

Proton Energy → 50 "MeV"



(This bottle is on displa
The real bottle is ~ 1.5m tall. Re

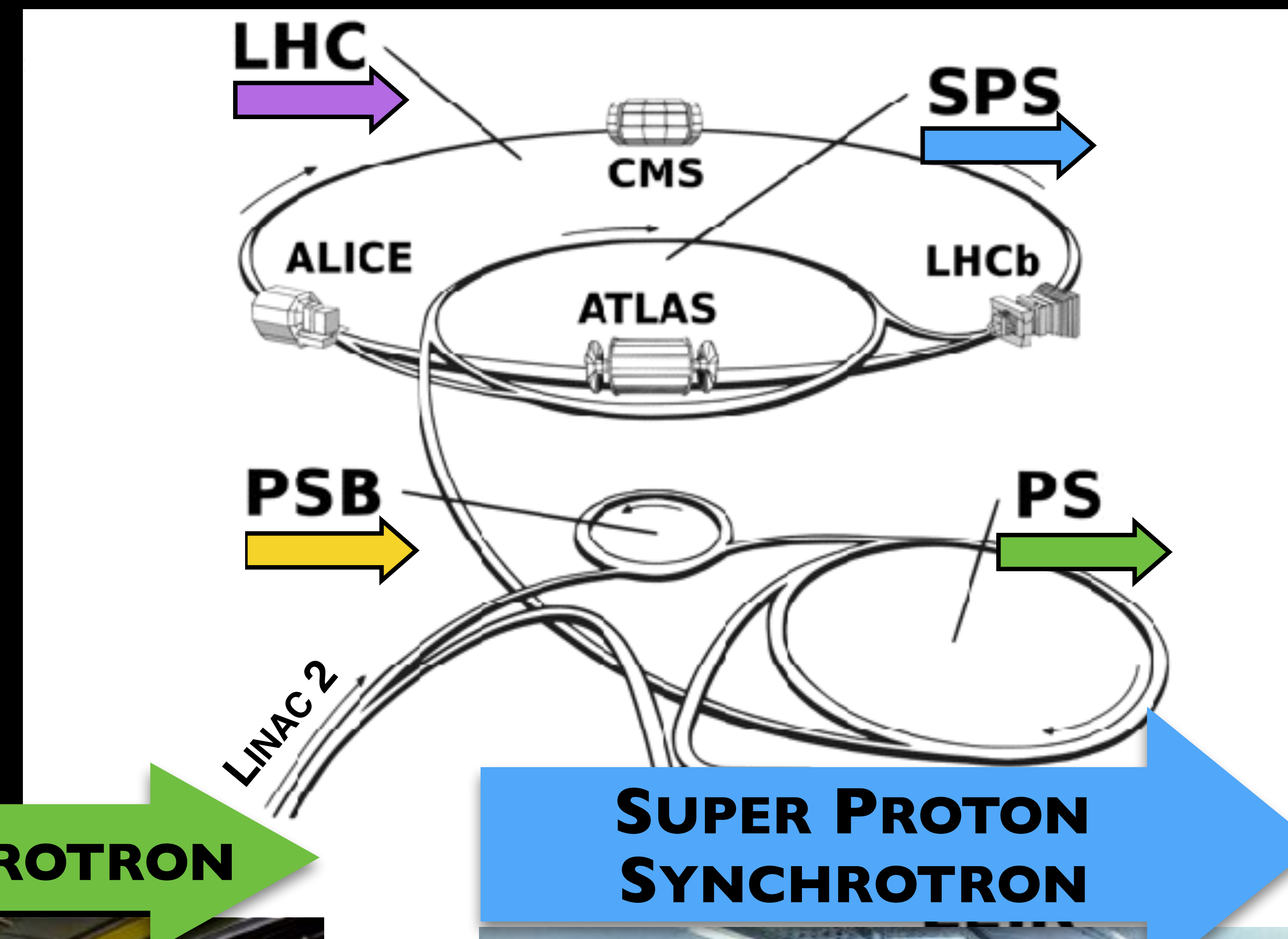
"Electron-Volt"

1 eV = kinetic energy gained by unit-charged particle accelerated by 1 Volt

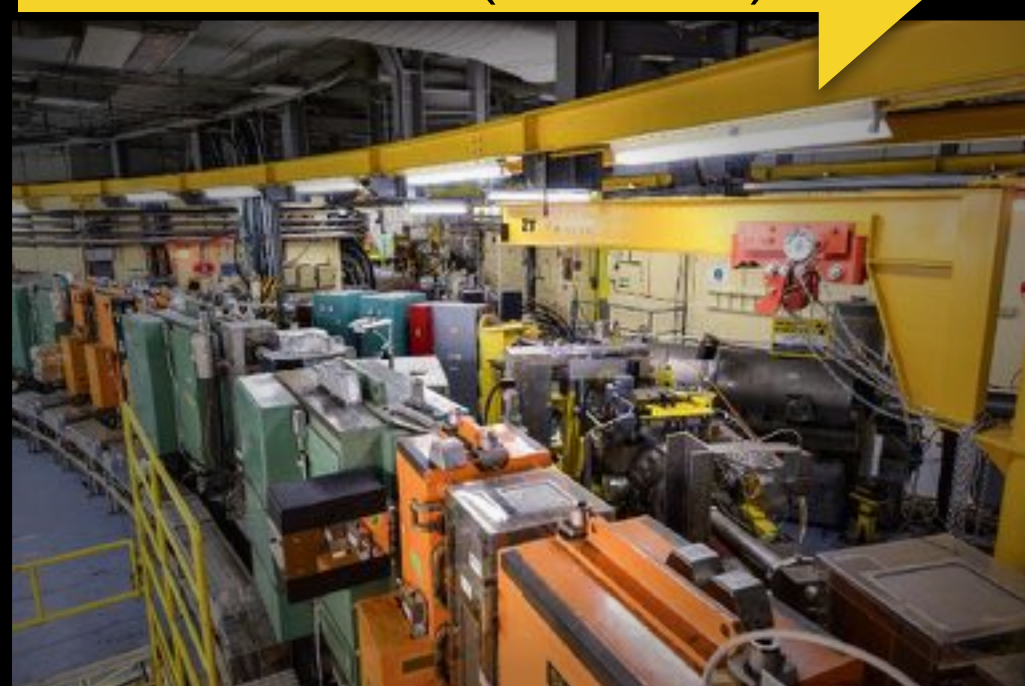
Up the Daisy Chain

"Recycling" at CERN

Each decade's top accelerator
→ pre-stage for the next step up



Proton Synchrotron Booster (4 Rings)



Length: 160 m
In : 50 MeV
Out: 1.4 GeV

Proton Synchrotron

(1959)
Length: 628 m
In : 50 MeV - 1.4 GeV
Out: 25 GeV

Super Proton Synchrotron

(1976)
Length: 7 km
In : 25 GeV
Out: 450 GeV

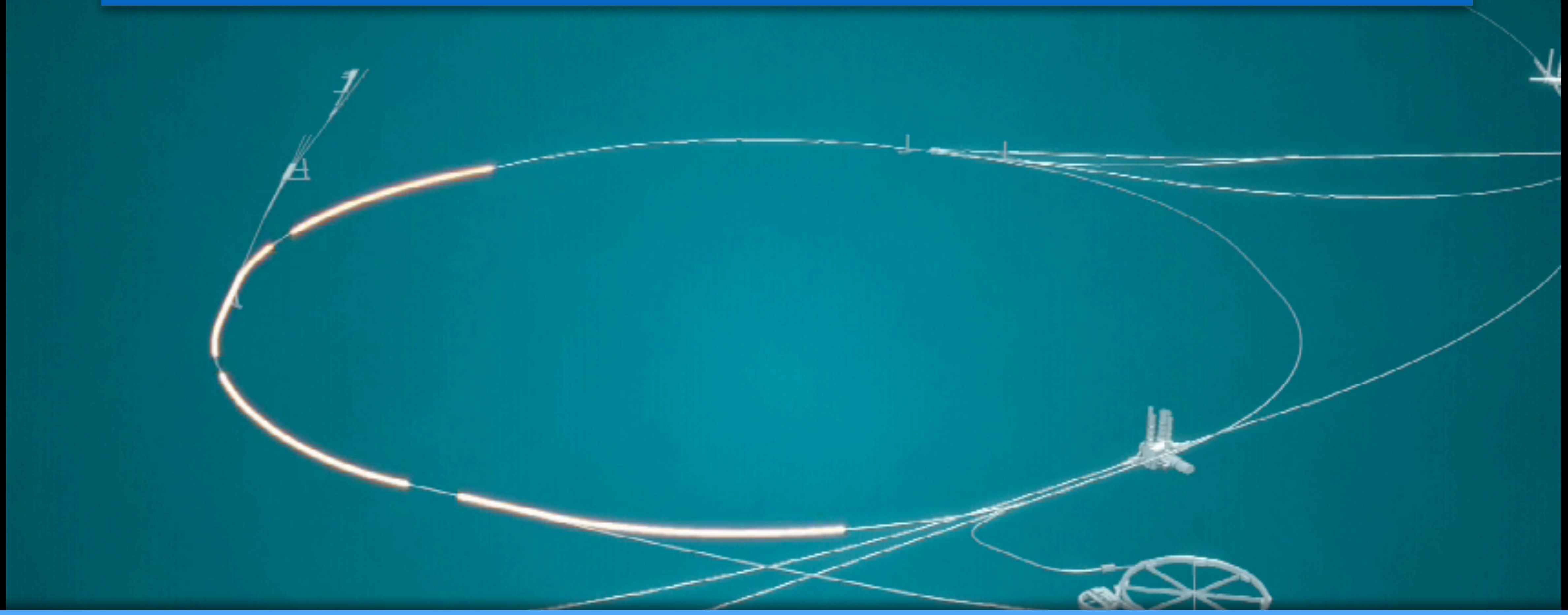
The Last Waypoint

Max energy of Super Proton Synchrotron: **450 GeV**

Corresponding to having been accelerated through a total of 450 billion Volts of potential drop

