Title: From Hydrogen to Higgs Bosons: Particle Physics at the Large Hadron Collider at CERN

Speakers:

Collection: Perimeter Public Lectures

Date: May 08, 2024 - 6:00 PM

URL: https://pirsa.org/24050023

Abstract: Explore particle physics with Dr. Clara Nellist at the Perimeter Institute on May 8, as she discusses CERN's groundbreaking research.

Free tickets to attend the event in person will be available on Monday, April 22 at 9:00 AM EDT.

Tickets for this event are 100% free. As always, our public lectures are live-streamed in real-time on our YouTube channel - available here: https://www.youtube.com/@PIOutreach

About Our Public Lectures:
Our Public Lectures feature experts from all areas of theoretical physics discussing topics such as quantum computing, black holes, and dark matter. Previous speakers include world-leading researchers such as Neil Turok and Juan Maldacena. These events are a unique chance to engage with some of the groundbreaking ideas in physics happening within the building.

An experimentalist's perspective

From Hydrogen to Higgs Bosons

Particle Physics at the Large Hadron Collider at CERN

Dr Clara Nellist

@ParticleClara (she/her)

Perimeter Institute Public Lecture

Nikhef

ATLAS EXPERIMENT

Universiteit van Amsterdam


CERN


CERN
But what are we looking for?
T.D. Gutierrez
3

1

$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \frac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu$$

2

$$- \partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \frac{1}{4}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \frac{1}{2}ig^2s_wA_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - g^1s_w^2A_\mu A_\mu\phi^+\phi^-$$

3

$$- \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_wA_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2 - 1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \frac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_jC^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)]$$

4

$$+ \frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_jC_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m_u^\lambda(\bar{u}^\lambda_jC_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_jC^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_jC^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m_u^\lambda}{M}H(\bar{u}^\lambda_ju^\lambda_j) - \frac{g}{2}\frac{m_d^\lambda}{M}H(\bar{d}^\lambda_jd^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5u^\lambda_j) - \frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5d^\lambda_j)$$

5

$$+ \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2Y + igc_wW^+_\mu(\partial_\mu\bar{X}^0X^- - \partial_\mu\bar{X}^+X^0) + igs_wW^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+Y) + igc_wW^-_\mu(\partial_\mu\bar{X}^-X^0 - \partial_\mu\bar{X}^0X^+) + igs_wW^-_\mu(\partial_\mu\bar{X}^-Y - \partial_\mu\bar{Y}X^+) + igc_wZ^0_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) + igs_wA_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) - \frac{1}{2}gM[\bar{X}^+X^+H + \bar{X}^-X^-H + \frac{1}{c_w^2}\bar{X}^0X^0H] + \frac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + igMs_w[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0]$$

T.D. Gutierrez

But what are we looking for?

3

Studying nature's building blocks and the forces that govern them

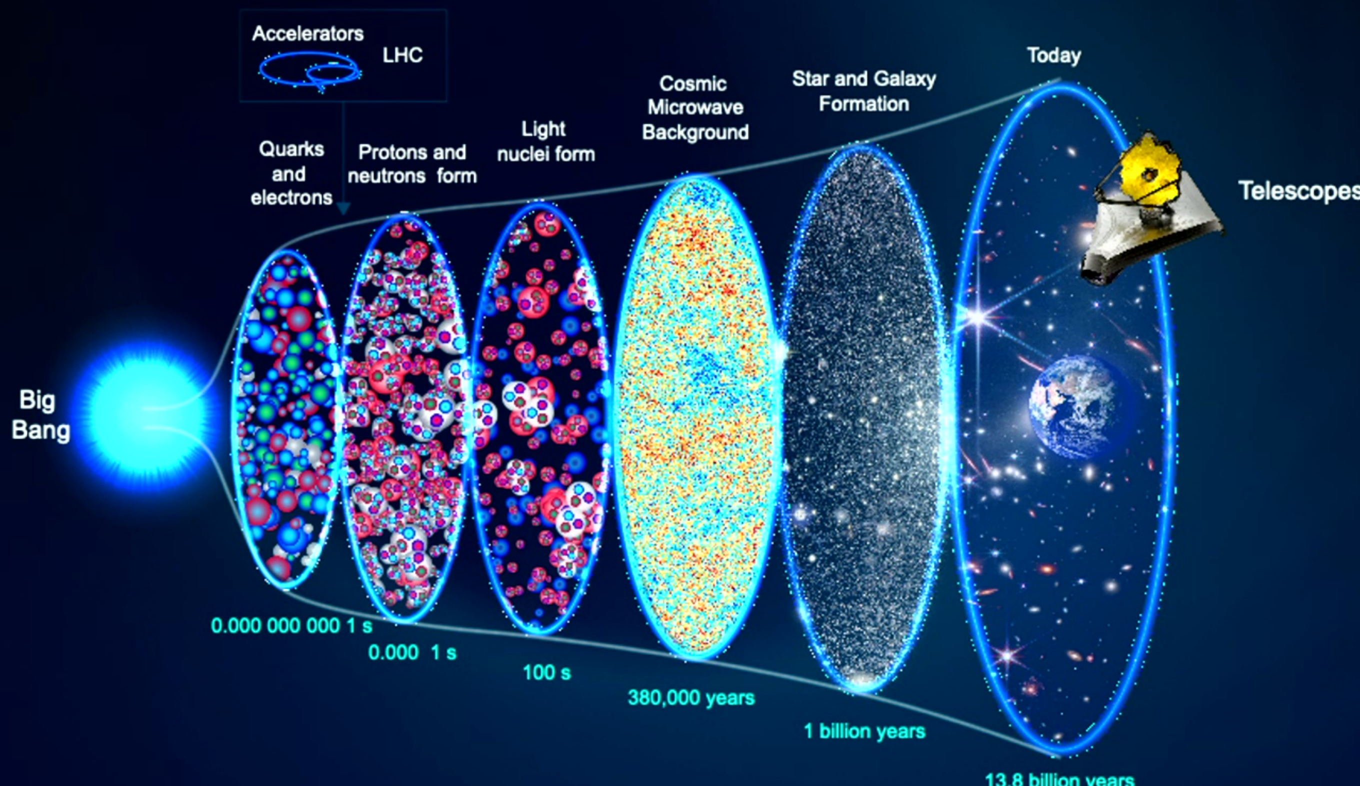
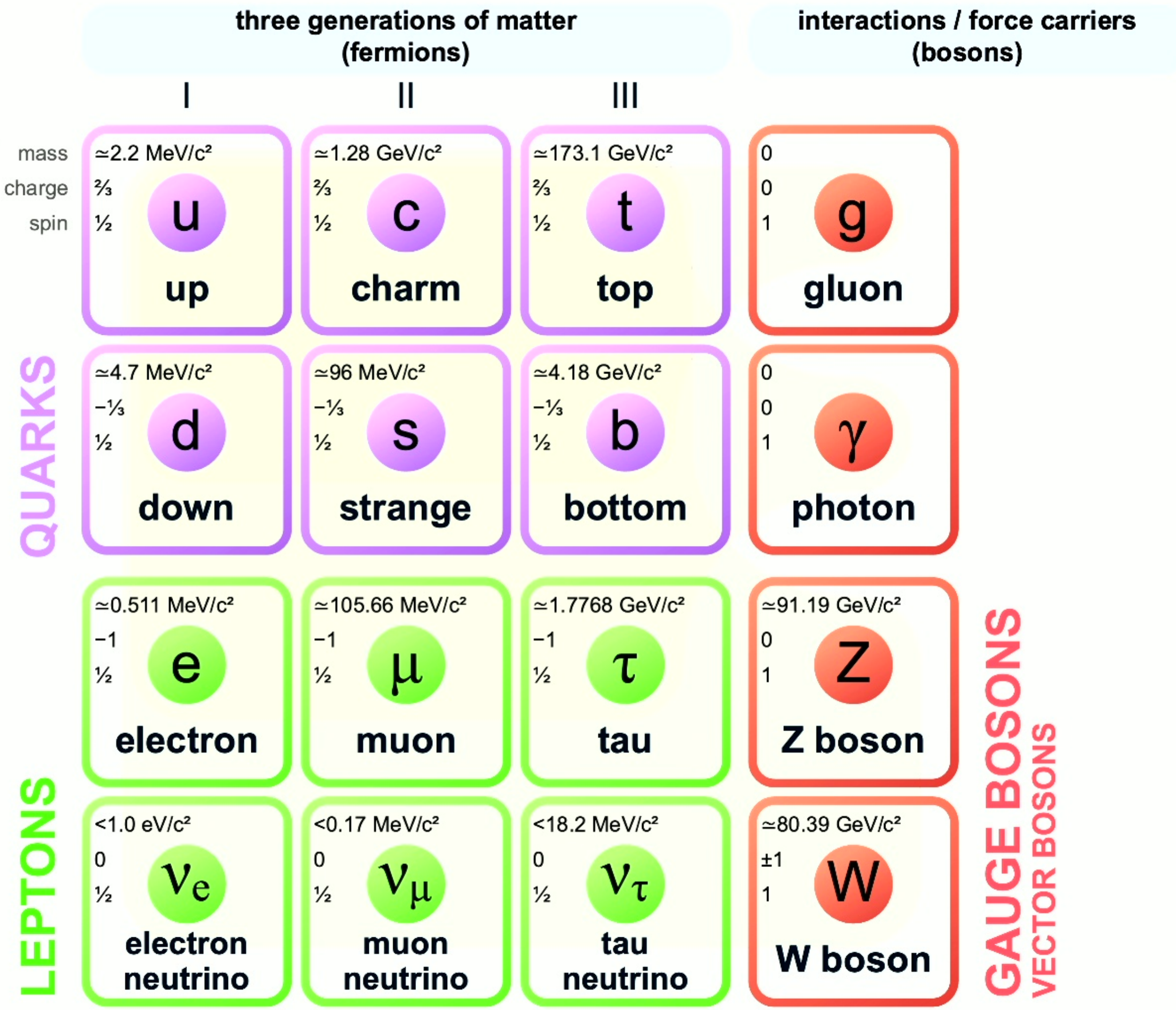


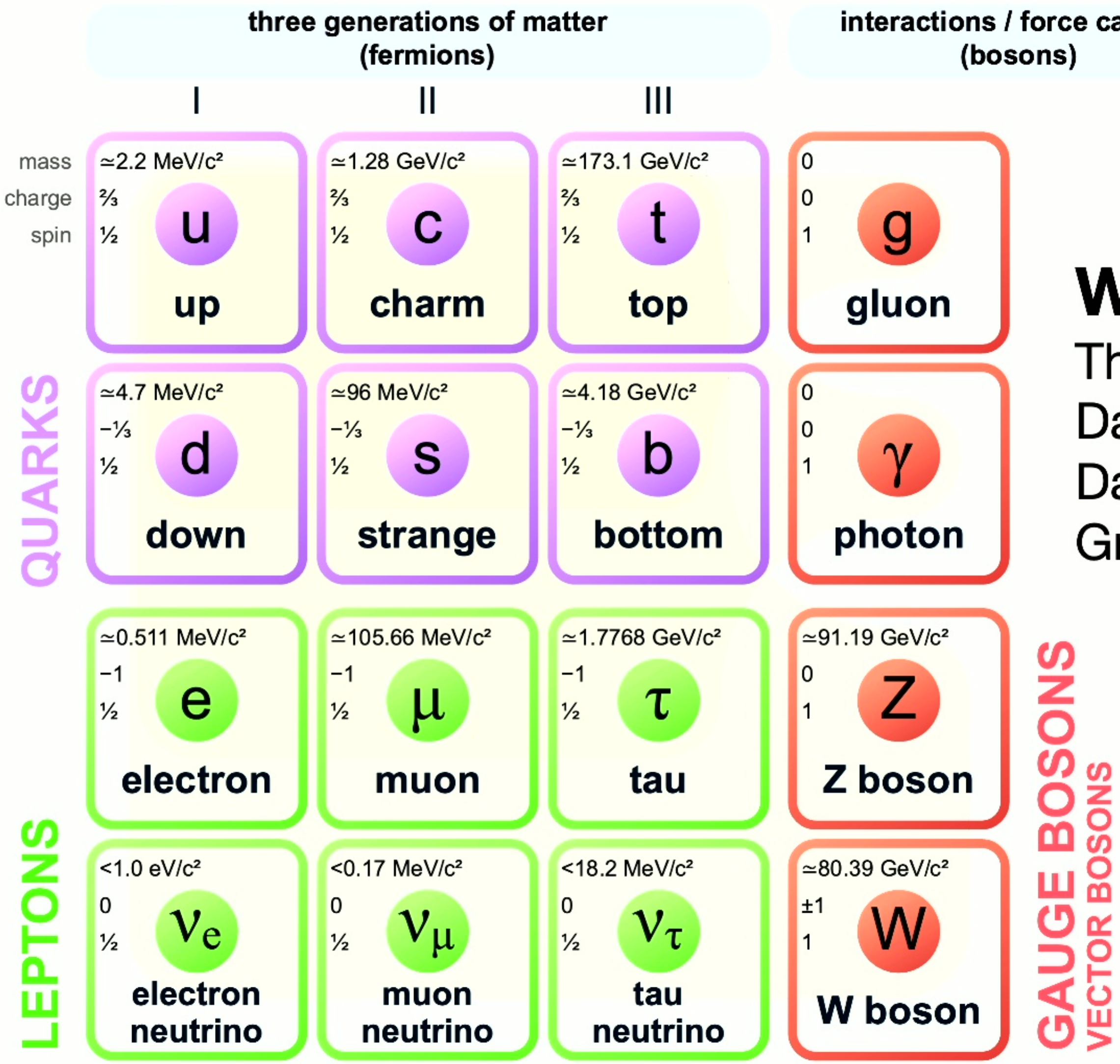
Image: CERN

4

The Standard Model (2000s)



The Standard Model (2000s)



What's missing?

The Higgs boson
Dark matter
Dark energy
Gravity!

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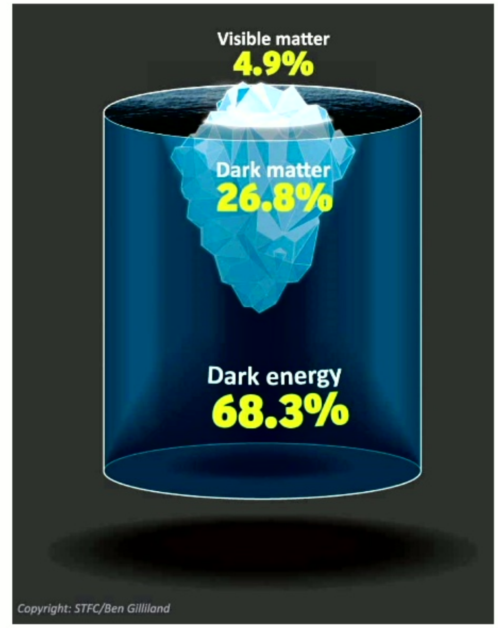
The Big Questions

Image: Jorge Cham / PhD Comics



The search for the Higgs boson

Aim: to understand the origin of the mass of elementary particles.

Image: Jorge Cham / PhD Comics

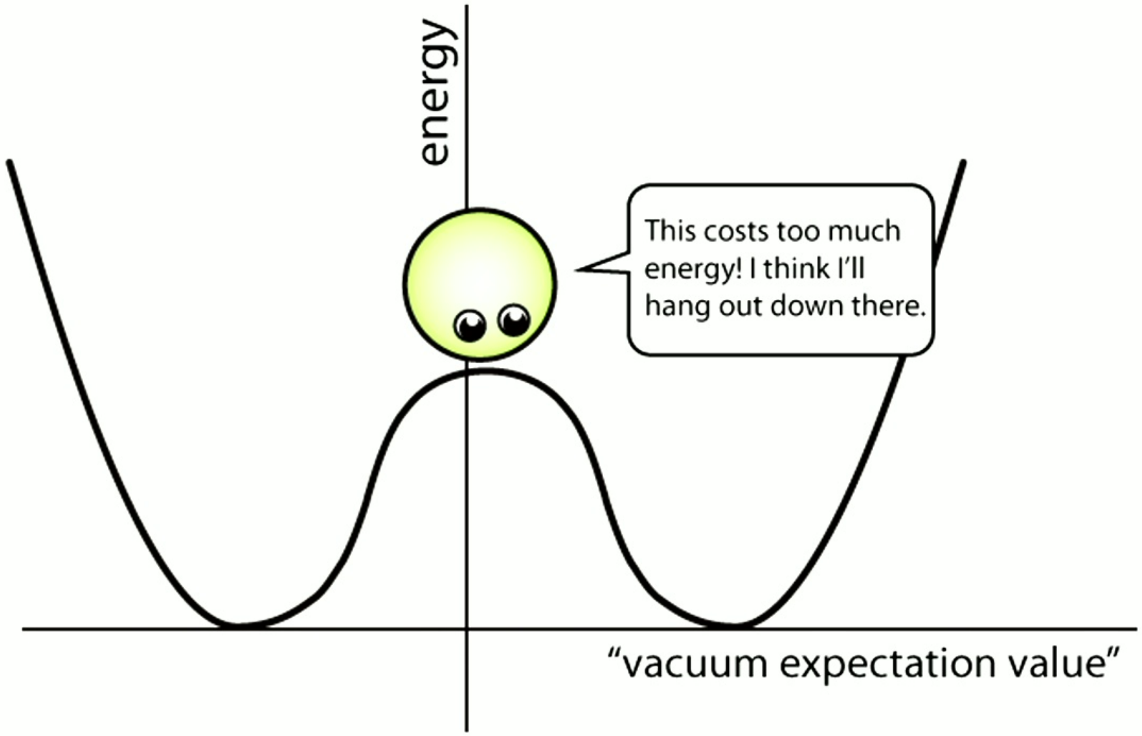


Image: Flip Tanedo/ Quantum Diaries

The search for the Higgs boson

Fun fact! If this happened very quickly, it might have caused gravitational echos that with bigger and better graviational waves detectors, maybe we can ‘see’ this

Aim: to understand the origin of the mass of elementary particles.

Image: Jorge Cham / PhD Comics

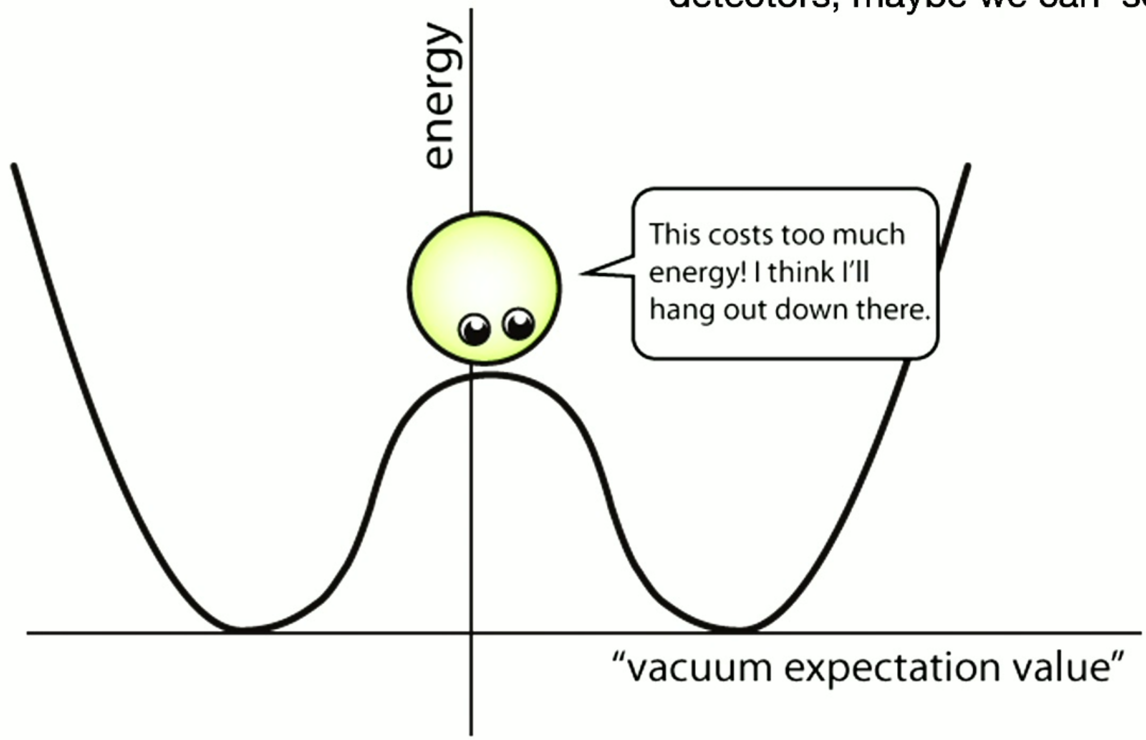


Image: Flip Tanedo/ Quantum Diaries

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The Higgs boson

Image: Jorge Cham / PhD Comics

Light particle

Heavy particle

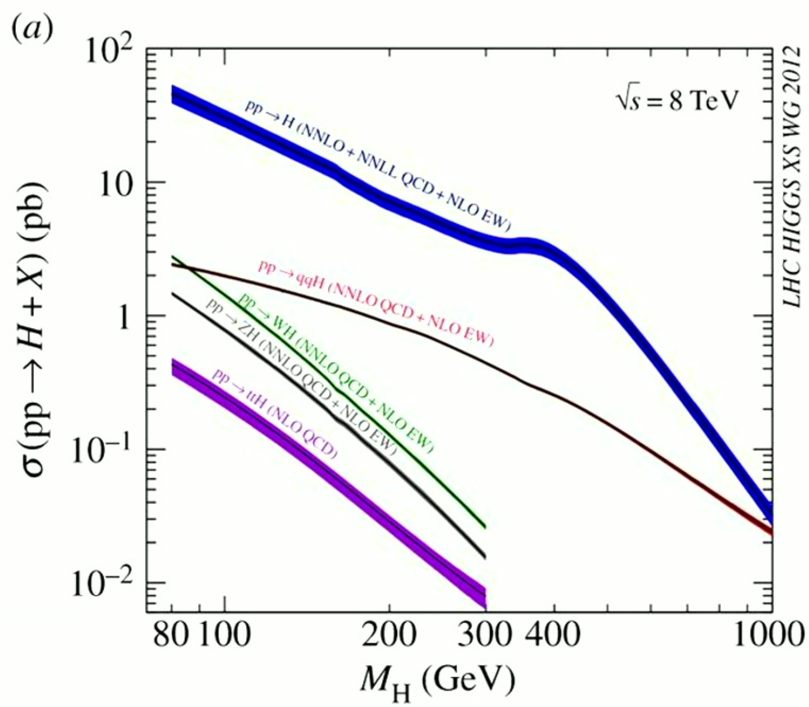
The Higgs boson

The Higgs boson

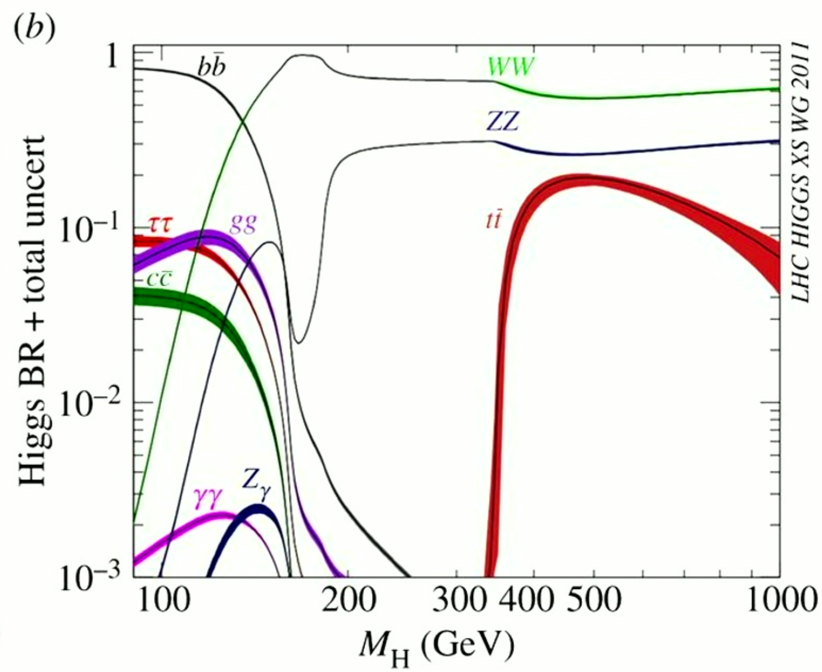
Image: Jorge Cham / PhD Comics

When we produce a Higgs boson in the LHC collisions, it is unstable and quickly changes into other particles

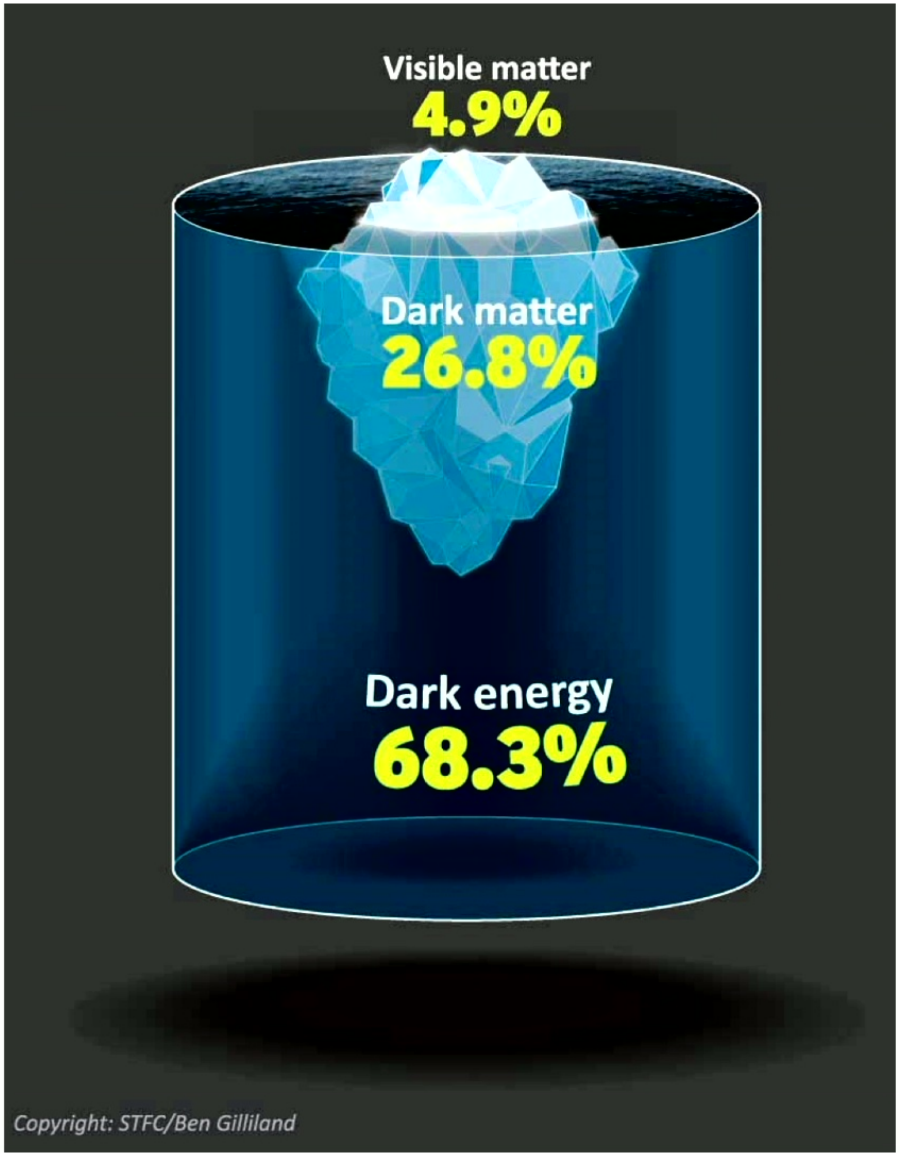
Production rate of Higgs bosons:



Which particles the Higgs will change into:



The search for new particles (dark matter?)



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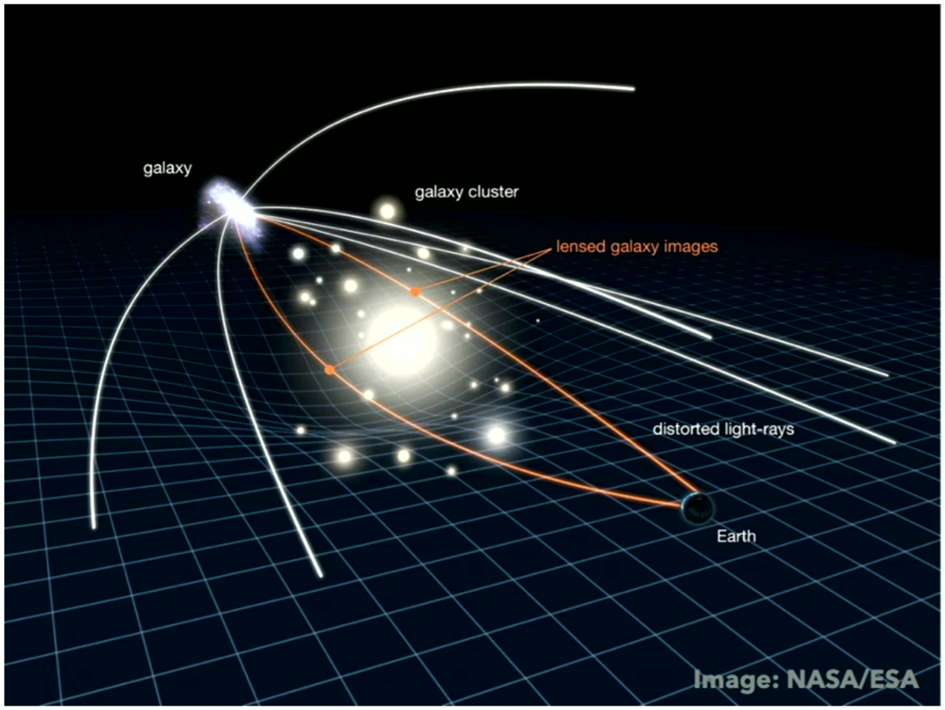
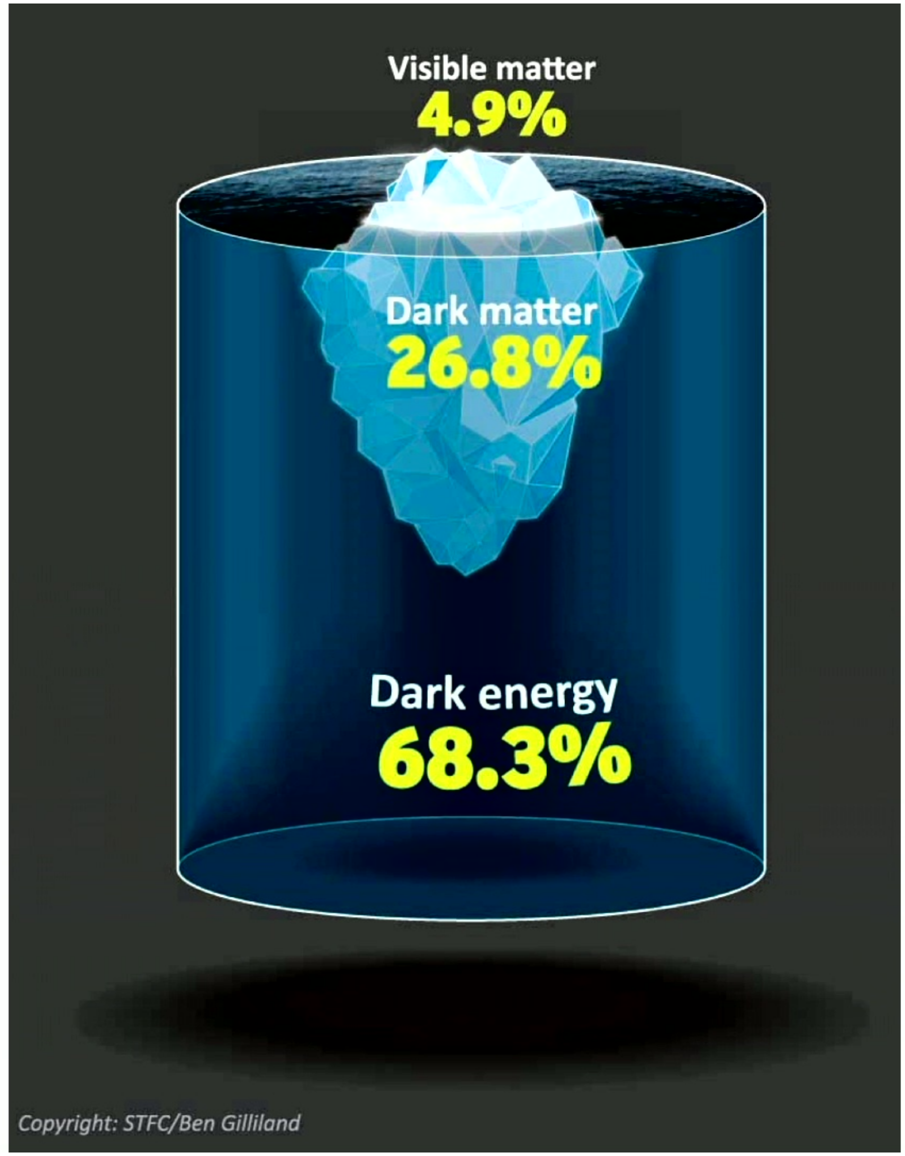
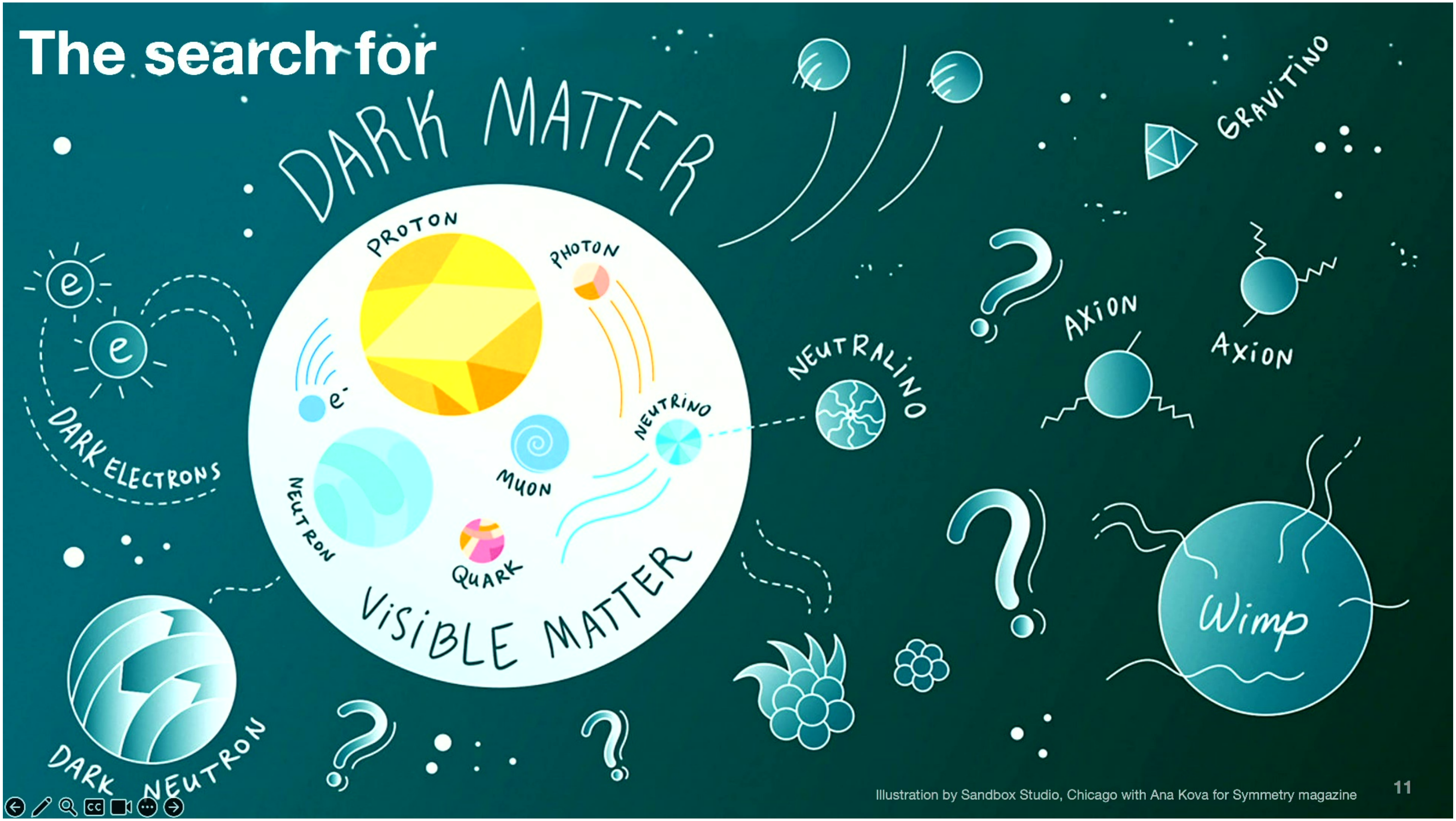
The search for new particles (dark matter?)