Operated in the 1980ies; discovered the **W** and **Z** bosons (Nobel Prize 1984)

Next step: transfer to the **LHC**



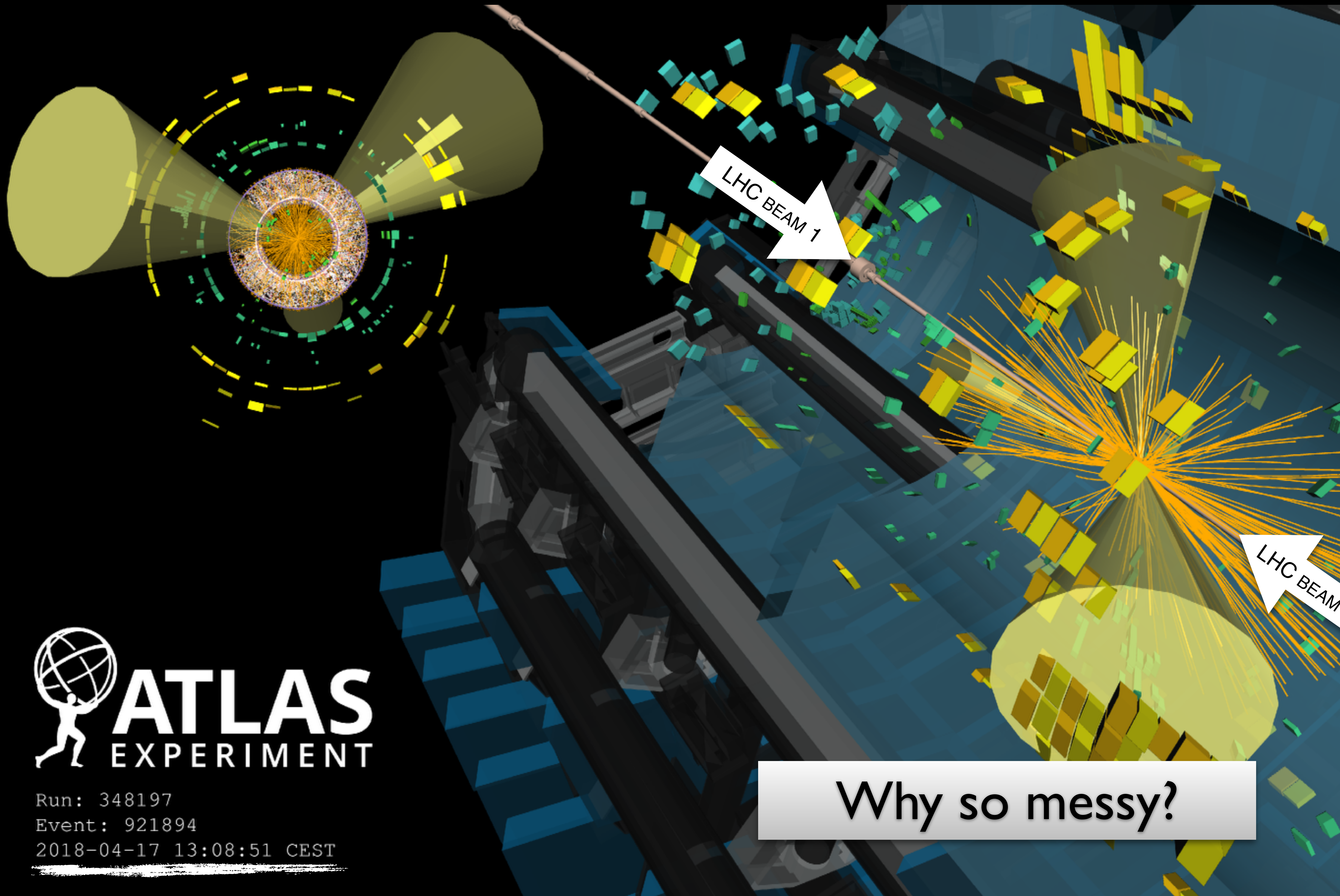
"Stable beams" for 2018 LHC run: **April 17th**

Collision Energy: 13,000 GeV

(~ 1 million times higher than nuclear fusion)

Twice what we had when Higgs boson was discovered **+** more intense beams

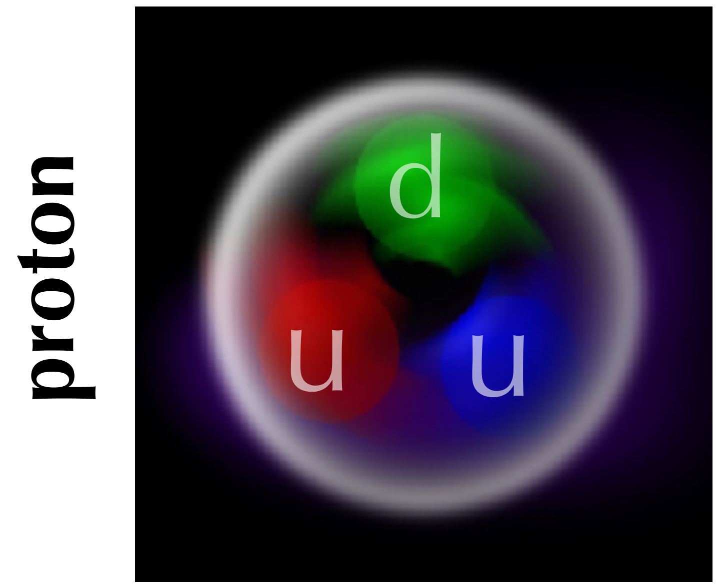
More than **3,000 physics publications** (= new measurement results) from the LHC **so far**

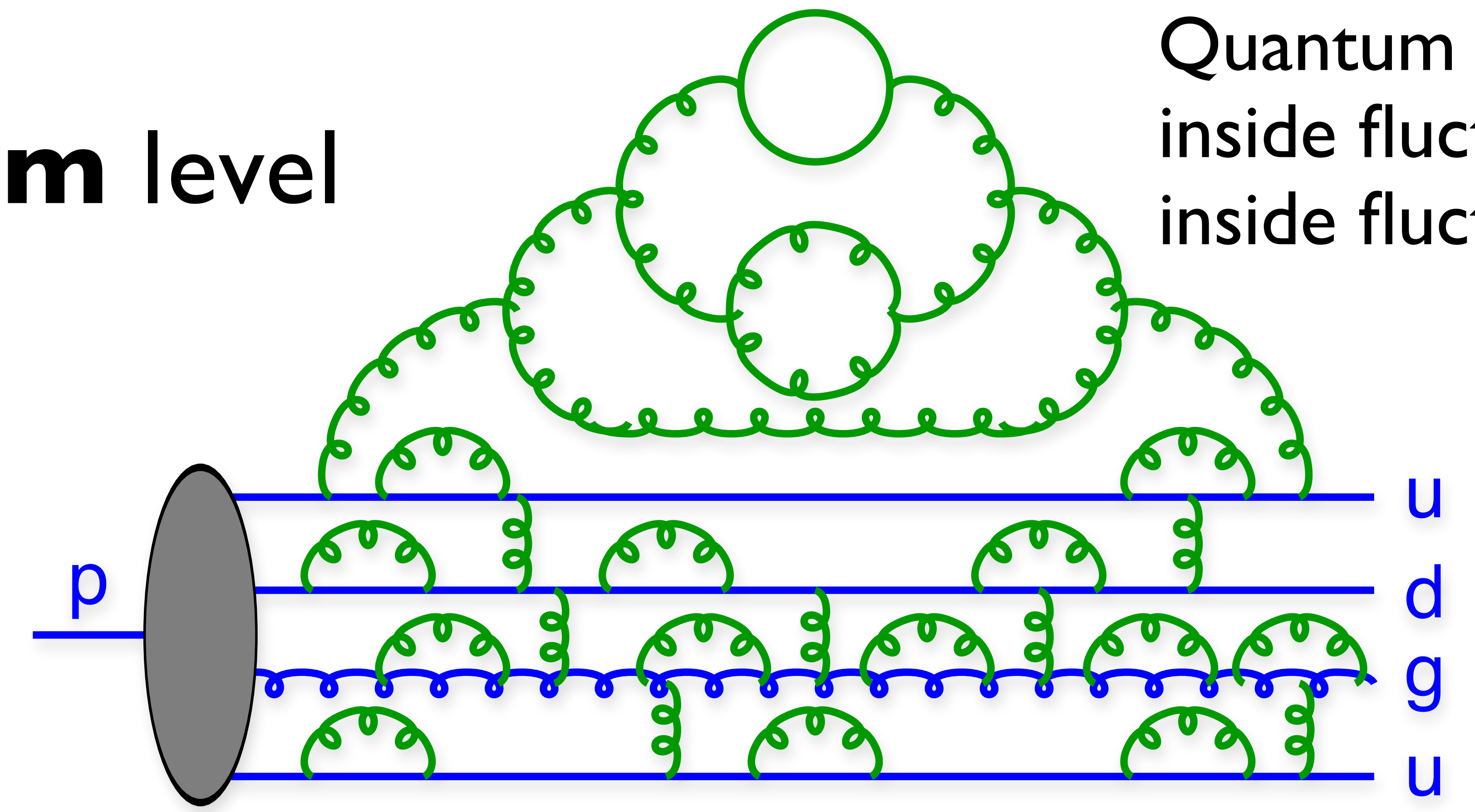


What are we really colliding?

Elementary Particles?

Take a look at the **quantum** level



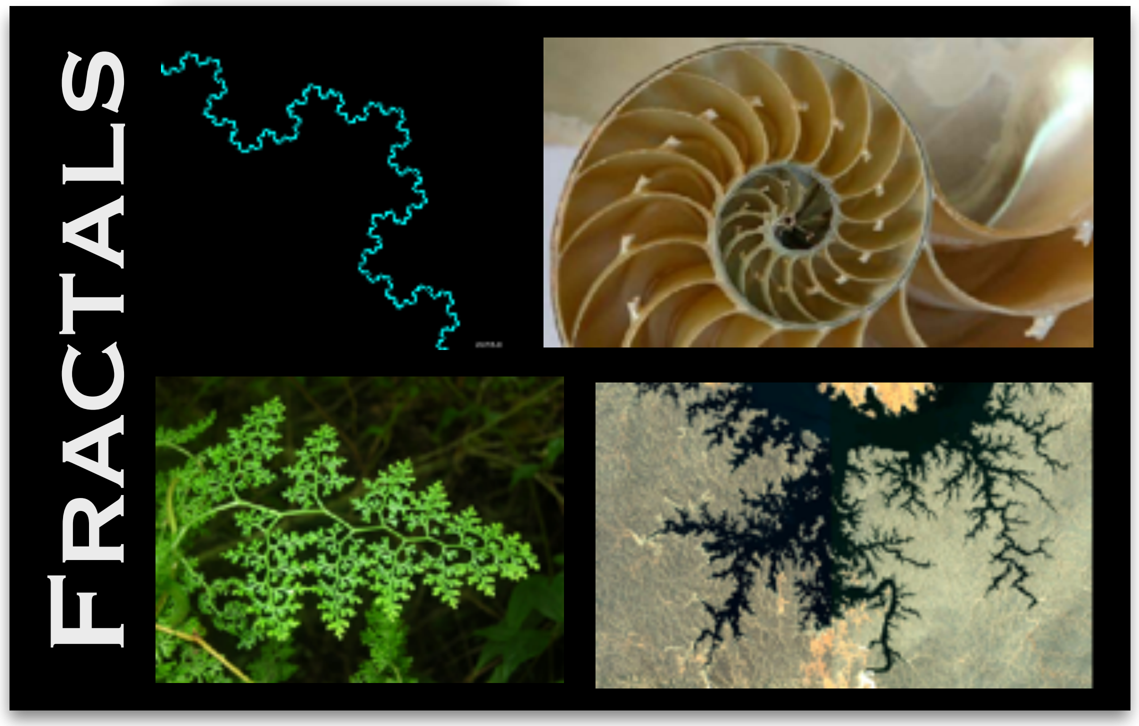


What we see when we look **inside the proton**

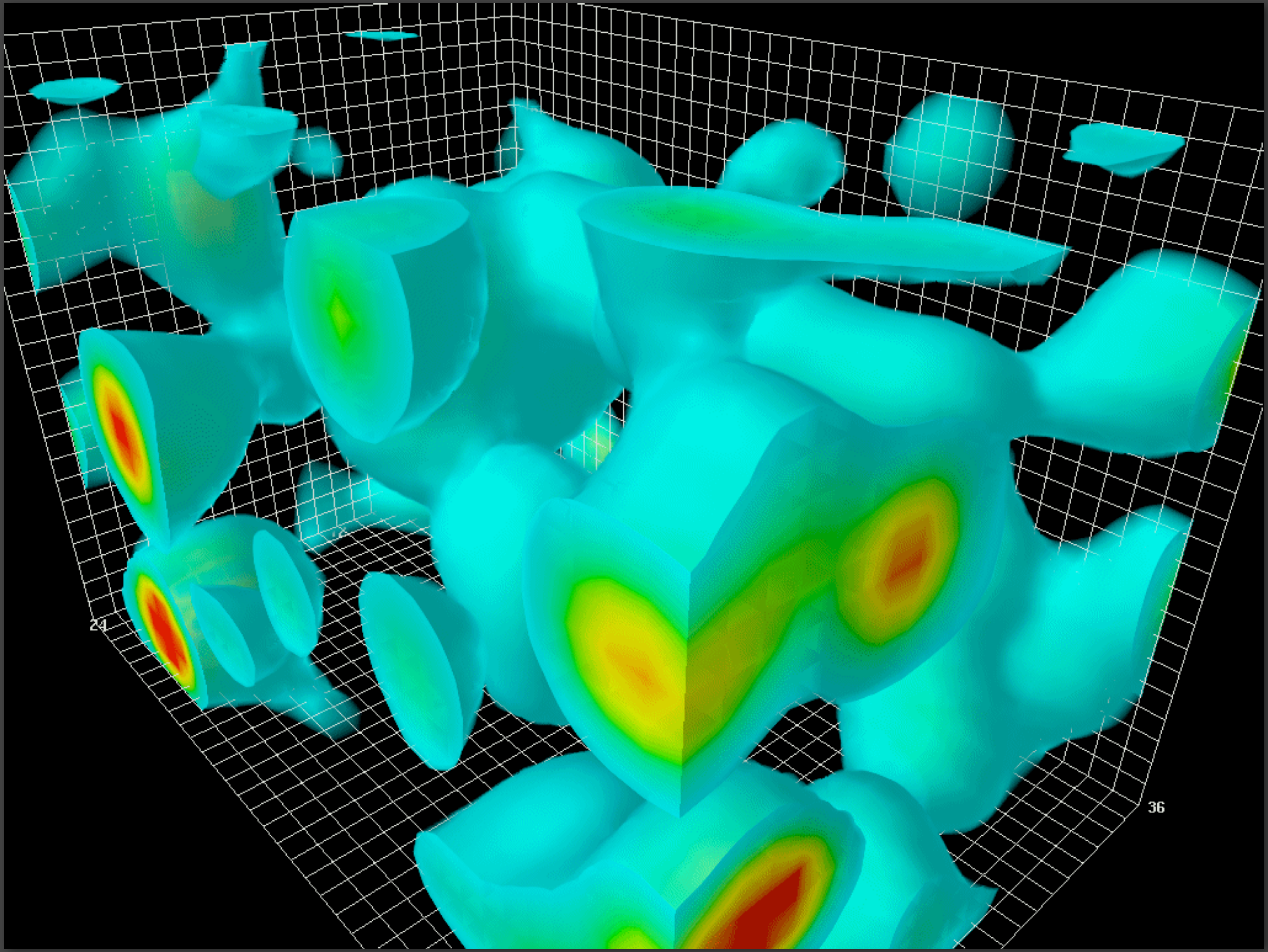
An **ever-repeating self-similar** pattern of quantum fluctuations

At **increasingly smaller distance scales**

To our best knowledge, this is what fundamental ('elementary') particles "really look like"



Quantum Field Theory on a Supercomputer



Simulation of empty space; by D. Leinweber, Adelaide U.