The search for
DARK MATTER
PROTON
PHOTON
e-
NEUTRON
MUON
NEUTRINO
QUARK
VISIBLE MATTER
DARK ELECTRONS
e
e
DARK NEUTRON
NEUTRALINO
AXION
AXION
GRAVITINO
Wimp
Illustration by Sandbox Studio, Chicago with Ana Kova for Symmetry magazine
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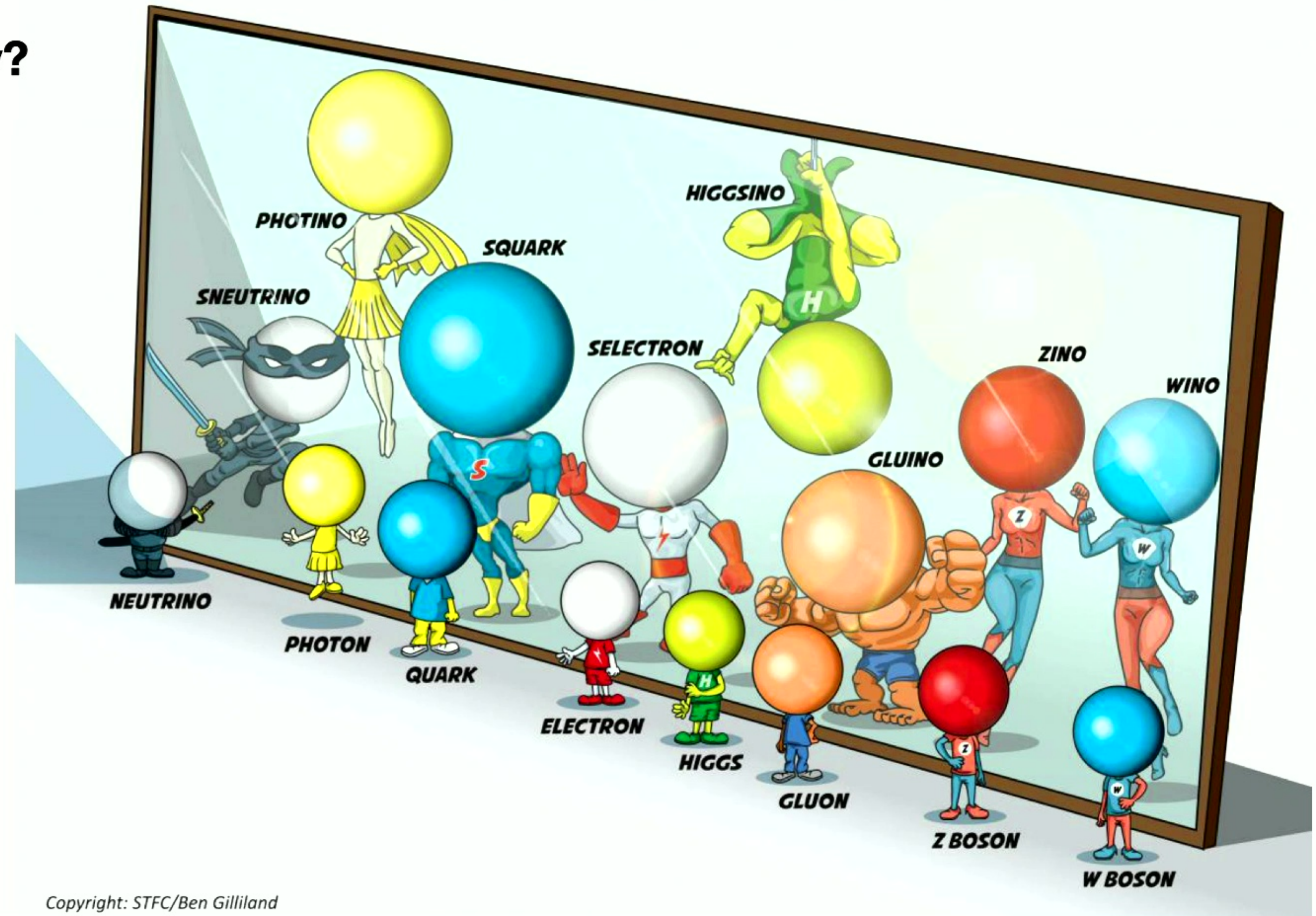
Dark Matter

Supersymmetry?



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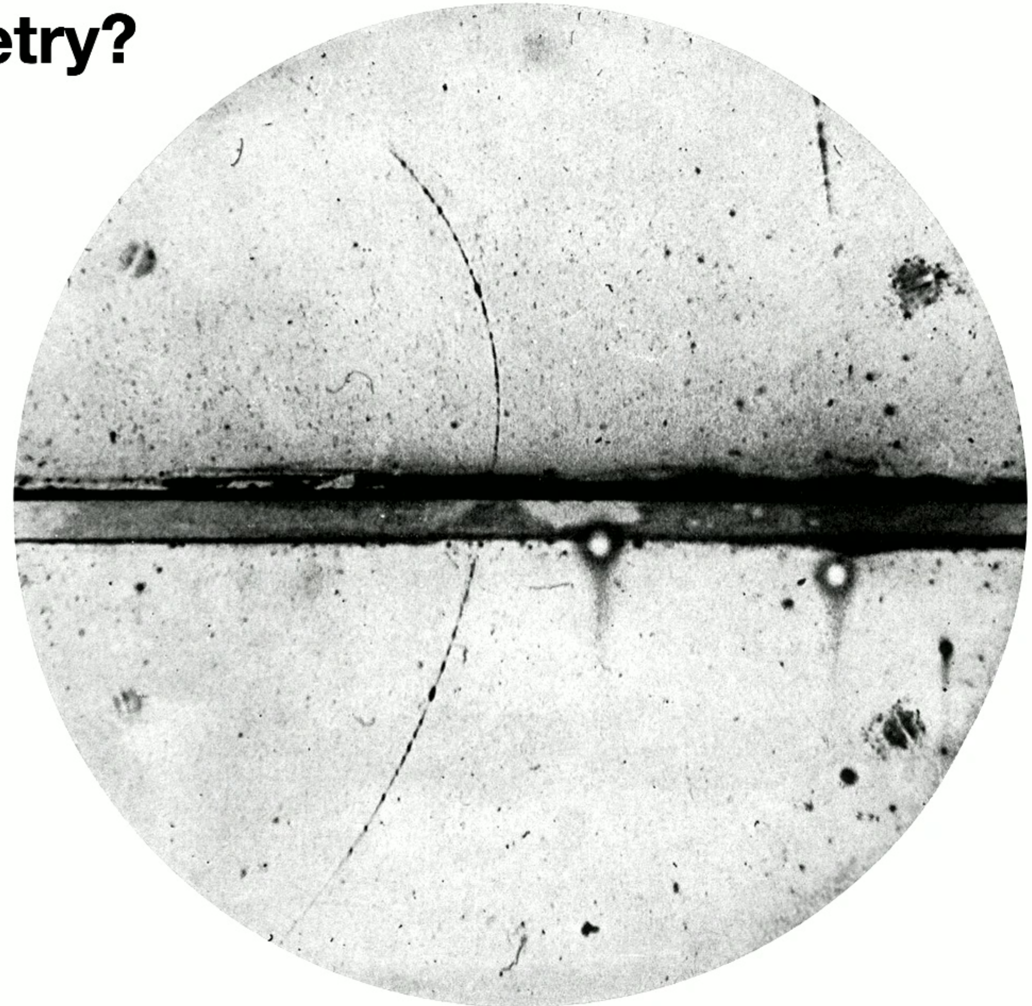
Matter-Antimatter asymmetry?



The Strength of Gravity?

Illustration by Carolina Deluca / ATLAS © CERN

The Strength of Gravity?

- Is there a graviton?
- Are there extra dimensions that gravity is leaking into?
- What is the strength of gravity for antimatter?

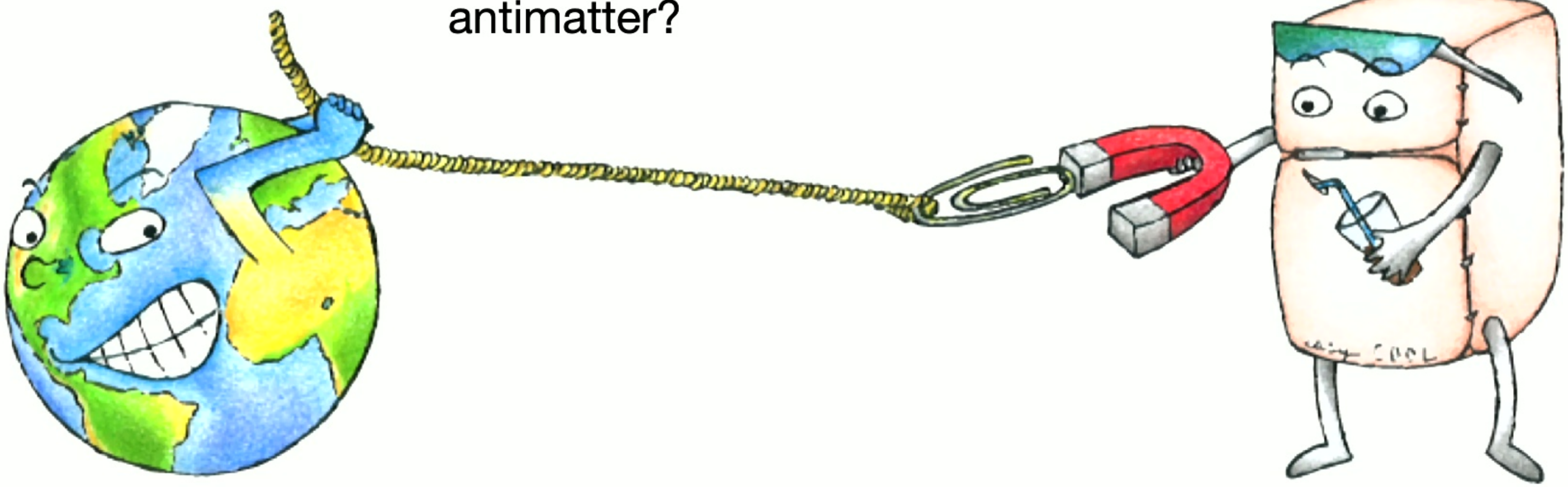
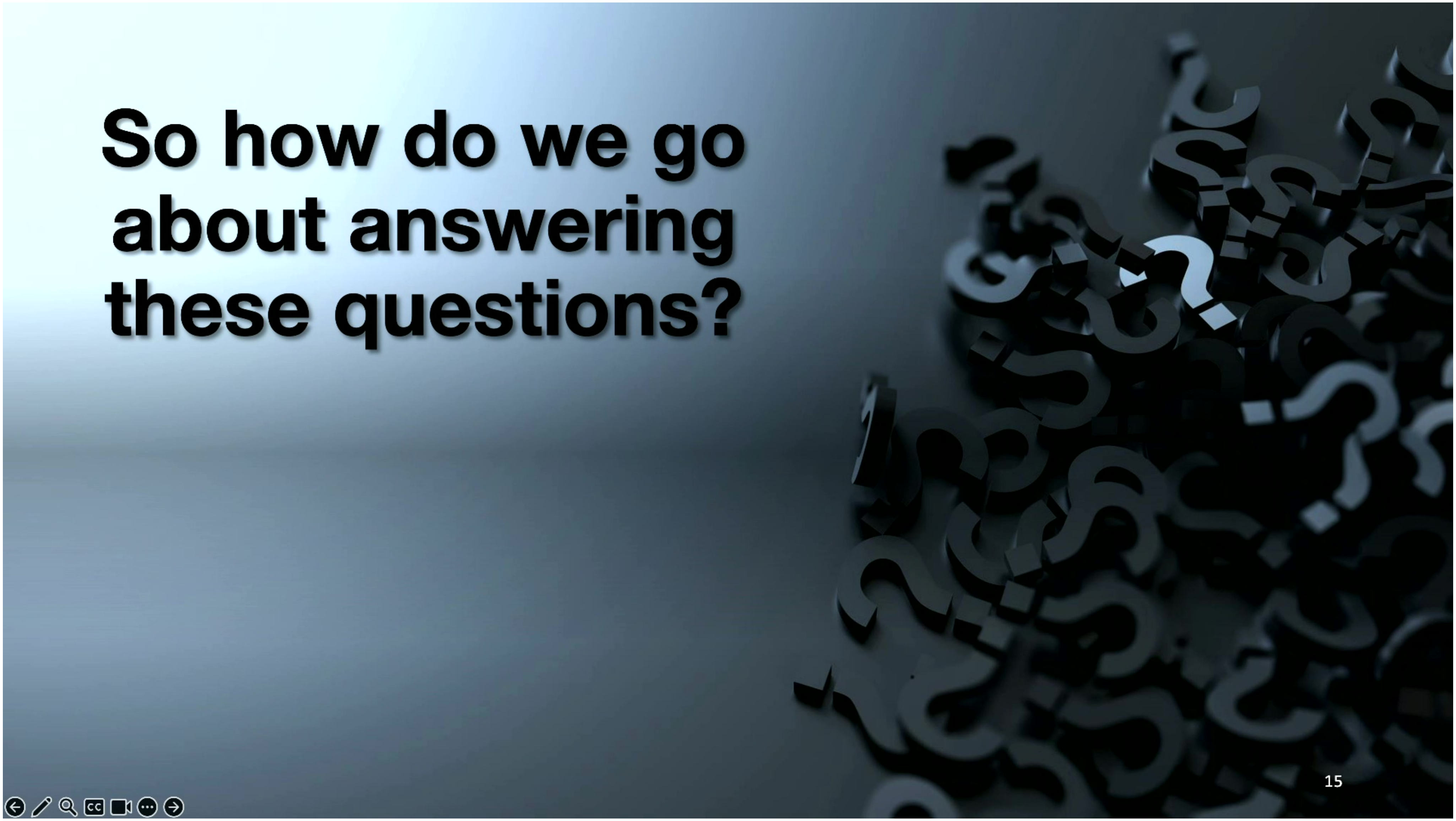
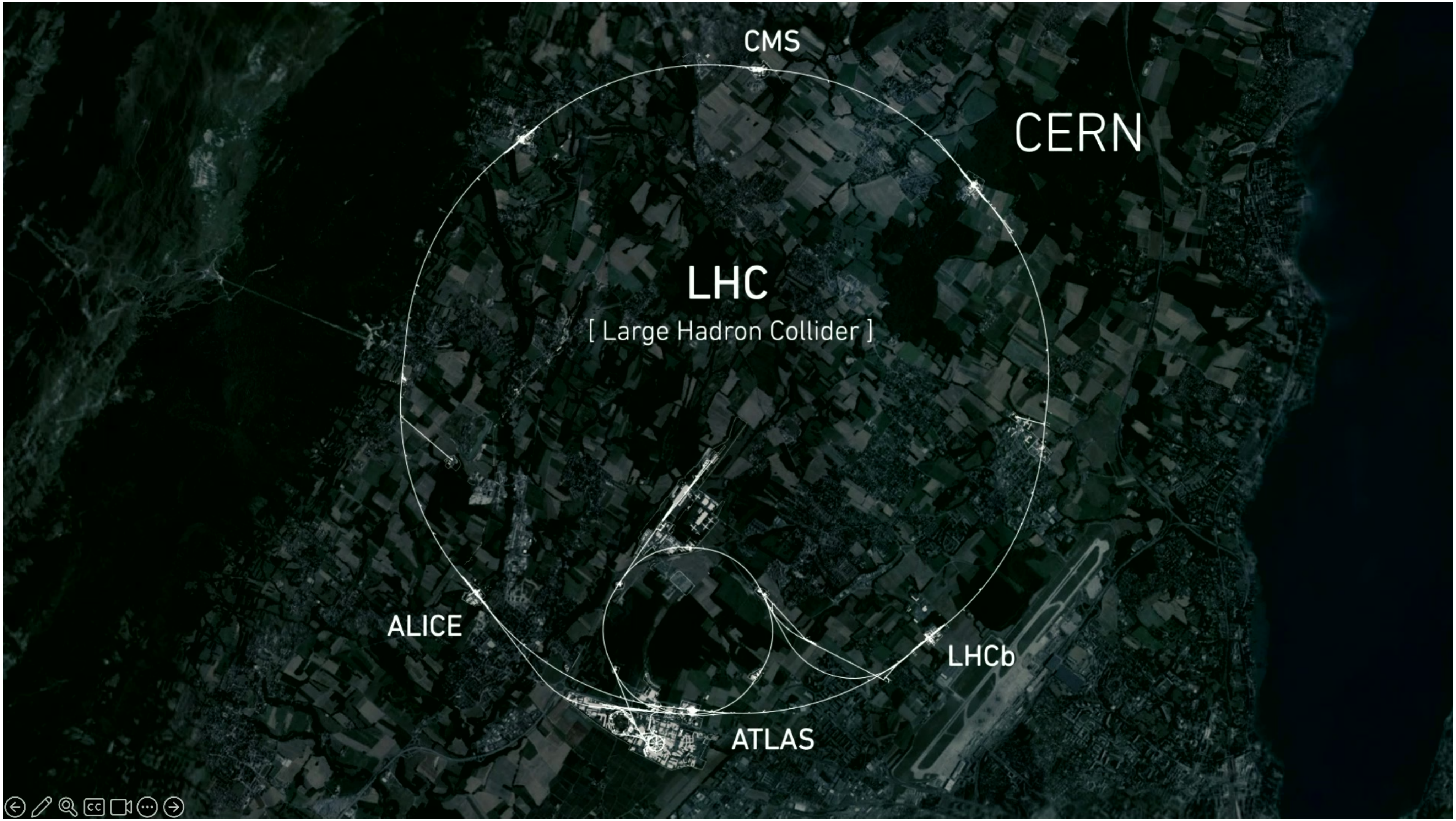
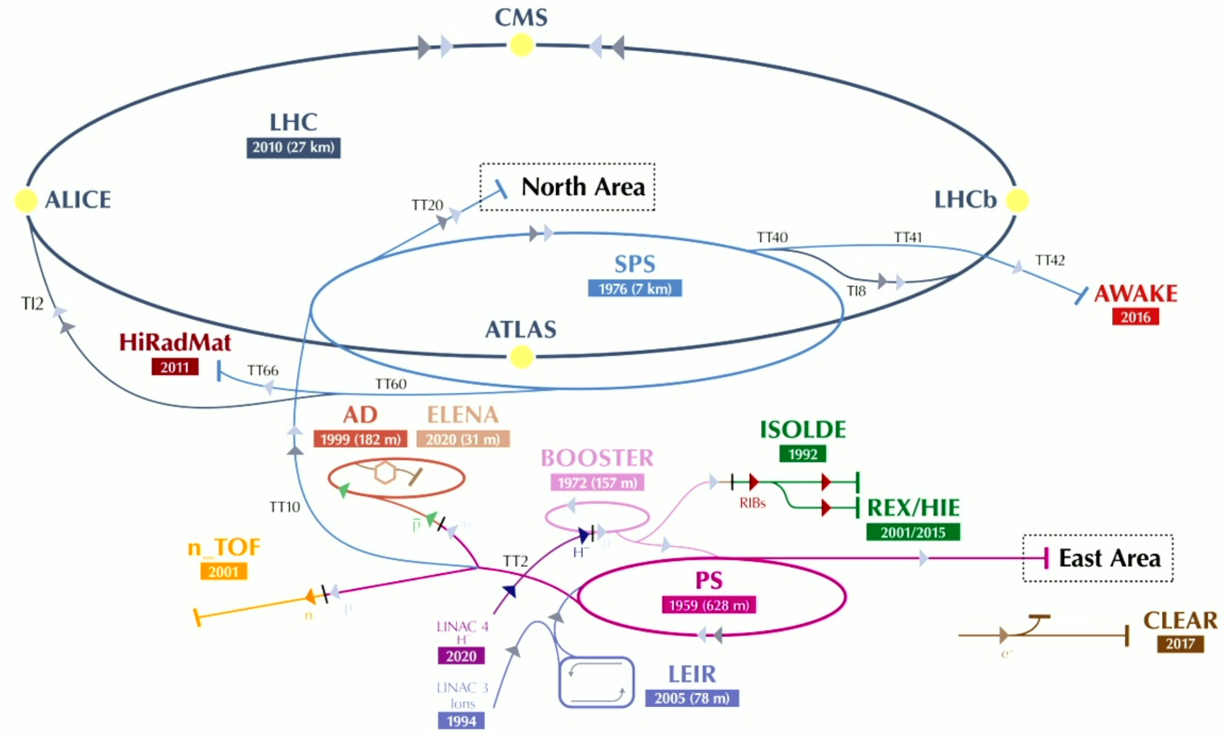