Such Stuff as Beams are Made Of

Lifetime of typical fluctuation ~ r_p/c (=time it takes light to cross a proton)

~ 10^{-23}s; Corresponds to a frequency of ~ **500 billion THz**

To the LHC, that's slow! (reaches "shutter speeds" thousands of times faster)

Planck-Einstein: E=hν ➜ ν_{LHC} = 13 TeV/h = **3 million billion THz**

➜ Protons look "frozen" at moment of collision

But they have a lot more than just three quarks inside

Hard to calculate, so use statistics to parametrise the structure

Every so often I will pick a gluon, every so often a quark (antiquark)

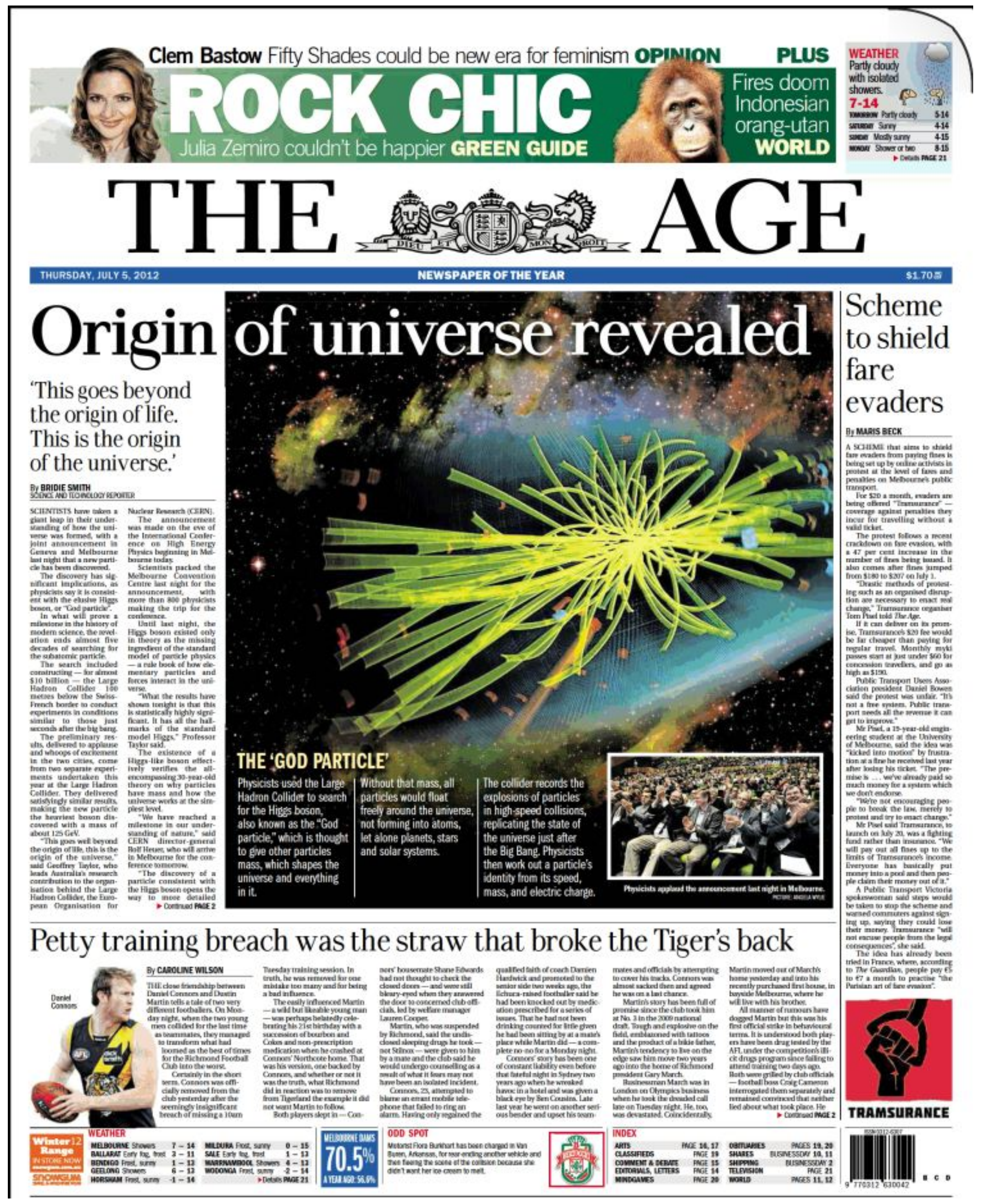
Measured at previous colliders, as function of energy fraction

Then **compute the probability** for all possible quark and gluon **reactions** and compare with experiments …

(Part of the work I do at Monash is writing computer codes that do that)

2012: The Higgs Discovery

July 5th 2012



F. Gianotti (now director of CERN)

P. Higgs

F. Englert

P. Higgs

What is "Mass"?

Consider a 'field' distributed evenly across the Universe, of uniform strength (and no preferred direction / polarisation)

Suppose that different particles experience this 'field' as being more or less transparent

- To a photon (light), the field is completely "translucent"
- But an electron (or a proton), will interact with it

Suppose that this field **condenses** around the particles which couple to it, causing an increased energy density around those particles. **Looks like mass** ($E=mc^2$).

We call this field the "**H**" *(or Brout-Englert-Higgs)* **Field**

This hypothesis made one spectacular prediction: it should be possible to excite waves in the Higgs field itself

The smoking gun

The Higgs Particle

Prediction: there should be a **resonant energy** at which a quasi-stable excitation could be produced: the '**Higgs Boson'** or **'Higgs Particle'**.

But the theory did not predict ***which*** energy; the search was on!

"Quasi-Stable"➜ should quickly dissolve (decay) into other particles, but should be detectable via its decay products

The discovery of a particle consistent with these properties was announced at CERN on July 4, 2012 (at $E = m_H c^2 = 125$ GeV)

2018: we now have a **factor 10 more data**, **+** more on the way

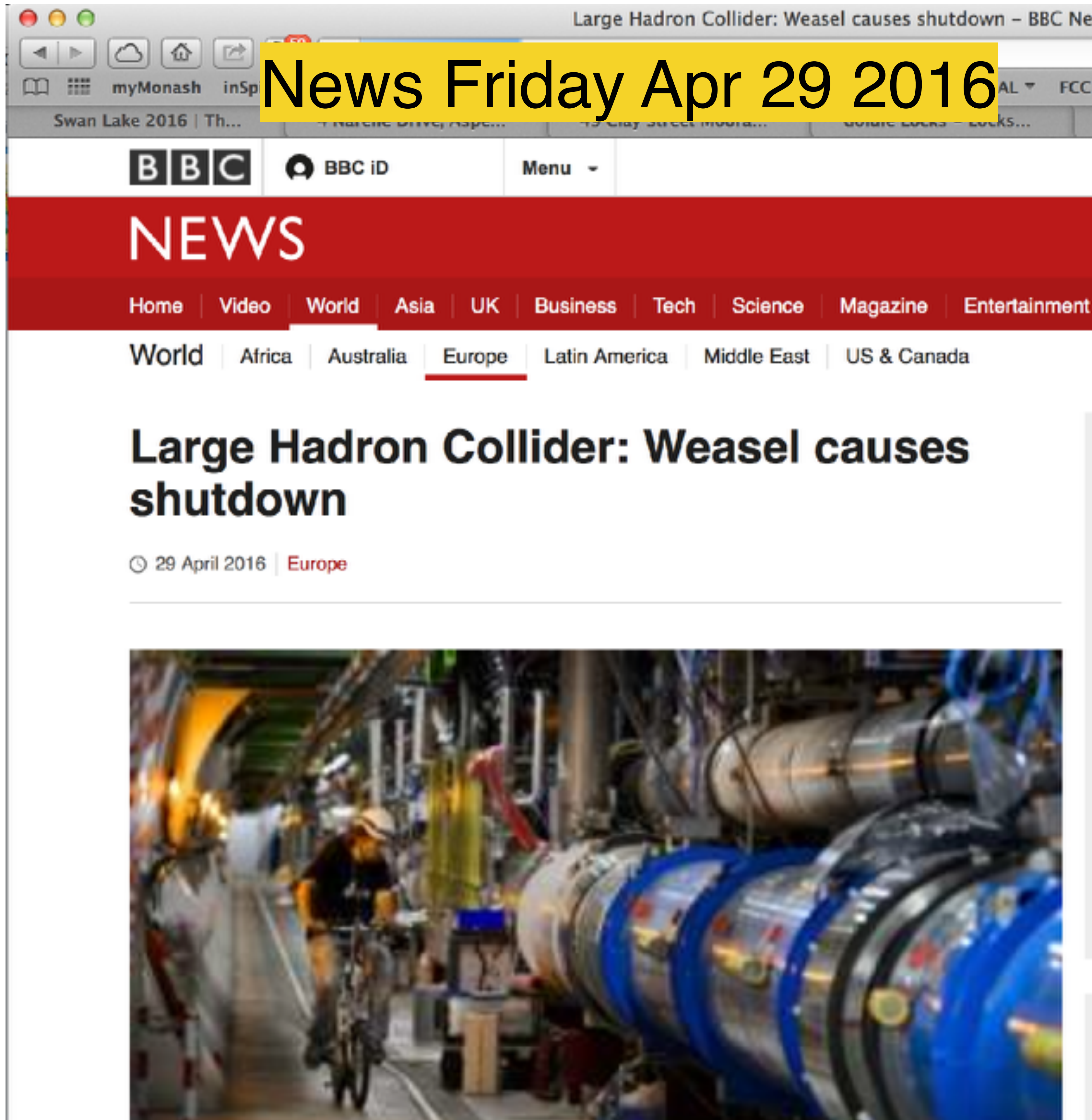
➜ can examine the **quantum properties** of this new H particle

So far, no **major** deviations from 'Simplest Higgs' predictions

This is now the **major puzzle** … and a very hard one it is …

LHC not much in the headlines since then, apart from that time in 2016 …

The Weasel


News Friday Apr 29 2016

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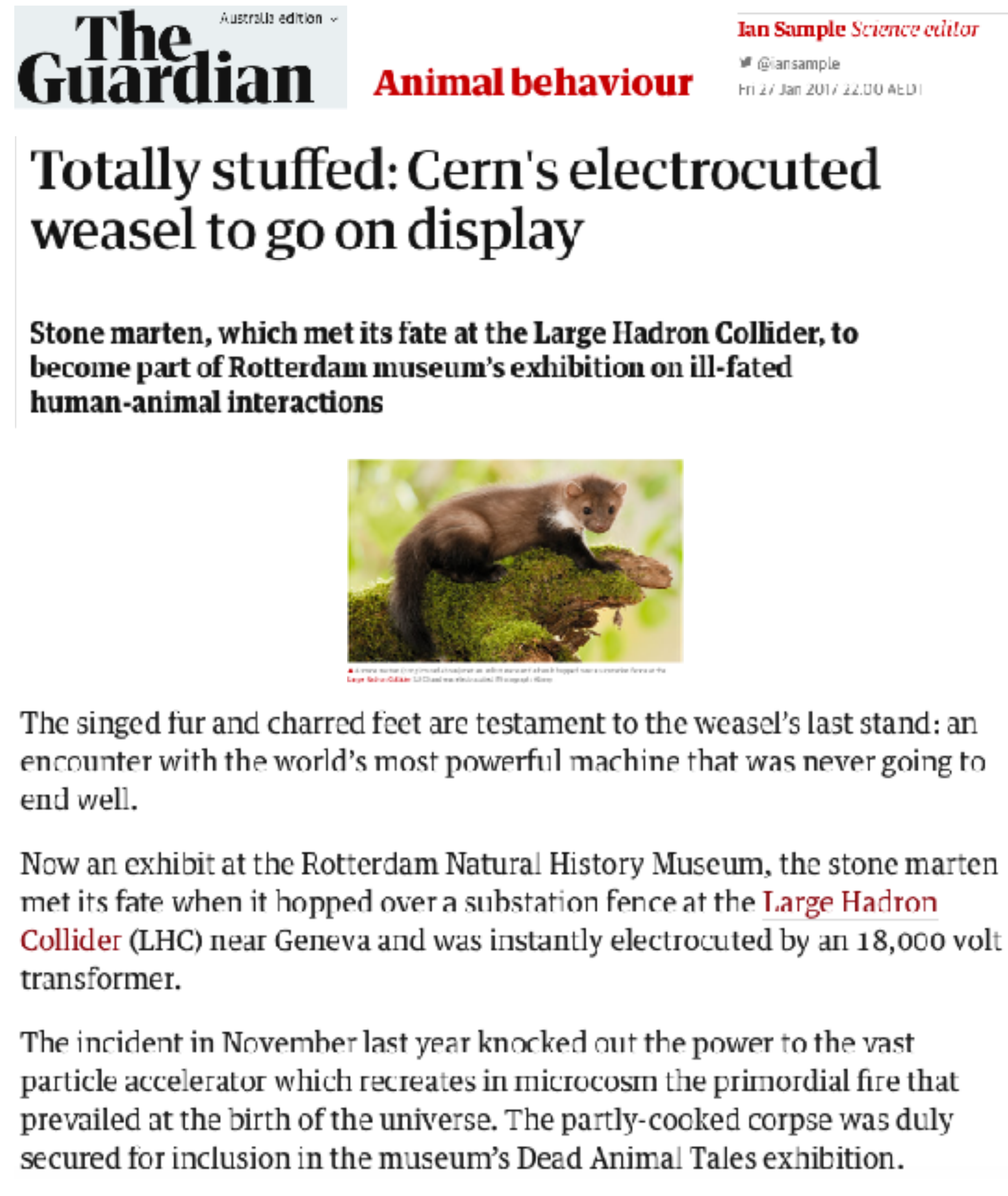
Large Hadron Collider: Weasel causes shutdown

29 April 2016 | Europe


The Guardian

Animal behaviour

Ian Sample Science editor

Totally stuffed: Cern's electrocuted weasel to go on display

Stone marten, which met its fate at the Large Hadron Collider, to become part of Rotterdam museum's exhibition on ill-fated human-animal interactions

The singed fur and charred feet are testament to the weasel's last stand: an encounter with the world's most powerful machine that was never going to end well.

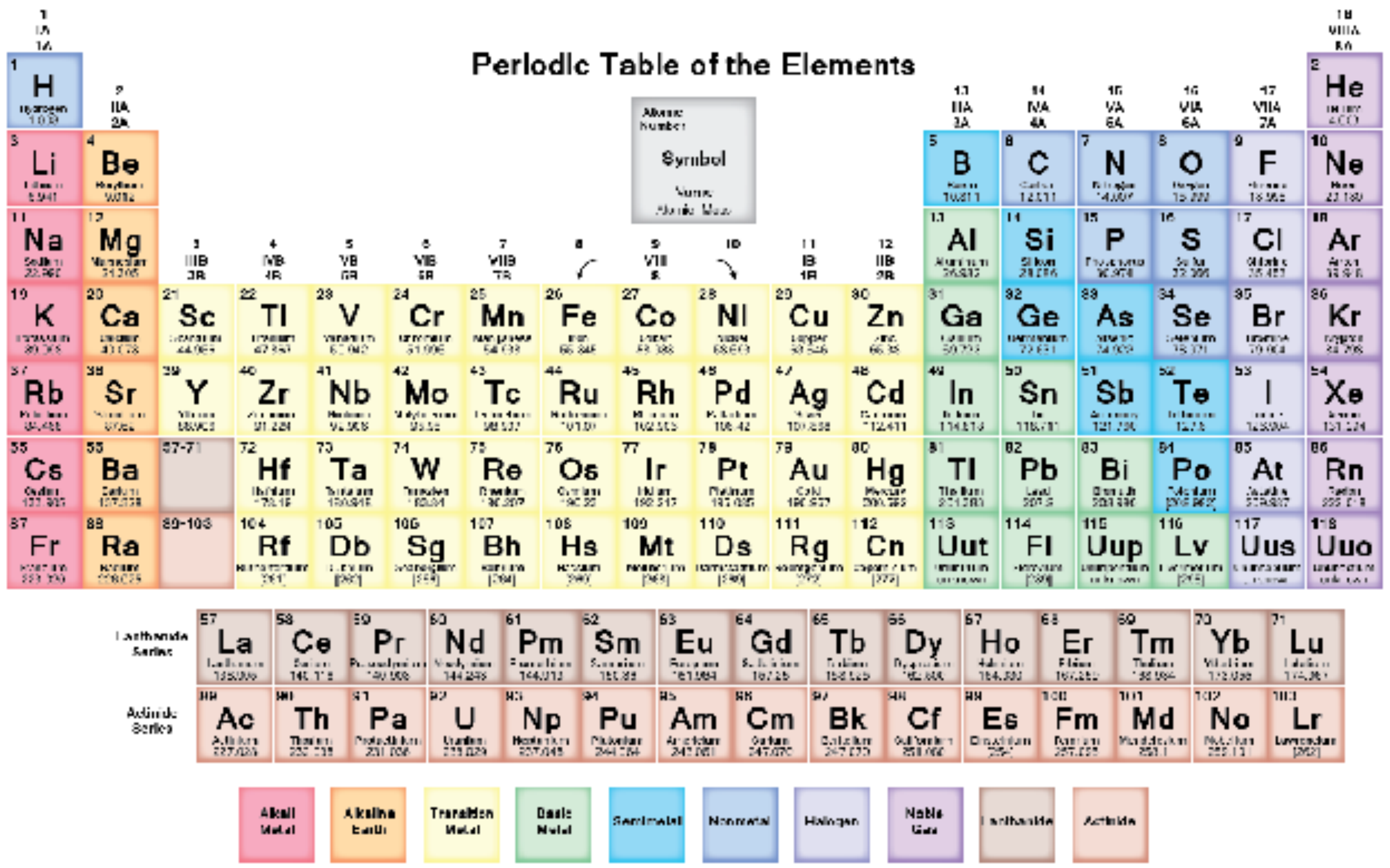
Now an exhibit at the Rotterdam Natural History Museum, the stone marten met its fate when it hopped over a substation fence at the Large Hadron Collider (LHC) near Geneva and was instantly electrocuted by an 18,000 volt transformer.