Illustration by Carolina Deluca / ATLAS © CERN


So how do we go about answering these questions?
15

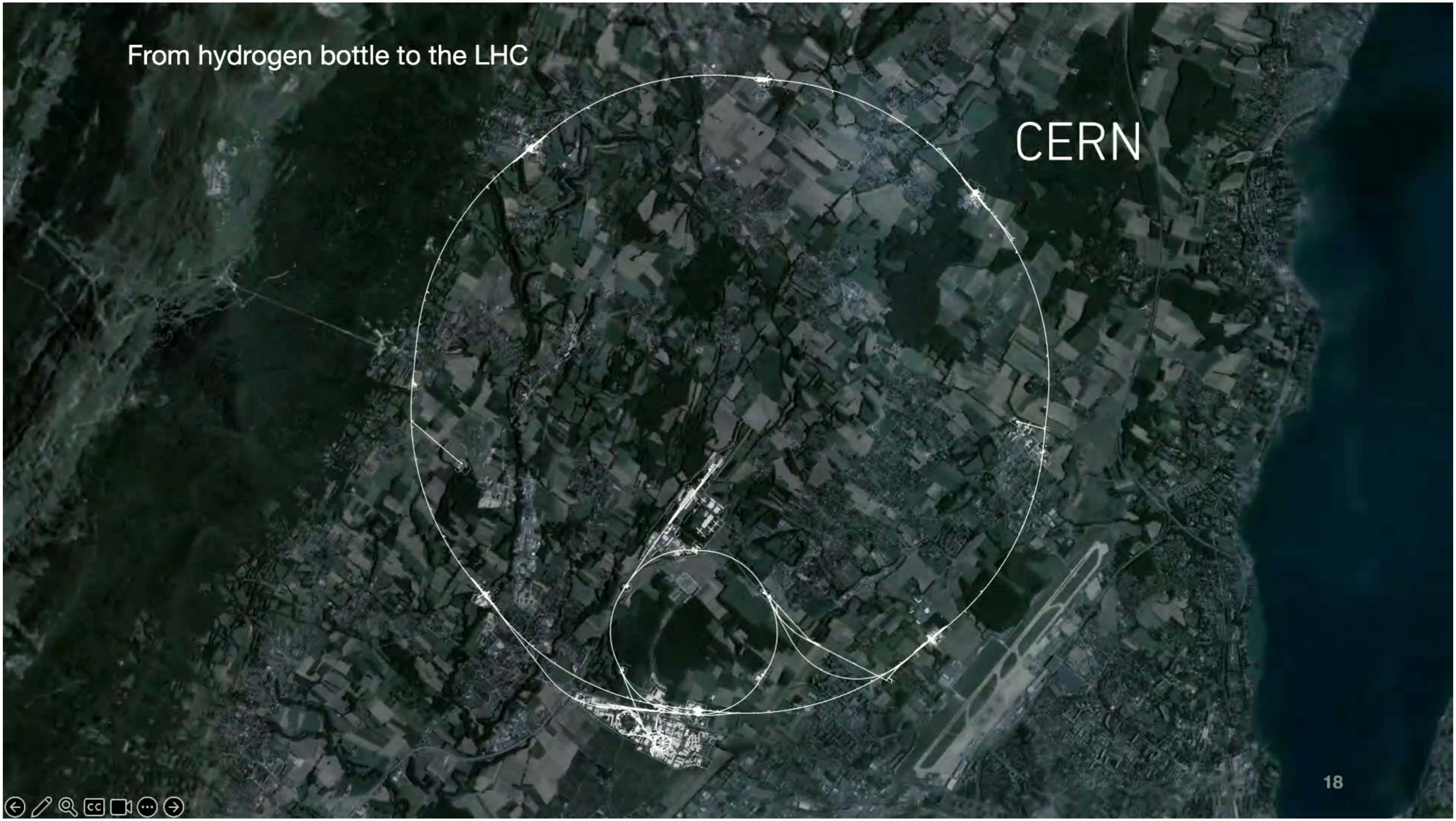

CMS
CERN
LHC
[Large Hadron Collider]
ALICE
LHCb
ATLAS

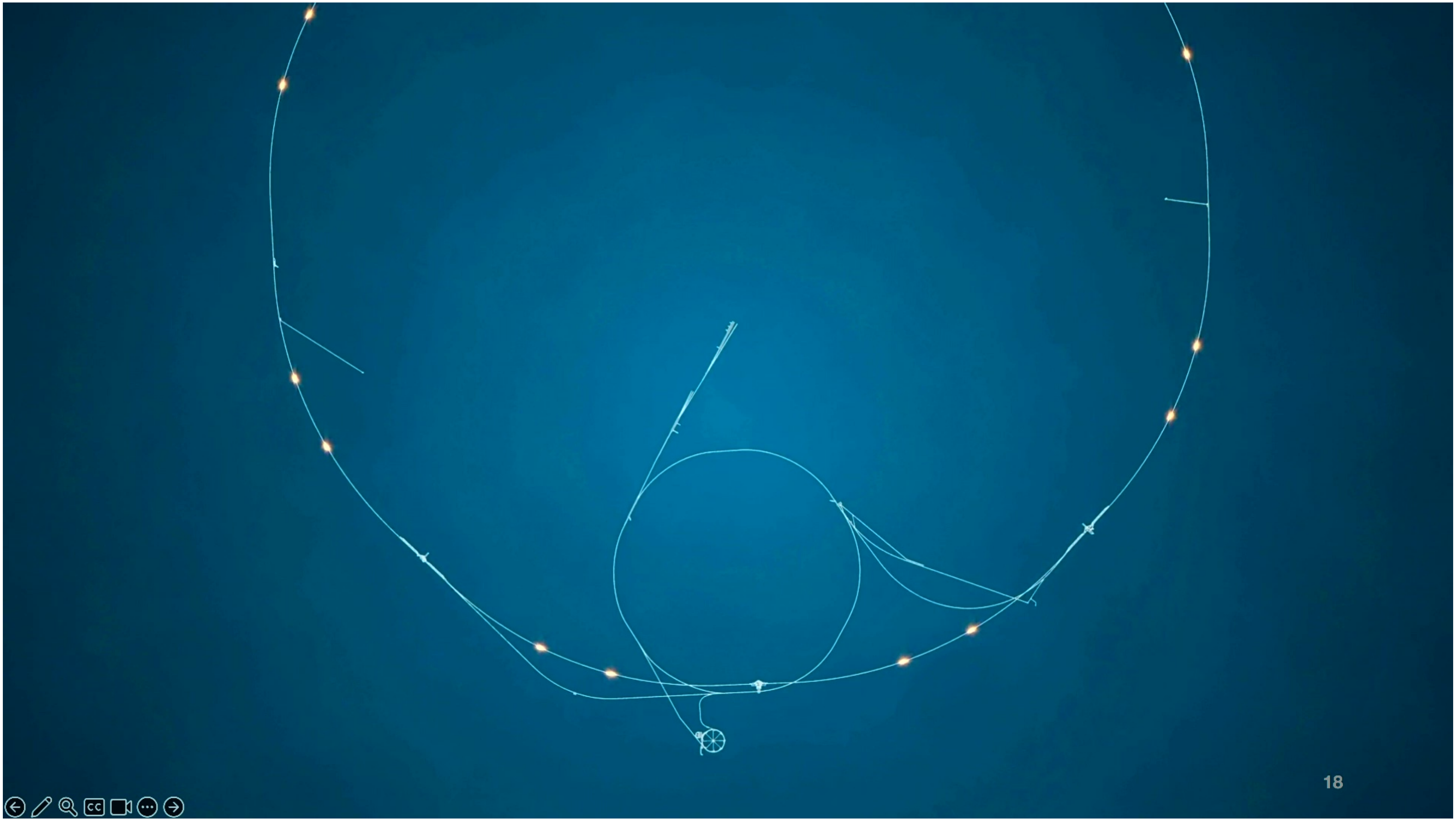
The CERN accelerator complex
Complexe des accélérateurs du CERN



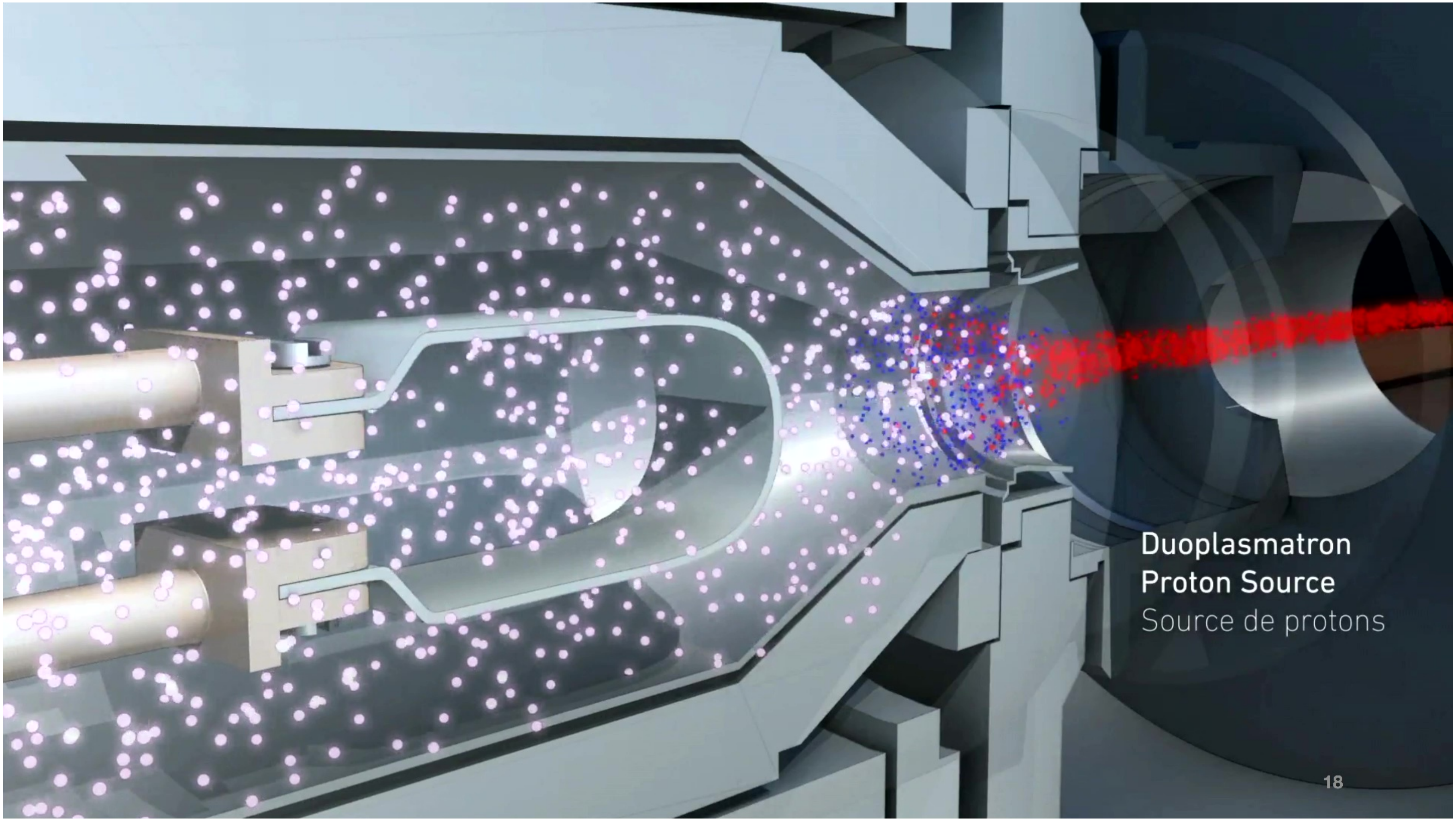
▶ H⁻ (hydrogen anions) ▶ p (protons) ▶ ions ▶ RIBs (Radioactive Ion Beams) ▶ n (neutrons) ▶ $\bar{p}$ (antiprotons) ▶ e⁻ (electrons)

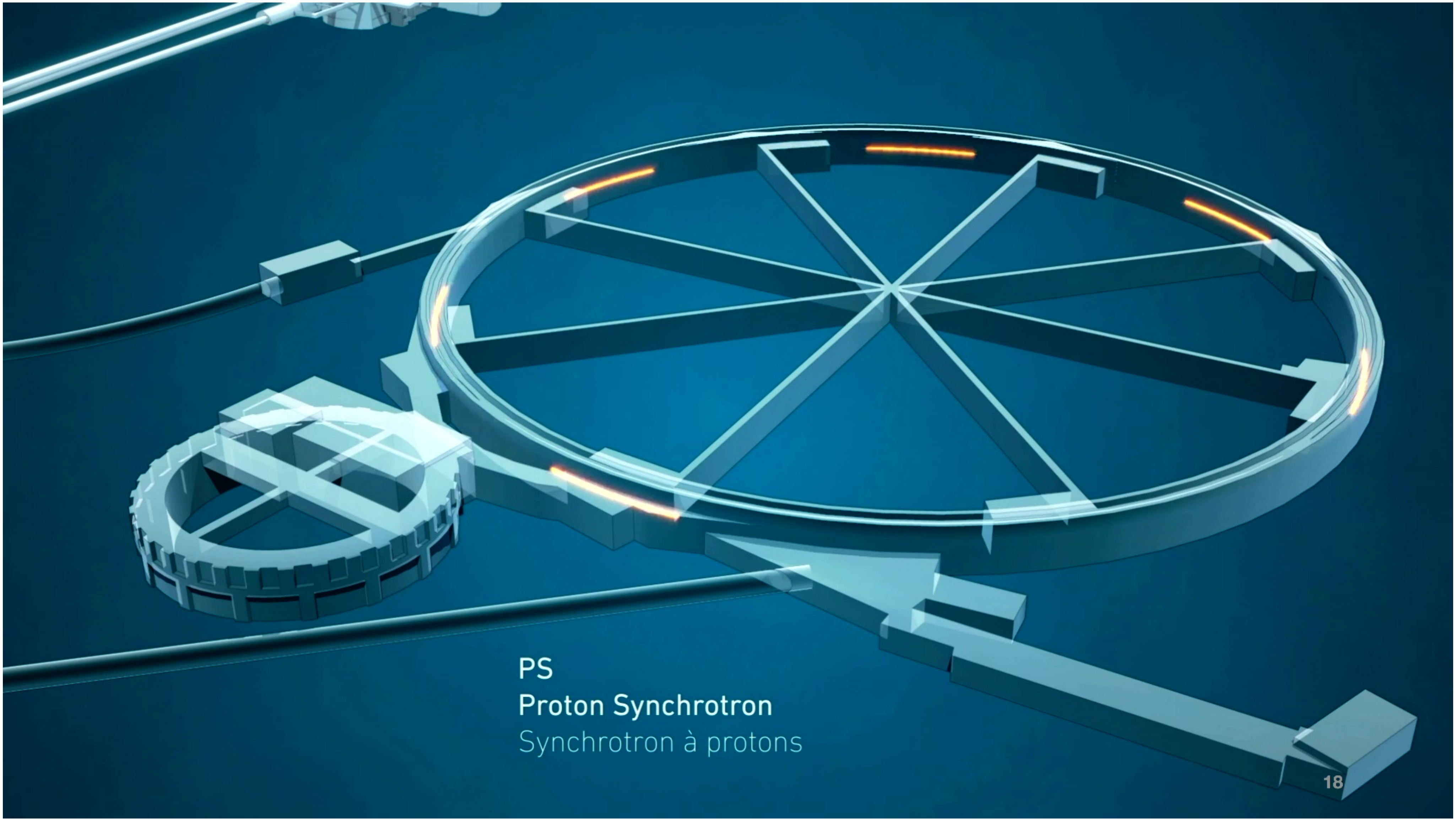
LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE - Radioactive EXperiment/High Intensity and Energy ISOLDE // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials