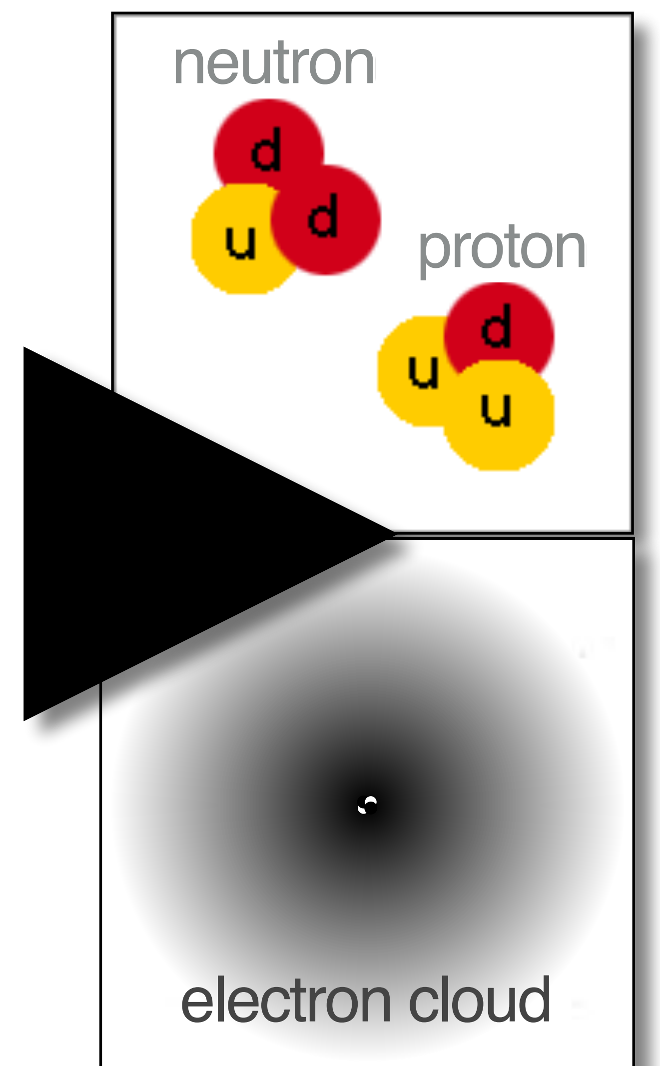
The incident in November last year knocked out the power to the vast particle accelerator which recreates in microcosm the primordial fire that prevailed at the birth of the universe. The partly-cooked corpse was duly secured for inclusion in the museum's Dead Animal Tales exhibition.

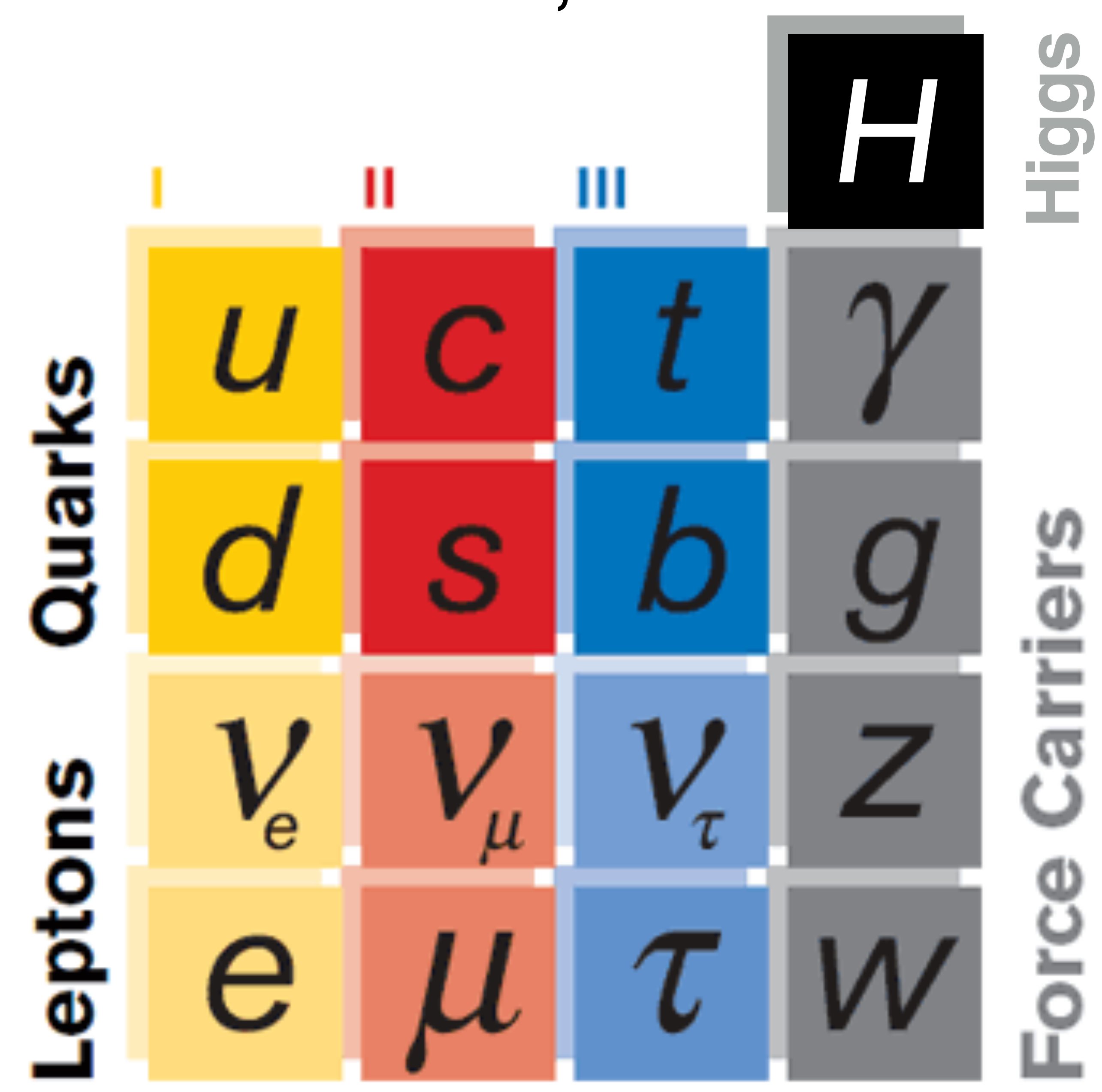
Note: when the LHC is 'fully loaded', the total stored energy in the circulating beams is equivalent to the *HMAS Canberra* moving at 13 knots. (~100 kg TNT equivalent.)

the Last Piece of the puzzle?

In the ~ 100 years since Mendeleev's periodic table, **physics** reduced to just a few **ultra-fundamental constituents**, and the **forces** that act between them



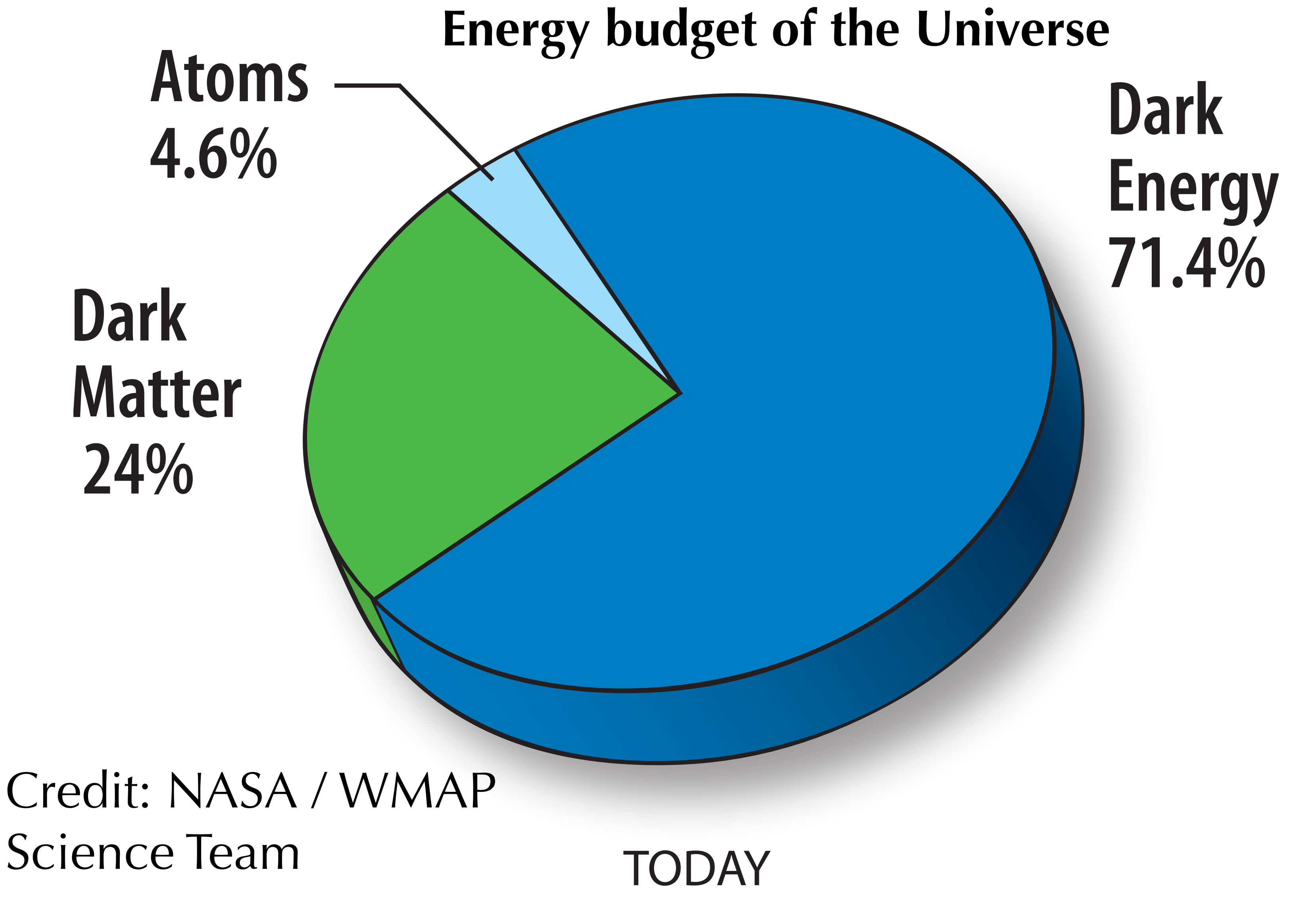


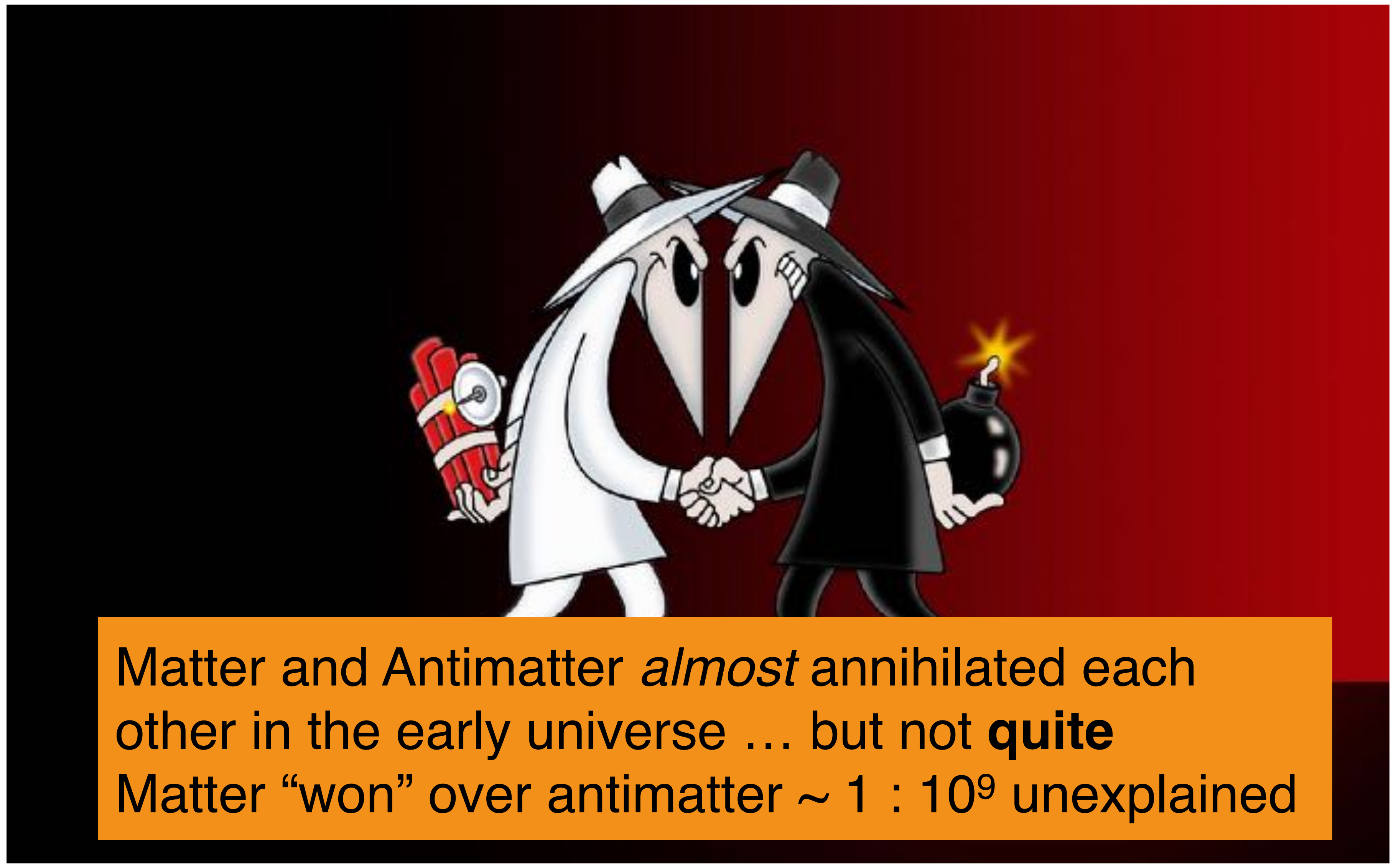


Is there something beyond?

Dark Matter, Matter vs Antimatter, Higgs Origins, Grand Unification, Quantum Gravity …

WHAT WE KNOW …





Sir William of Occam may like the Higgs

…

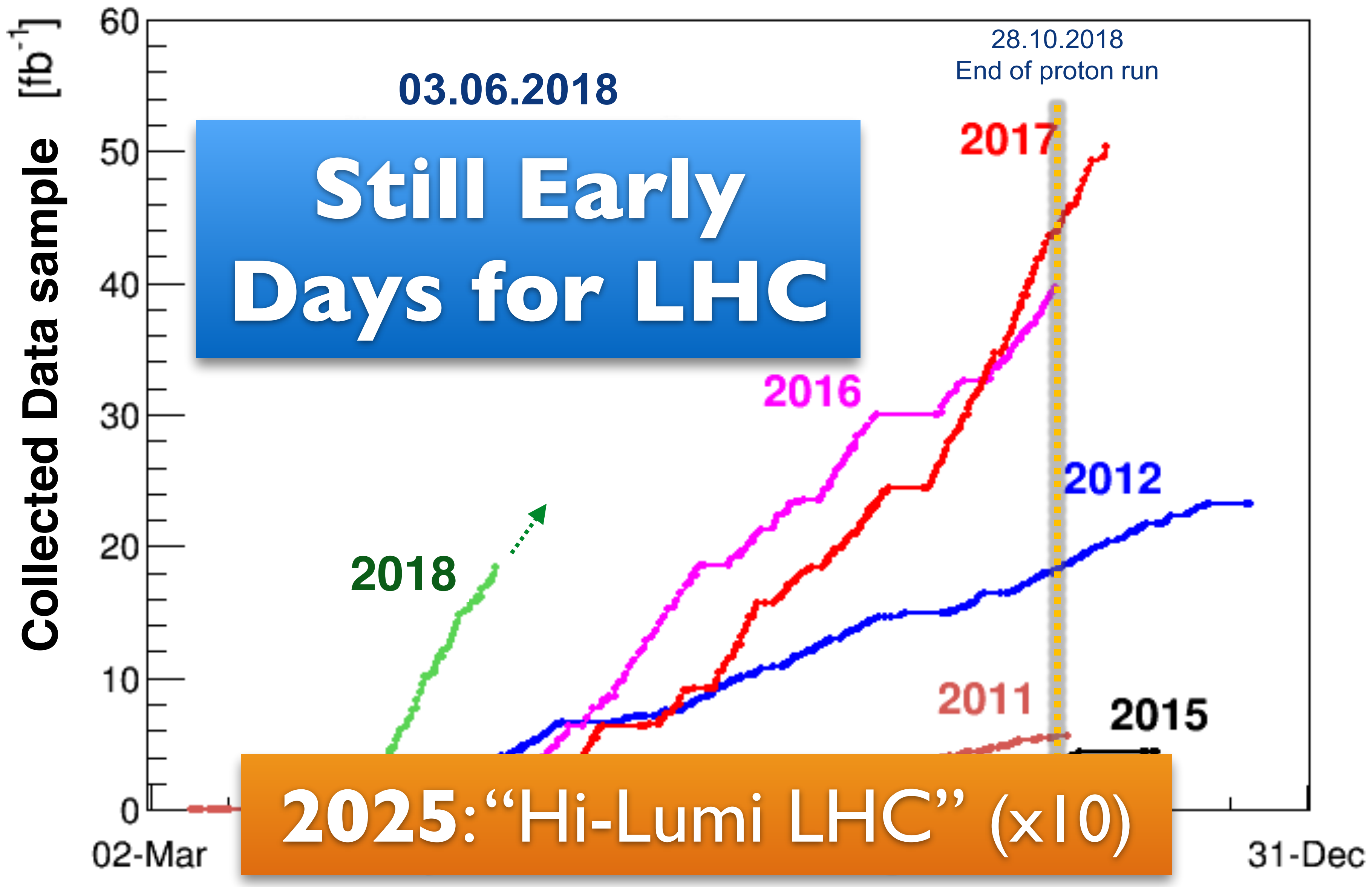
But theoretical physicists do **not**

Educated guess ~ factor 10^{16} wrong

➜ Call that educated ?!

…

Better guesses all based on new principles, like **supersymmetry**



Stay Tuned

Thank you for your attention!

Stay Tuned

Thank you for your attention!