From hydrogen bottle to the LHC
CERN
18

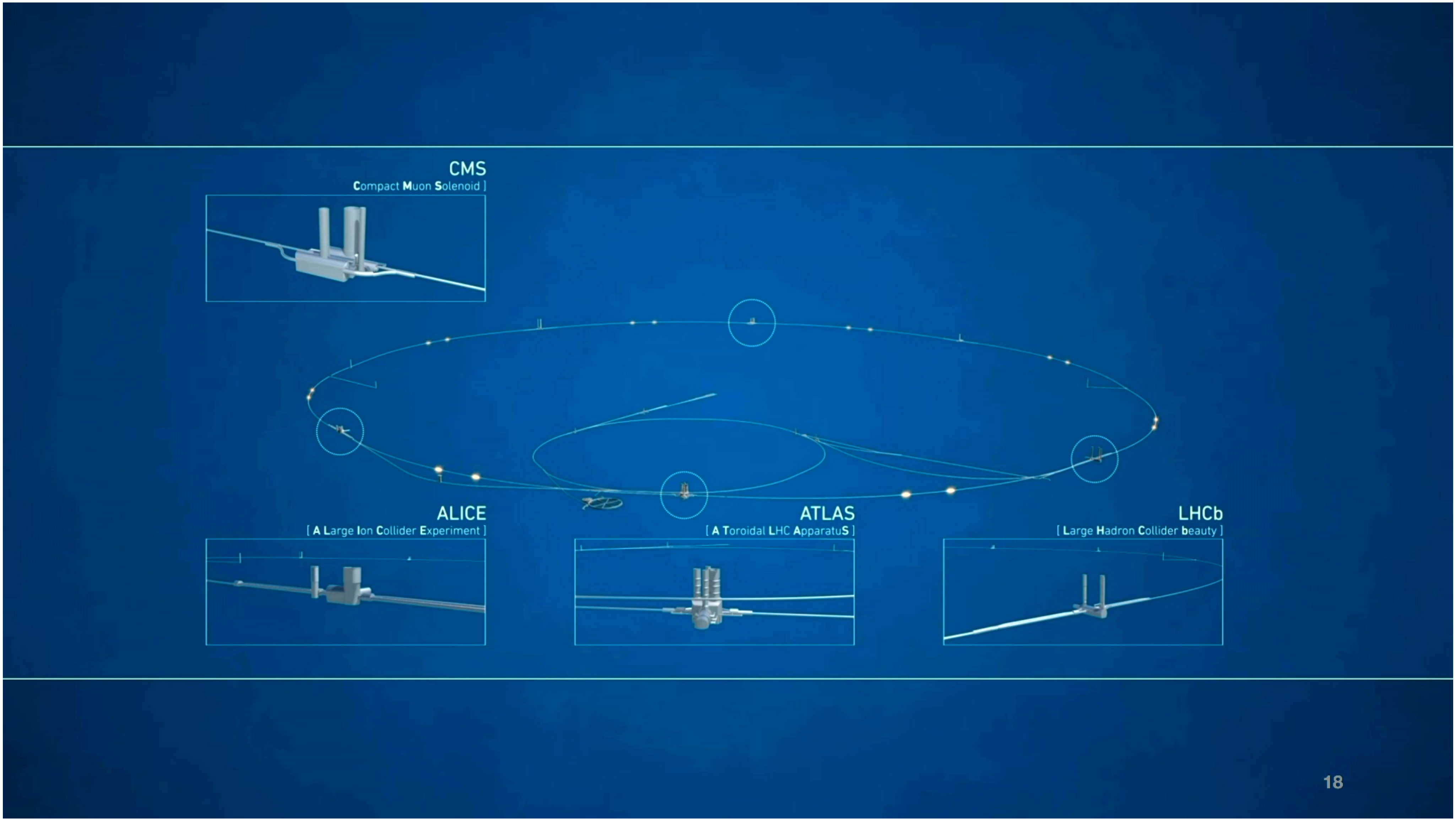

18


Hydrogen Bottle
Bouteille d'hydrogène
H2
18

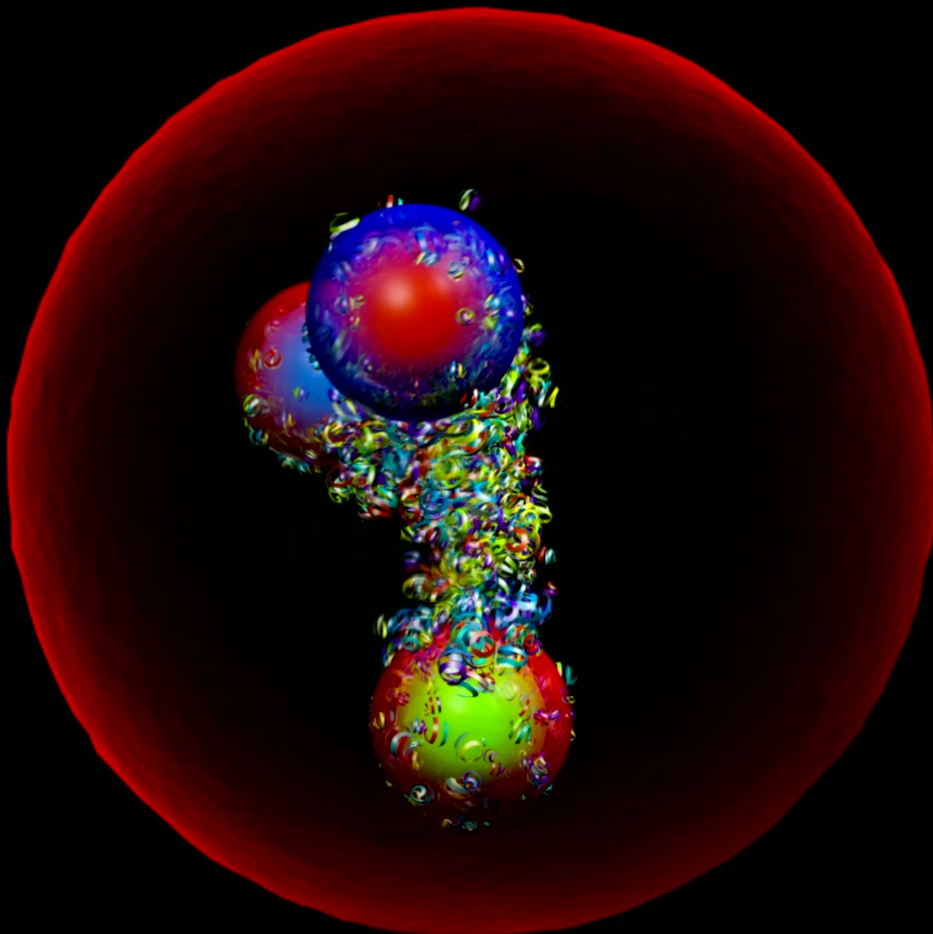

Duoplasmatron
Proton Source
Source de protons
18

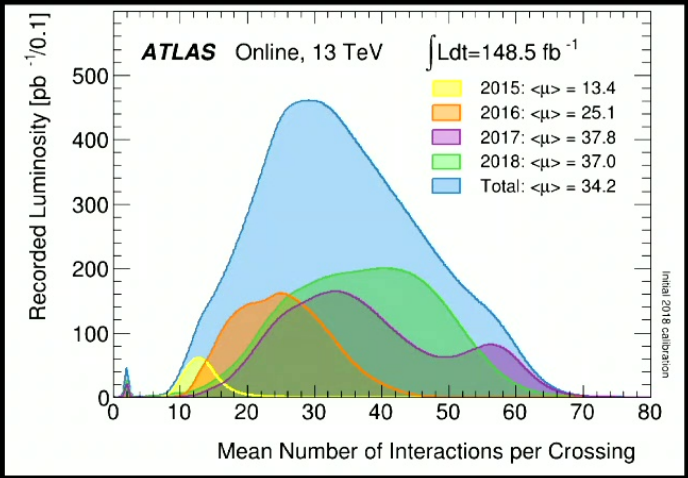

PS
Proton Synchrotron
Synchrotron à protons
18


LHC
Large Hadron Collider
Grand collisionneur de hadrons
18


CMS
[Compact Muon Solenoid]
ALICE
[A Large Ion Collider Experiment]
ATLAS
[A Toroidal LHC ApparatuS]
LHCb
[Large Hadron Collider beauty]
18

Colliding protons





We wanted to explore a high range of masses: from 50 GeV to 1 TeV

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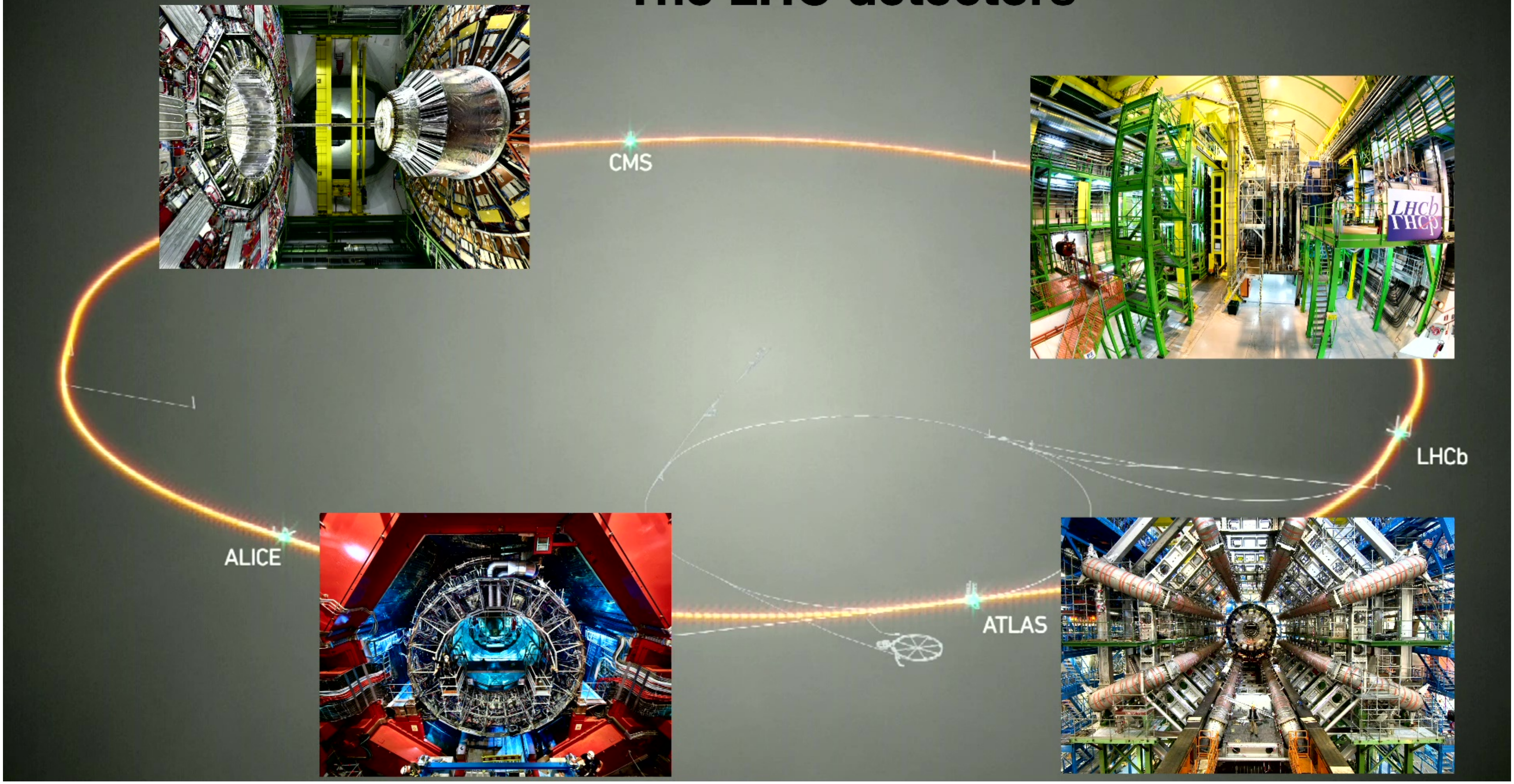
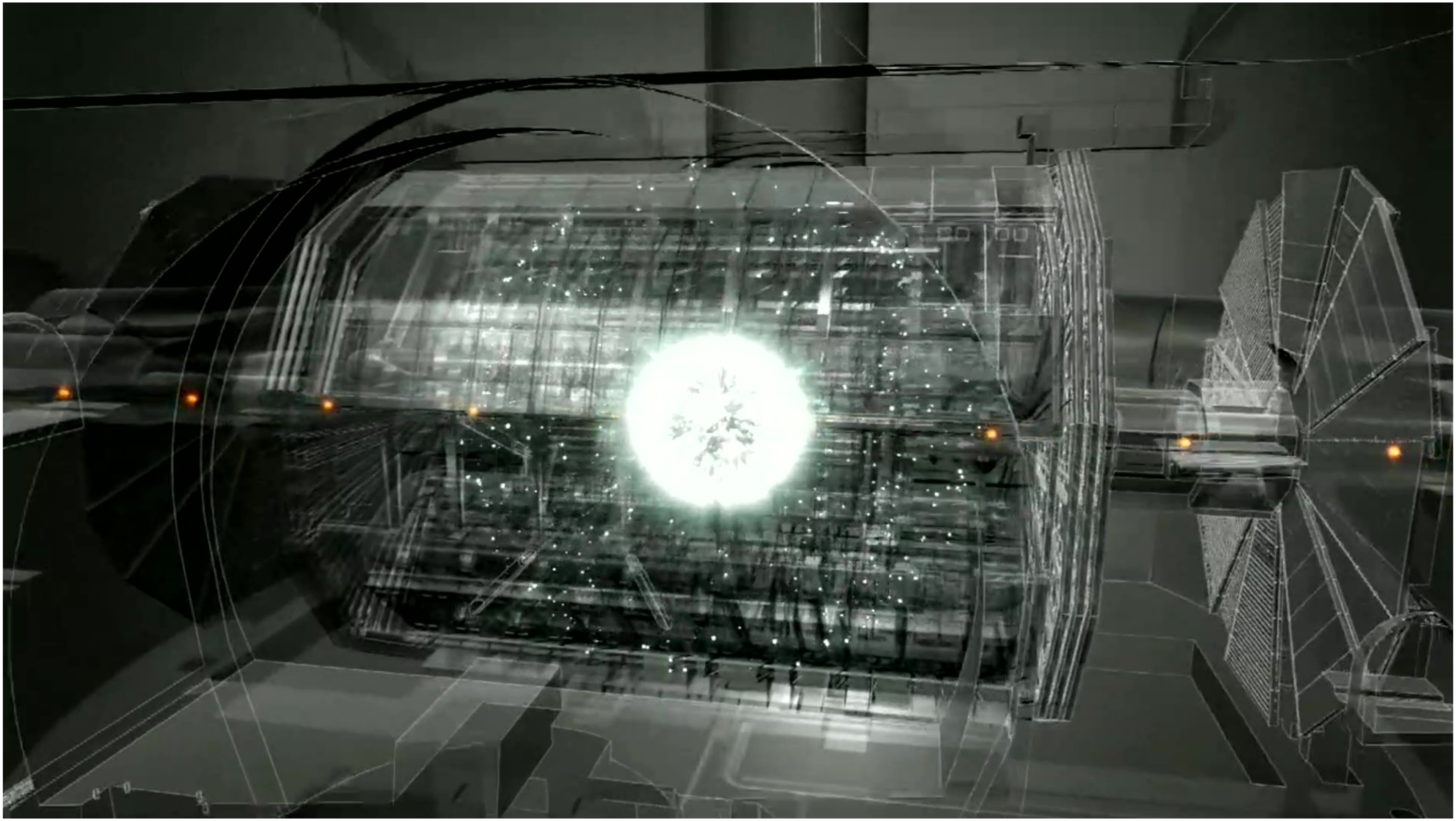
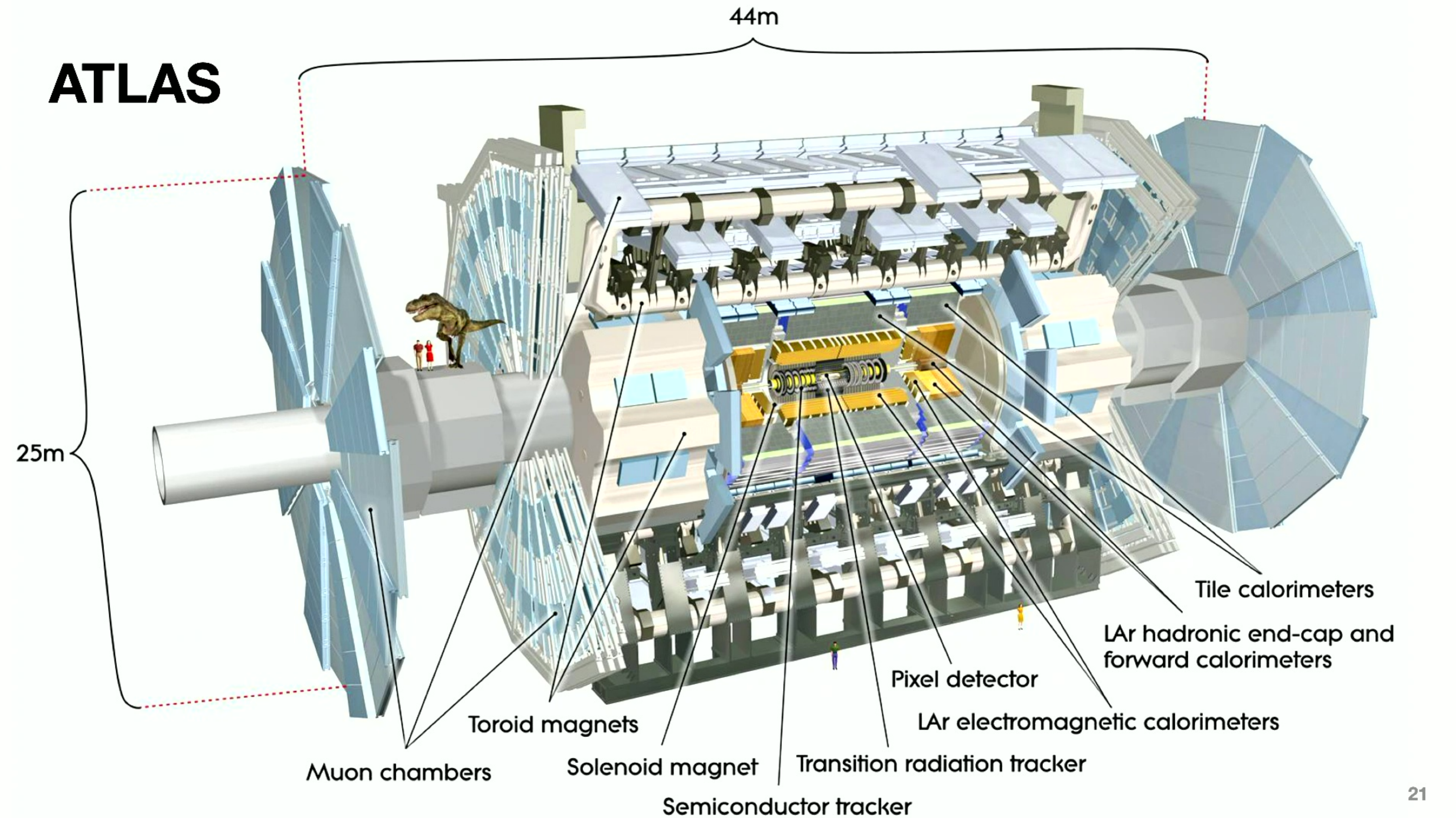
The LHC detectors





ATLAS


44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker

21

2002

ATLAS Installation in the cavern

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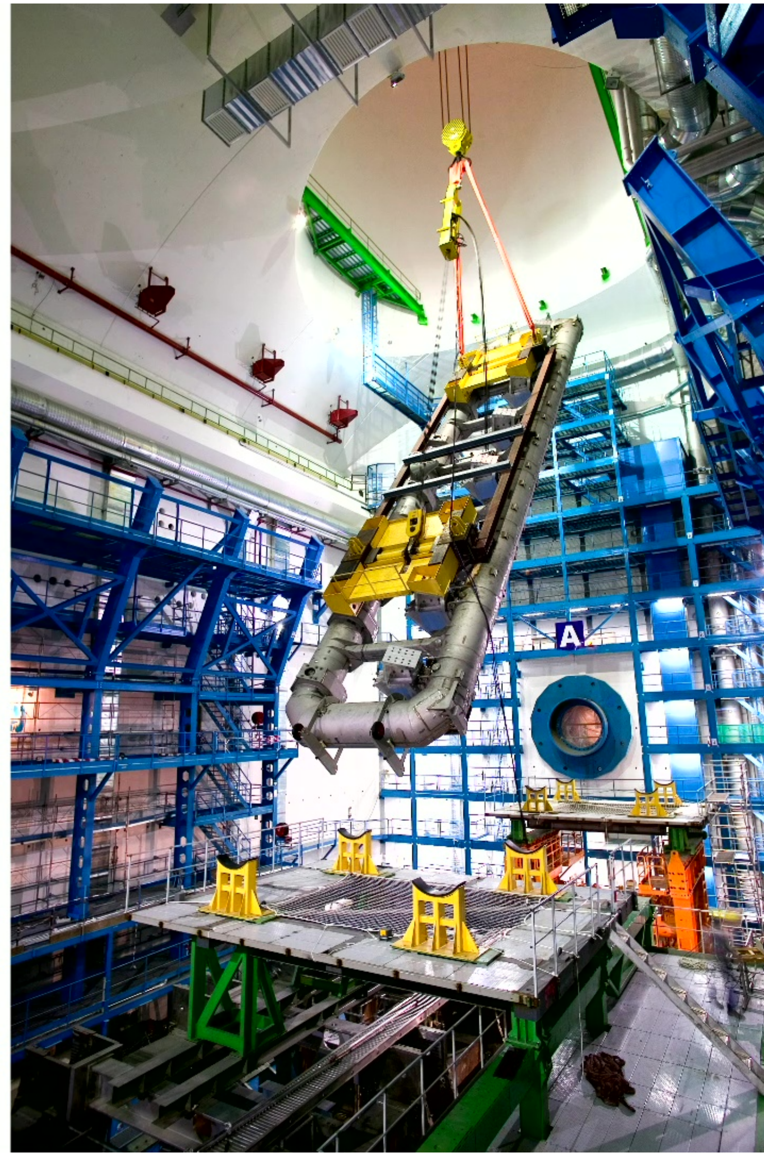
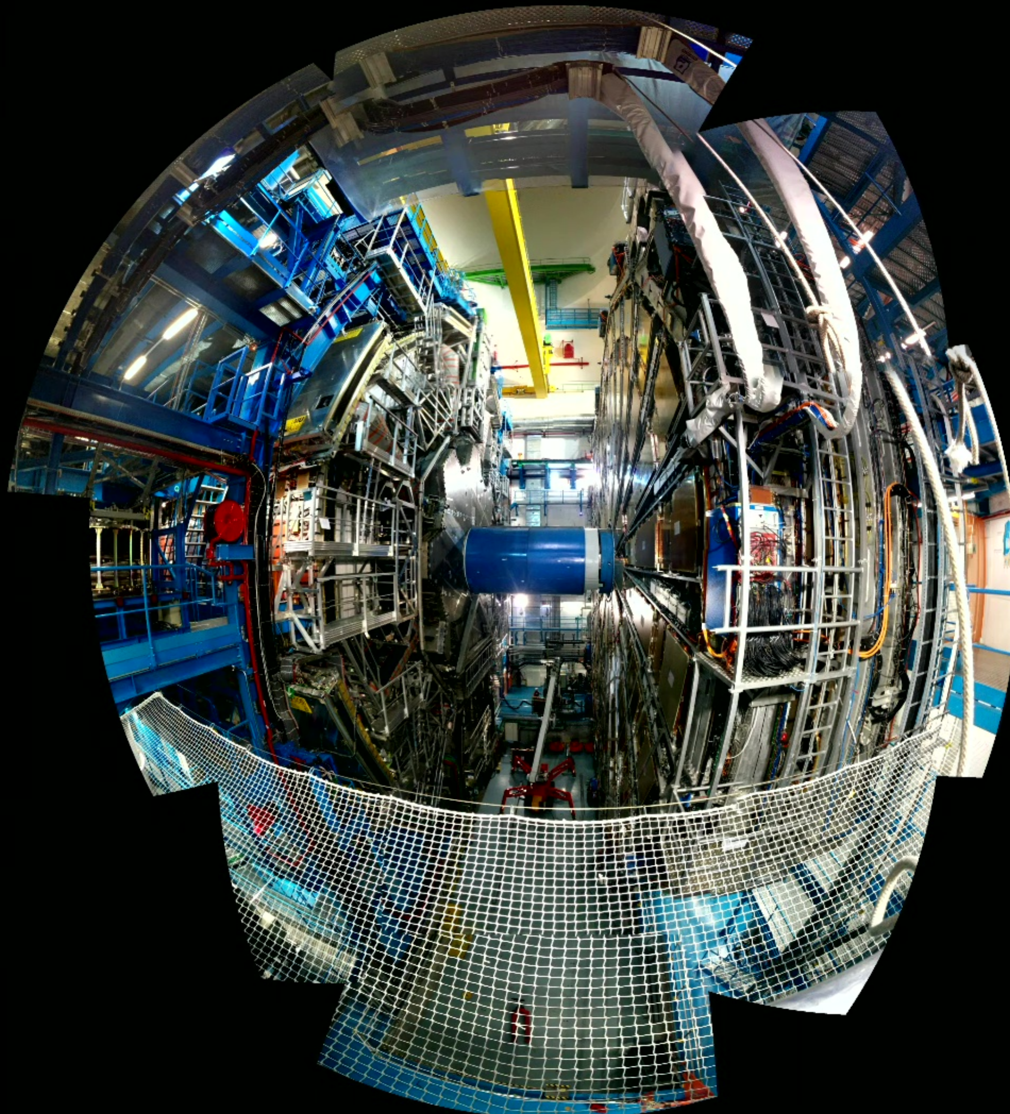
2004

ATLAS Installation in the cavern





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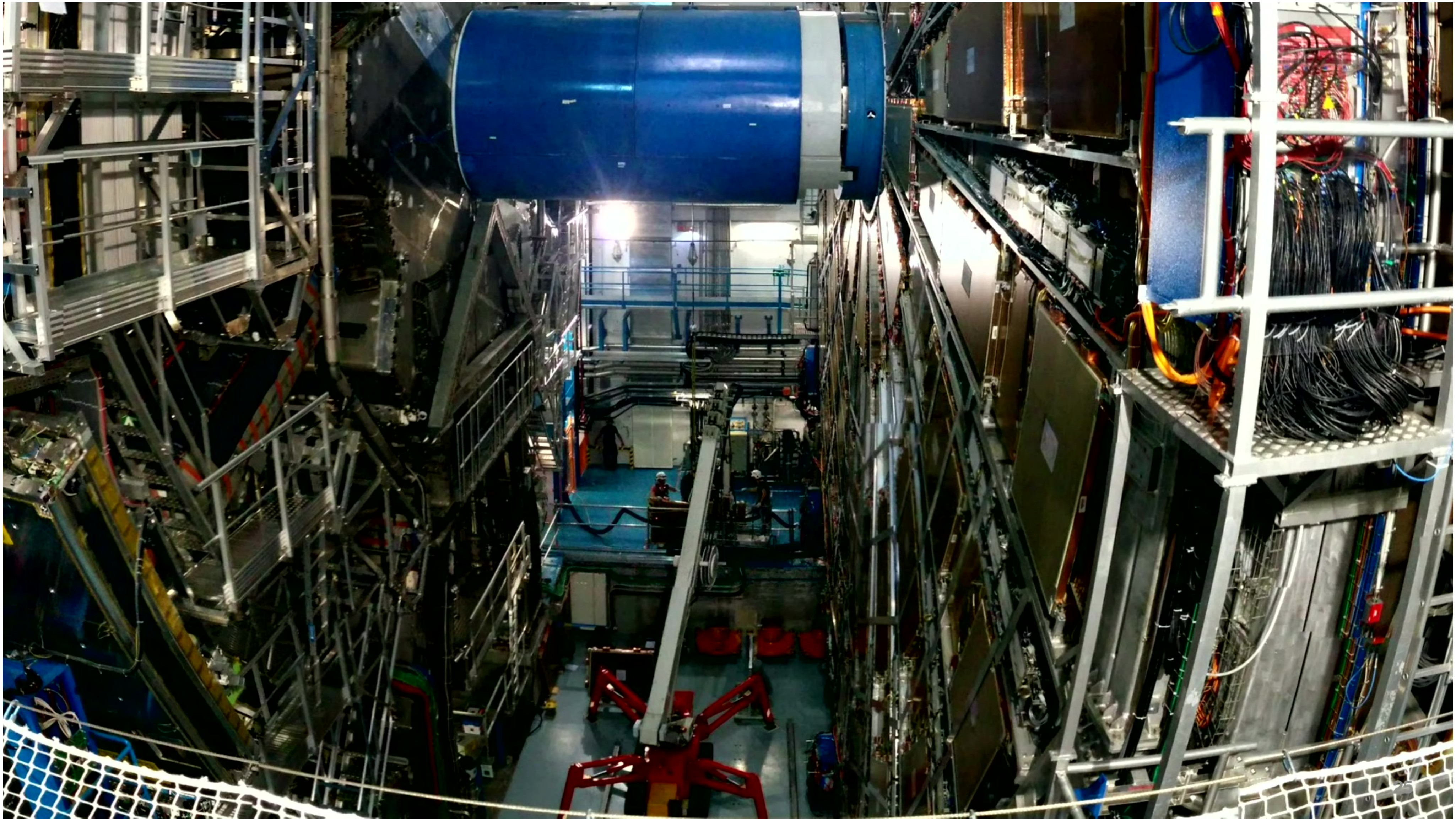

Status: November 2018
Albania
Algeria
Argentina
Armenia
Australia
Austria
Azerbaijan
Bangladesh
Belarus
Belgium
Bosnia and Herzegovina
Botswana
Brazil
Bulgaria
Burundi
Canada
Chile
China
Colombia
Costa Rica
Croatia
Cuba
Cyprus
Czech Republic
Denmark
Ecuador
Egypt
Finland
France
Georgia
Germany
Ghana
Greece
Honduras
Hong Kong
Hungary
Iceland
India
Indonesia
Iran
Iraq
Ireland
Israel
Italy
Japan
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Kazakhstan
Kenya
Kyrgyzstan
Latvia
Lebanon
Lithuania
Luxembourg
Madagascar
Malaysia
Malta
Mauritius
Mexico
Mongolia
Montenegro
Morocco
Nepal
Netherlands
New Zealand
Niger
Nigeria
Norway
Pakistan
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Peru
Philippines
Poland
Portugal
Romania
Russia
Saudi Arabia
Senegal
Serbia
Slovakia
Slovenia
South Africa
South Korea
Spain
Sri Lanka
Sudan
Swaziland
Sweden
Switzerland
Syria
Taiwan
Thailand
Tunisia
Turkey
Ukraine
UAE
UK
USA
Uruguay
Uzbekistan
Venezuela
Vietnam
Zambia
Zimbabwe
ATLAS Collaboration member nationalities
Over 5500 members of 103 nationalities
ATLAS EXPERIMENT