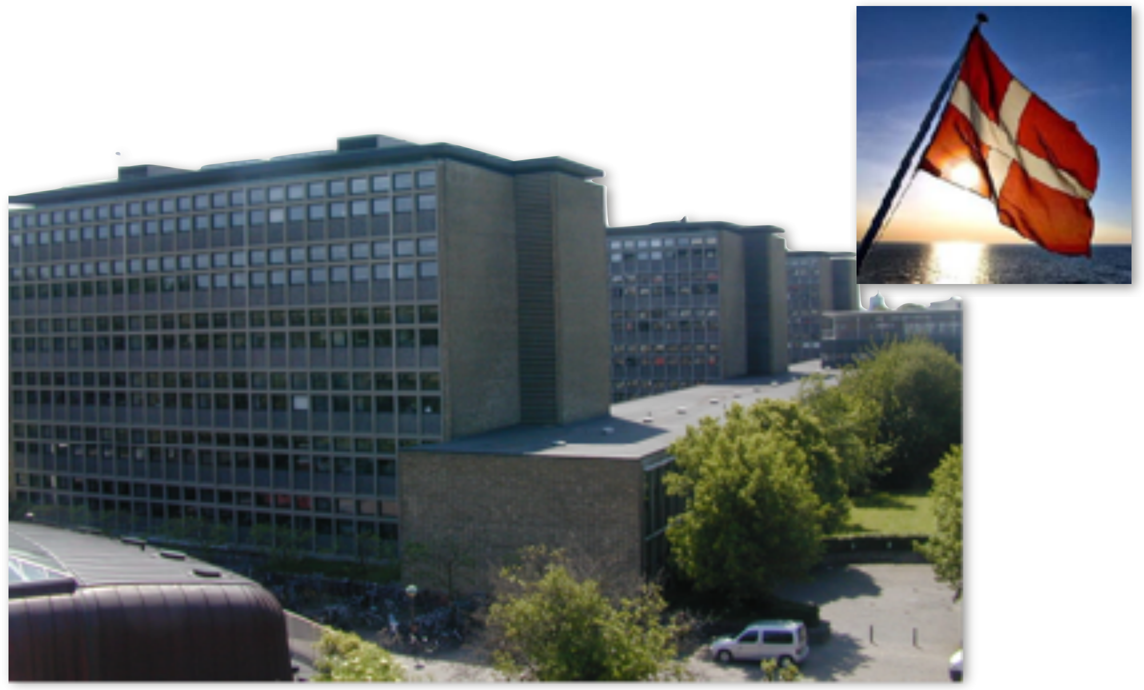
Who am I?

So I thought I wanted to be an **astronomer** …

Studied physics & astronomy at
Copenhagen Uni (Denmark)
(Masters degree: 5 years)

Learned Quantum Mechanics
(and didn't understand it)

UNIVERSITY OF COPENHAGEN



➜ Got interested in Particle Physics
the study of matter and force at the most fundamental level

→ Lund University (Sweden):
Theoretical (high-energy) Physics
(PhD: 3 years; Graduated 2004)

Monte Carlo : computer simulations of the fundamental laws based on random numbers (chosen according to Q.M. probabilities)

Who am I?

After the PhD, you typically spend a number of years as a “post doc”
- preferably abroad at great centres of learning

→ Fermilab (Chicago)
(Theoretical Physics Dept.)

Became an expert on Monte Carlo simulations of **proton-antiproton** collisions at the Tevatron

(+ met my wife)

I had thought physics = books, maths, experiments, maybe computers …
It was a (nice) surprise that it turned out to also mean traveling the globe, and meeting all kinds of interesting people, at the top of their profession

I was very happy at Fermilab. But after 5 years, I got an offer I couldn’t refuse

Rates and Triggers

We get ~ 40 million collisions / sec.

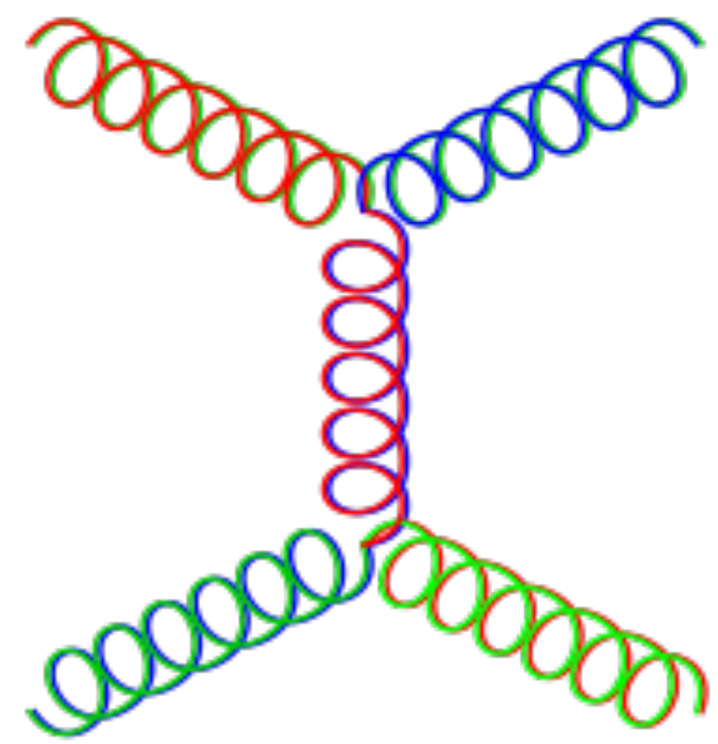
We can save ~ 100 / sec to disk.

WHICH ONES?

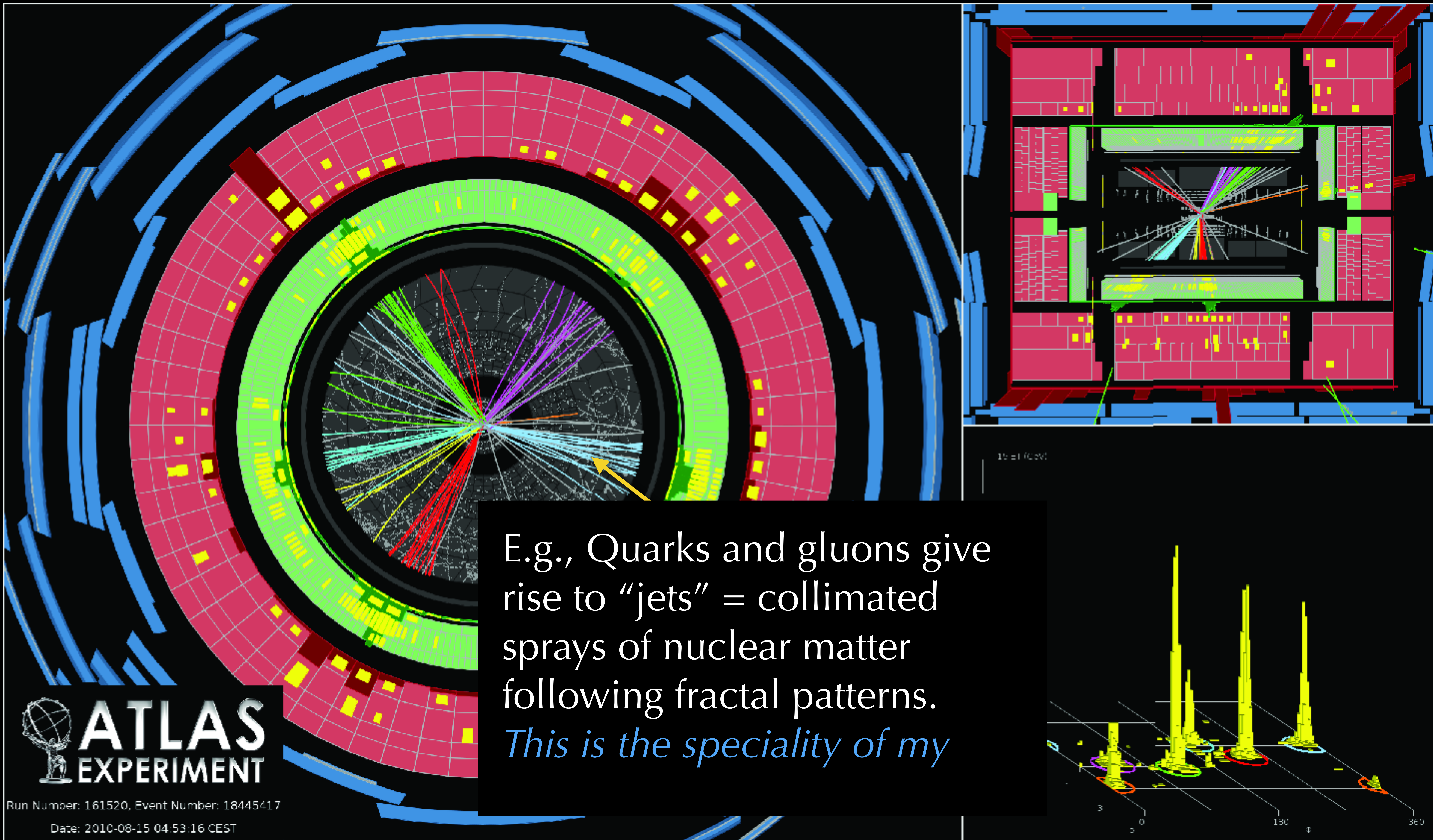
Automated "trigger" systems decide which collisions may be interesting

Not all reactions are created equally

- The most likely collision type is gg → gg
- The top quark is the heaviest elementary particle
  - Discovered in 1995 by Fermilab's Tevatron accelerator.
  - The LHC can make ~ 1 top quark / second.
- The reaction gg → Higgs will happen ~ 1 / minute



+ Complications: *Bremsstrahlung radiation, confinement (quarks/gluons→**hadrons**), probabilities, …*



E.g., Quarks and gluons give rise to "jets" = collimated sprays of nuclear matter following fractal patterns.
This is the speciality of my

The basic law of quantum mechanics: anything that ***can*** happen ***will*** happen