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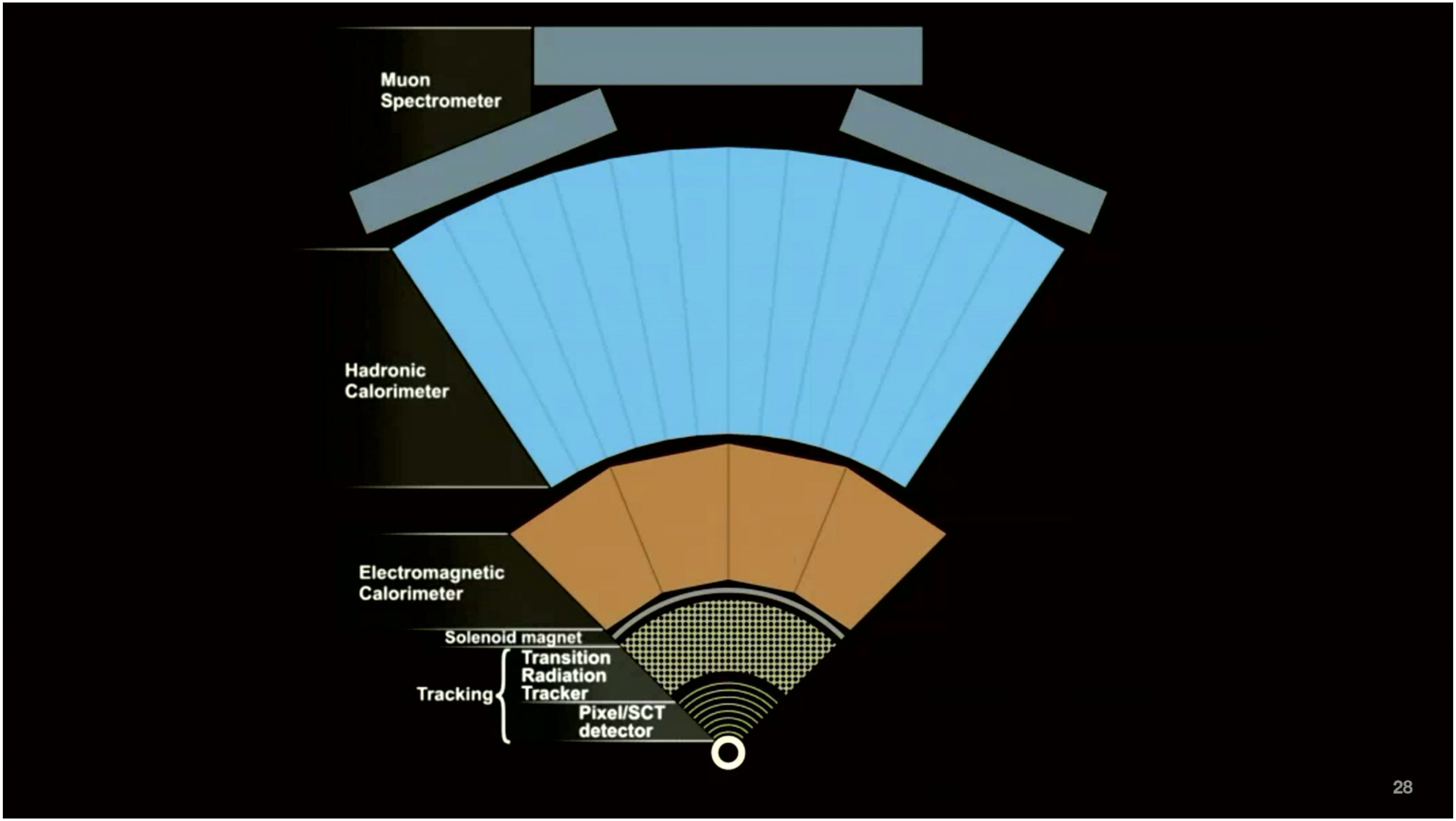
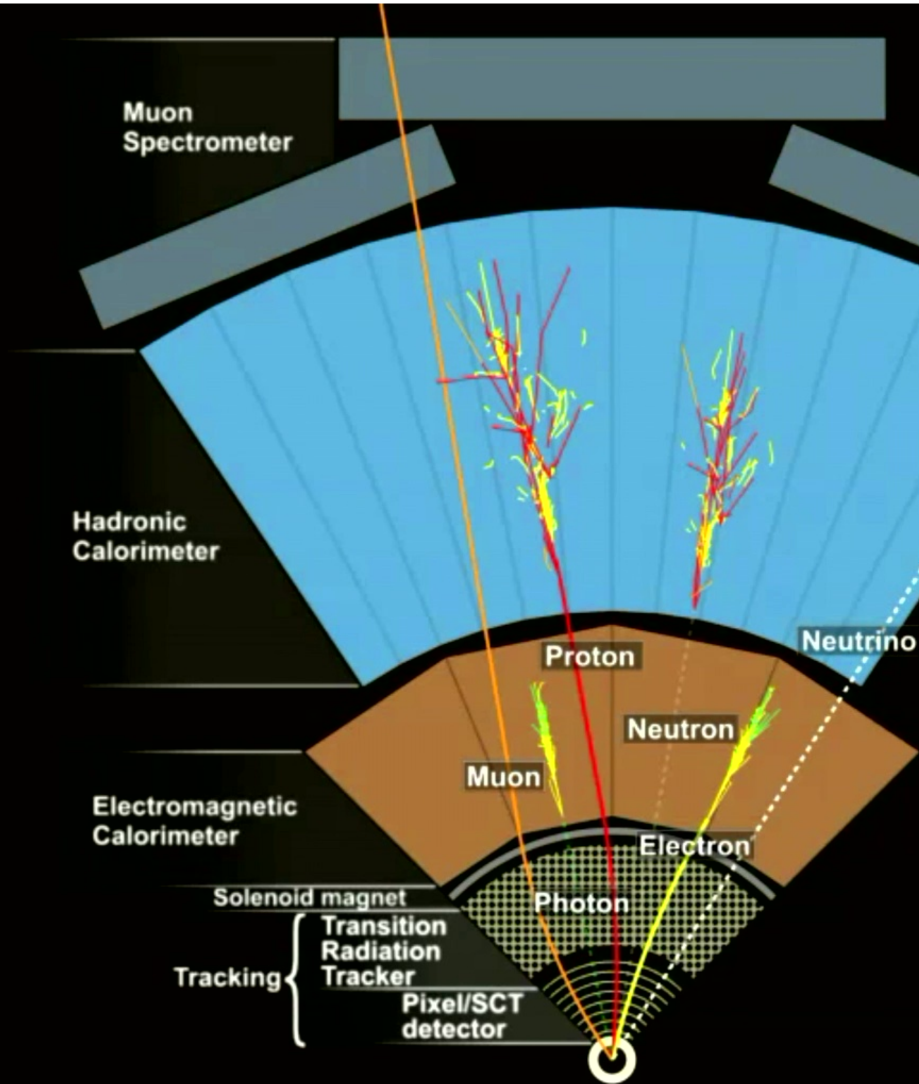
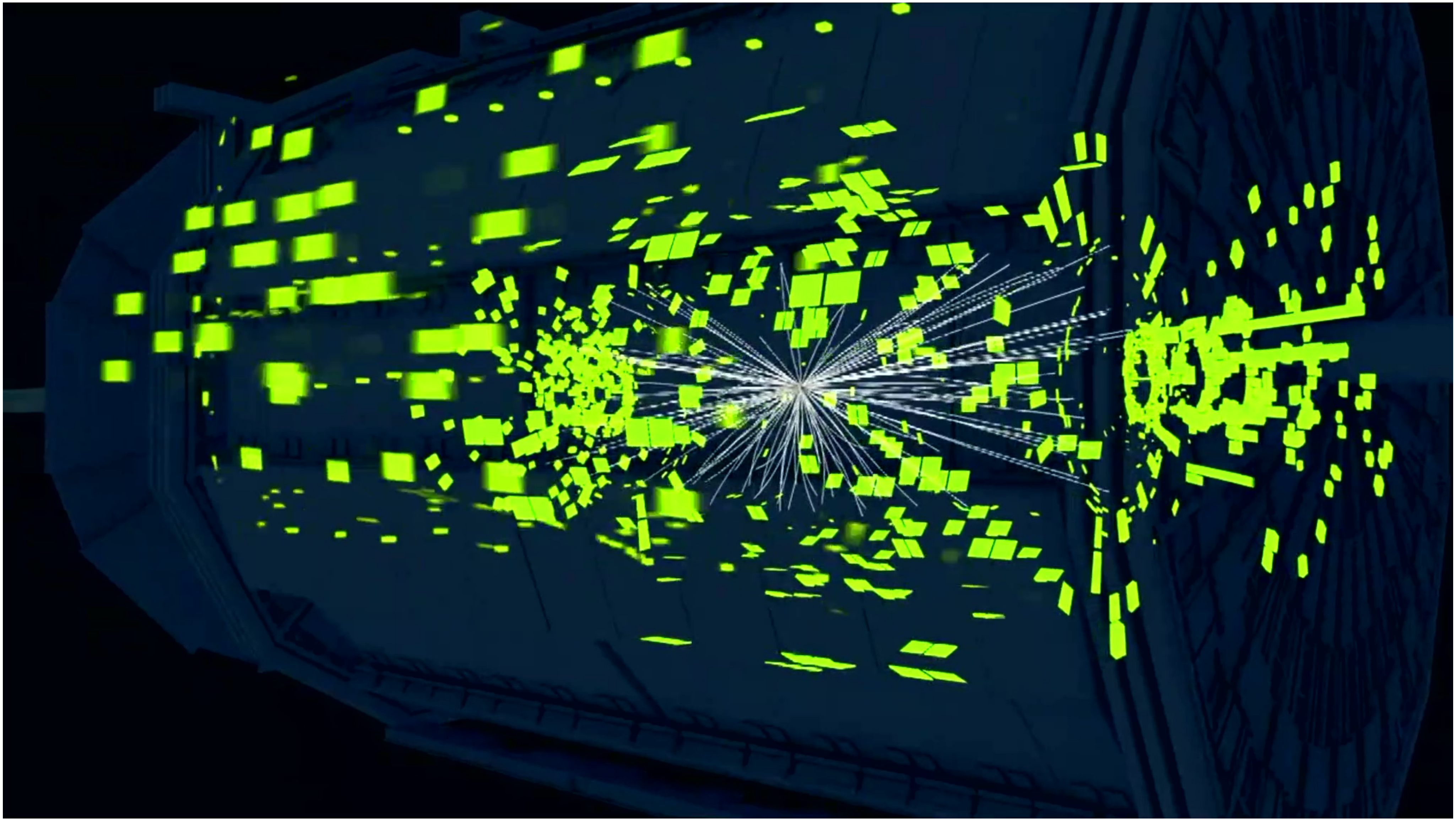
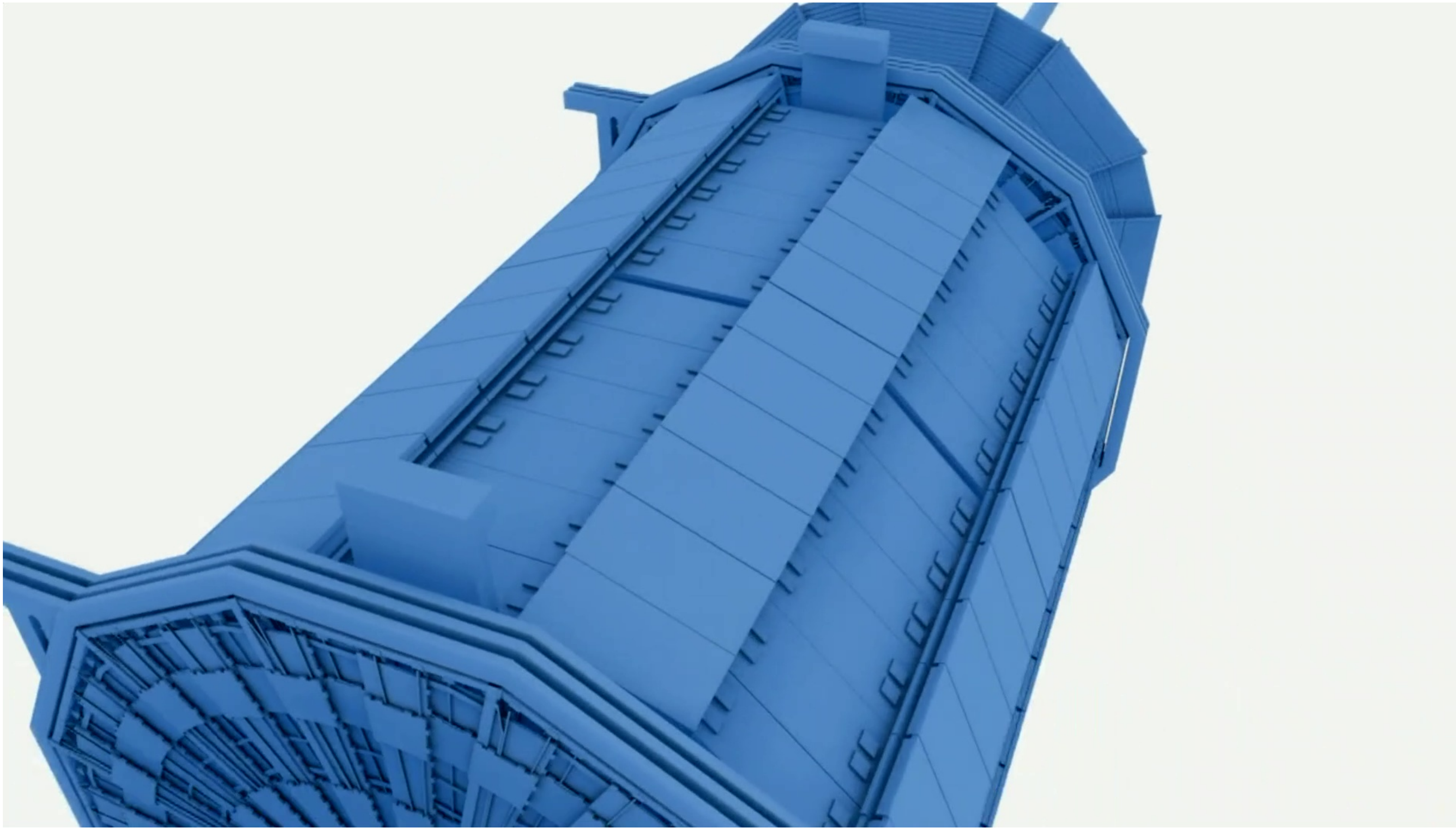
LHCb
ATLAS
EXPERIMENT
27

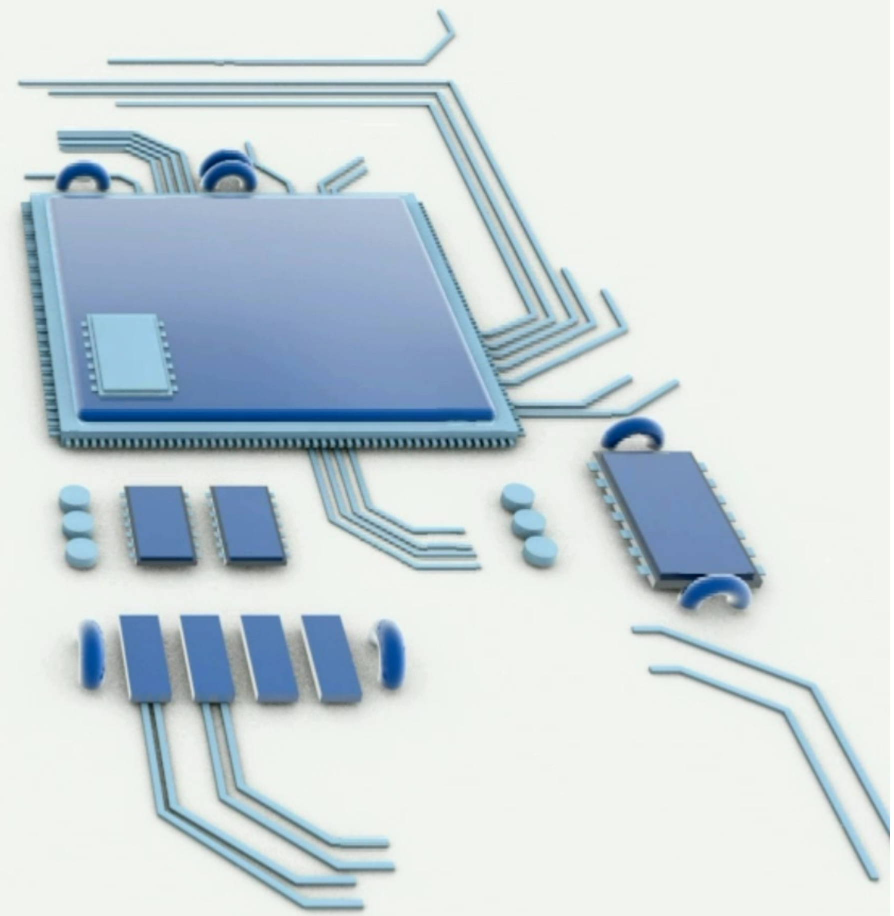

Muon
Spectrometer
Hadronic
Calorimeter
Electromagnetic
Calorimeter
Solenoid magnet
Tracking
Transition
Radiation
Tracker
Pixel/SCT
detector
28

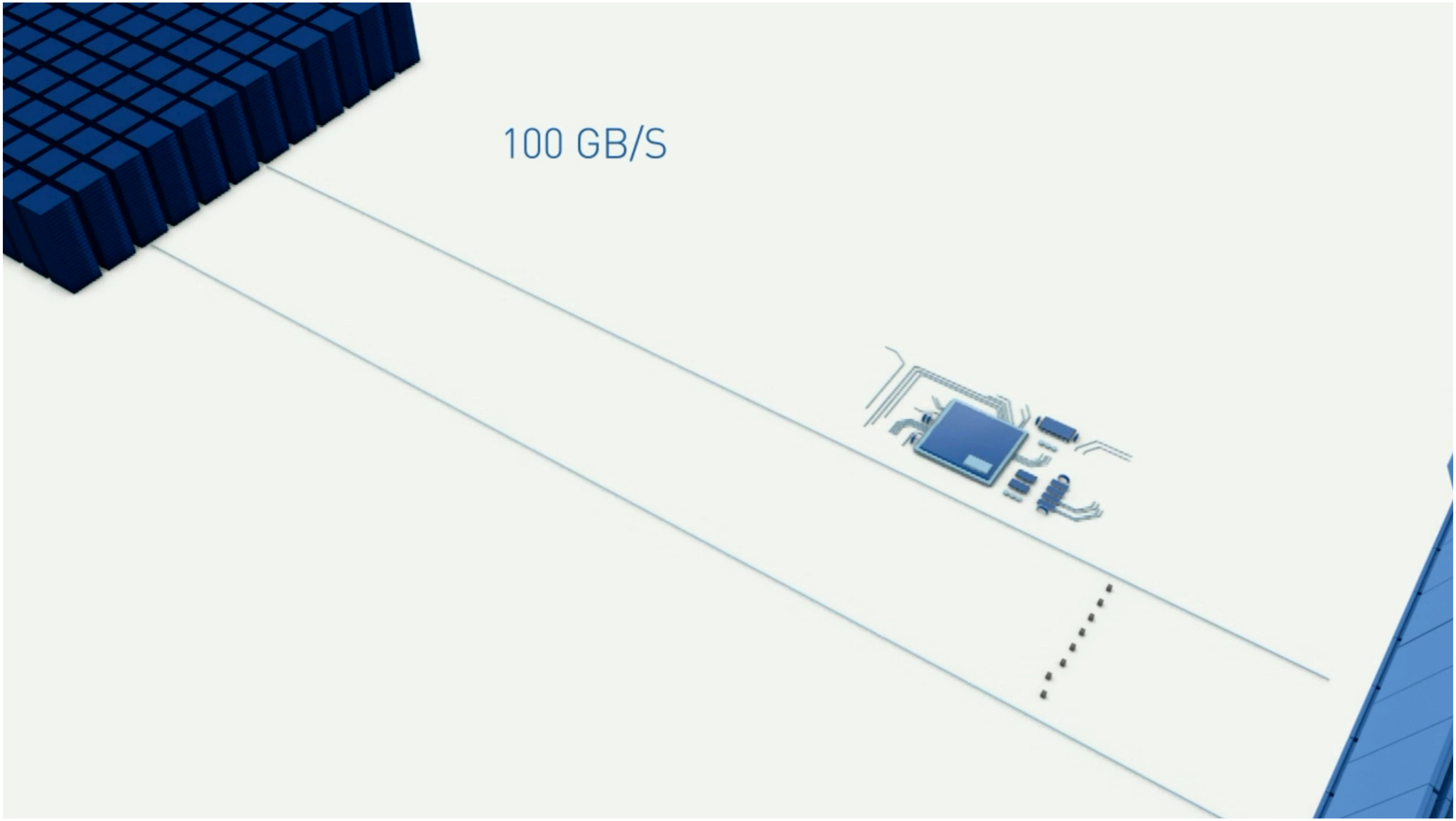

Muon
Spectrometer
Hadronic
Calorimeter
Electromagnetic
Calorimeter
Solenoid magnet
Tracking
Transition
Radiation
Tracker
Pixel/SCT
detector
Proton
Neutrino
Neutron
Muon
Electron
Photon
The dashed tracks
are invisible to
the detector

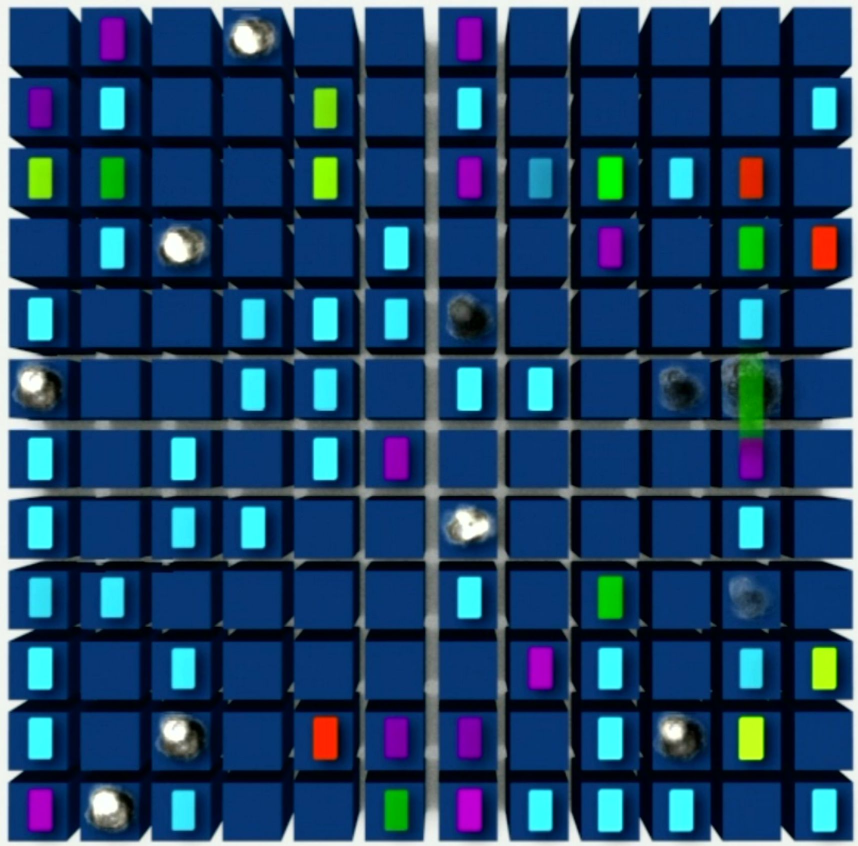


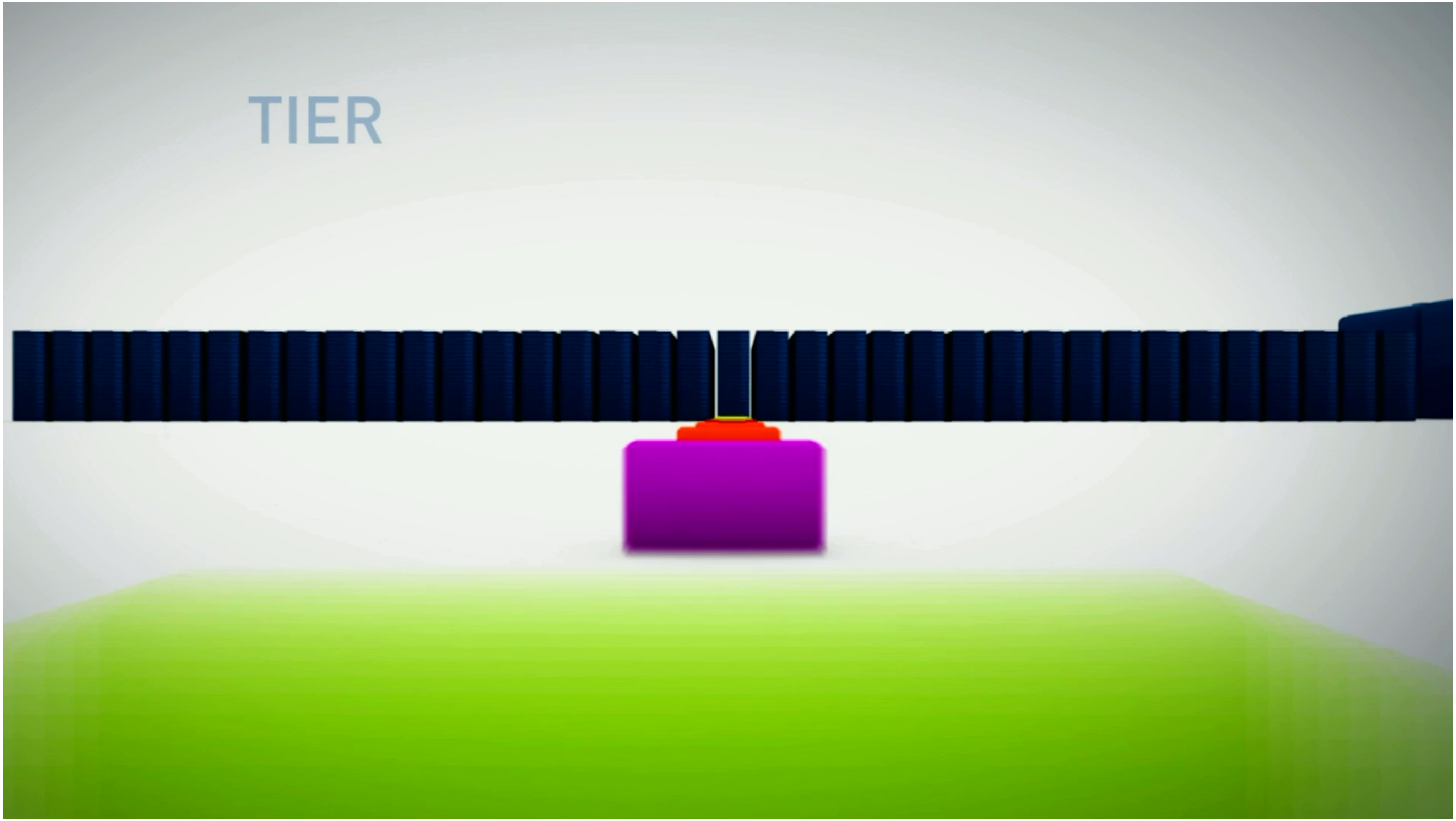


Fast electronic
preselection passes
1 out of 10 000 events
and stores them
on computer memory




100 GB/S




TIER


• TIER 0

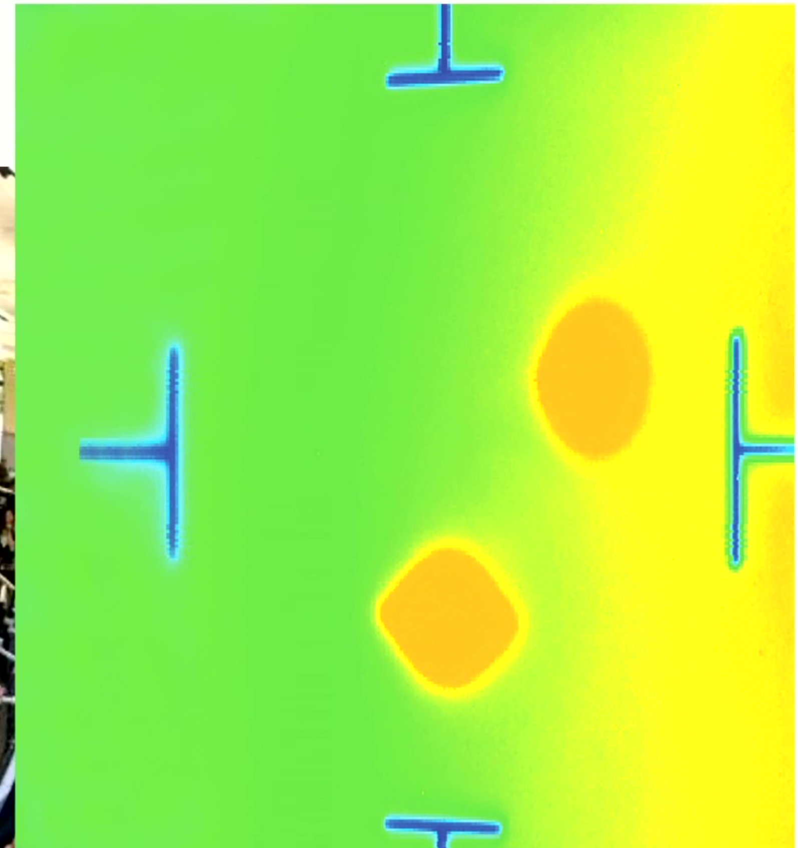
2008 First beams in the LHC

10th September

Images: CERN

2008 First beams in the LHC

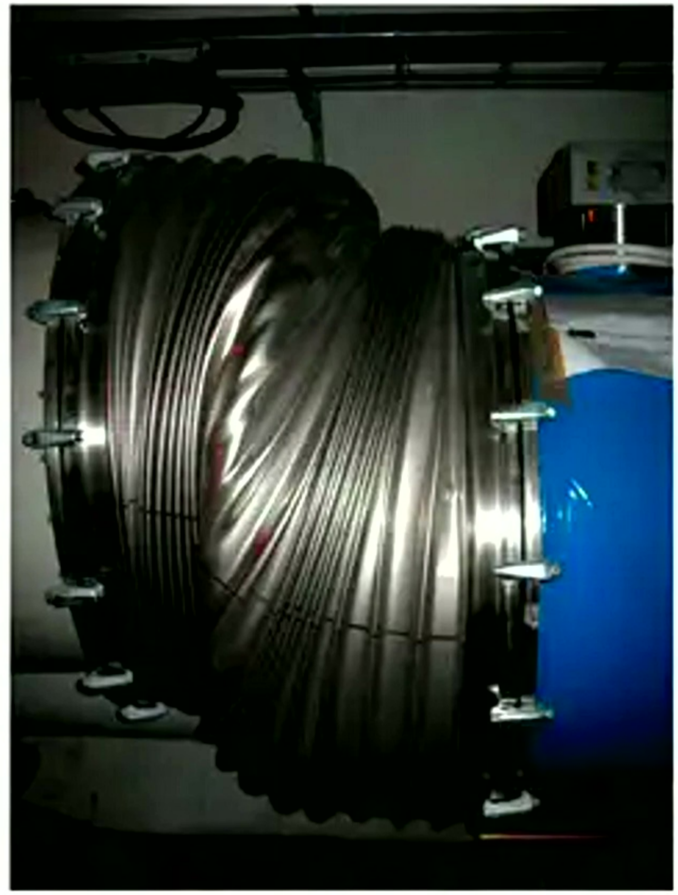
10th September



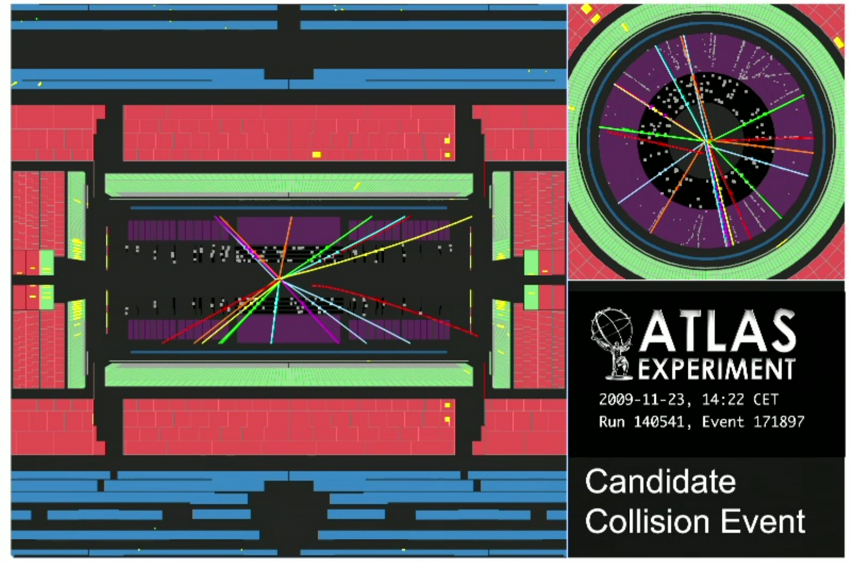
Images: CERN

2008 Magnet incident - QUENCH

19th September, 11.45am



2009 First collisions in the LHC!



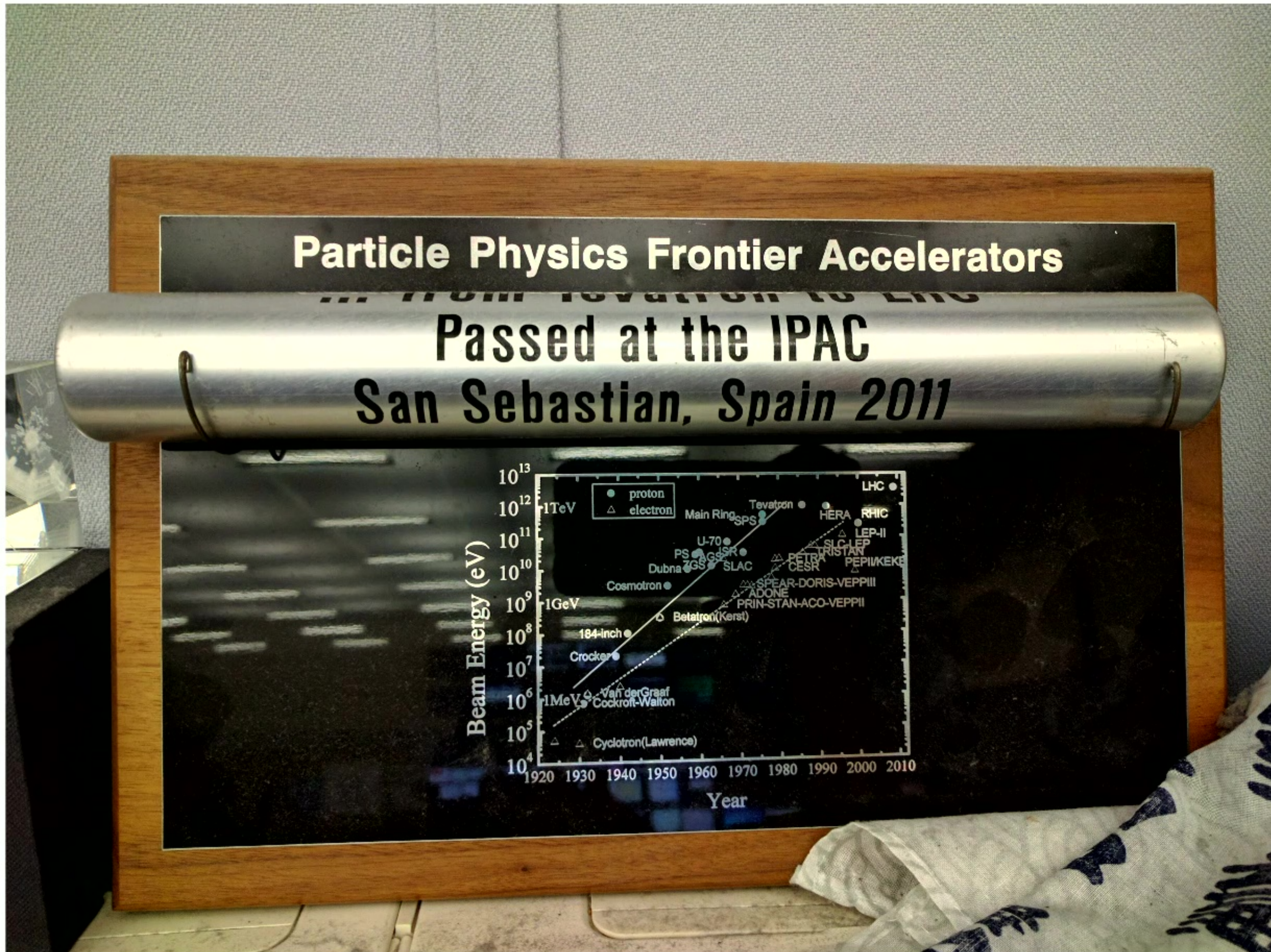
http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

2009 Highest energy particle collider in the world!

First collisions at 900 GeV. Then to 2.36 TeV - a new record!

Continued ramping up through to 2010 to reach 7 TeV centre of mass.

From Fermilab to CERN



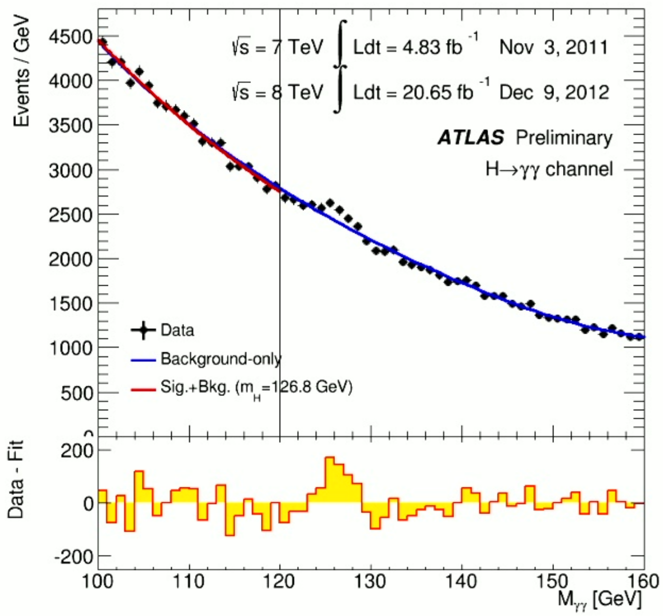
33

2012

The discovery of a new boson!

The Higgs boson – a major success of the first LHC run.

Image: Jorge Cham / PhD Comics



2012

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Image: Jorge Cham / PhD Comics

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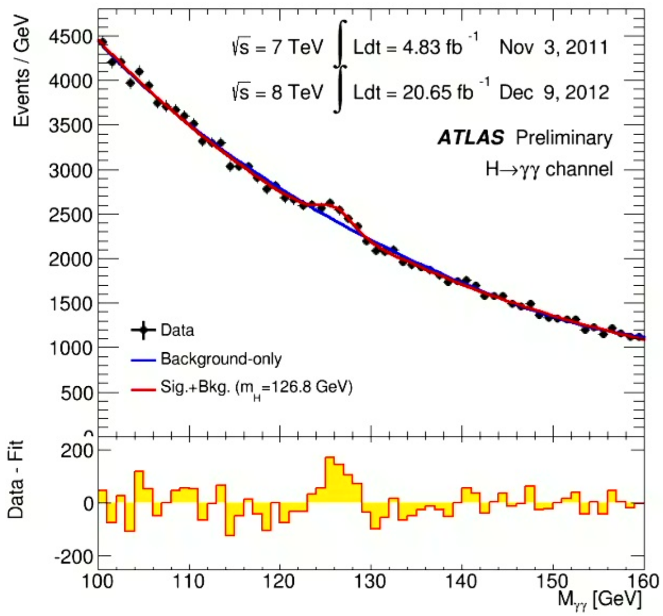
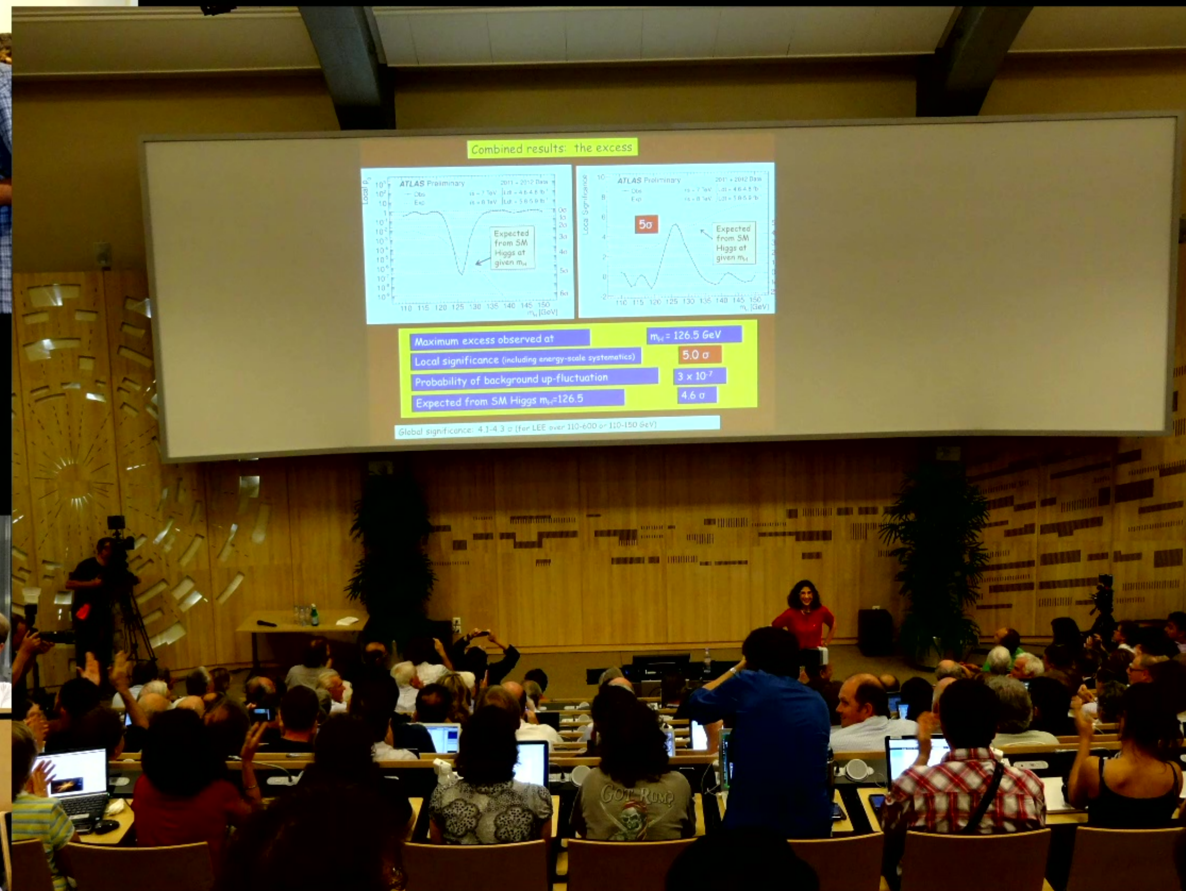
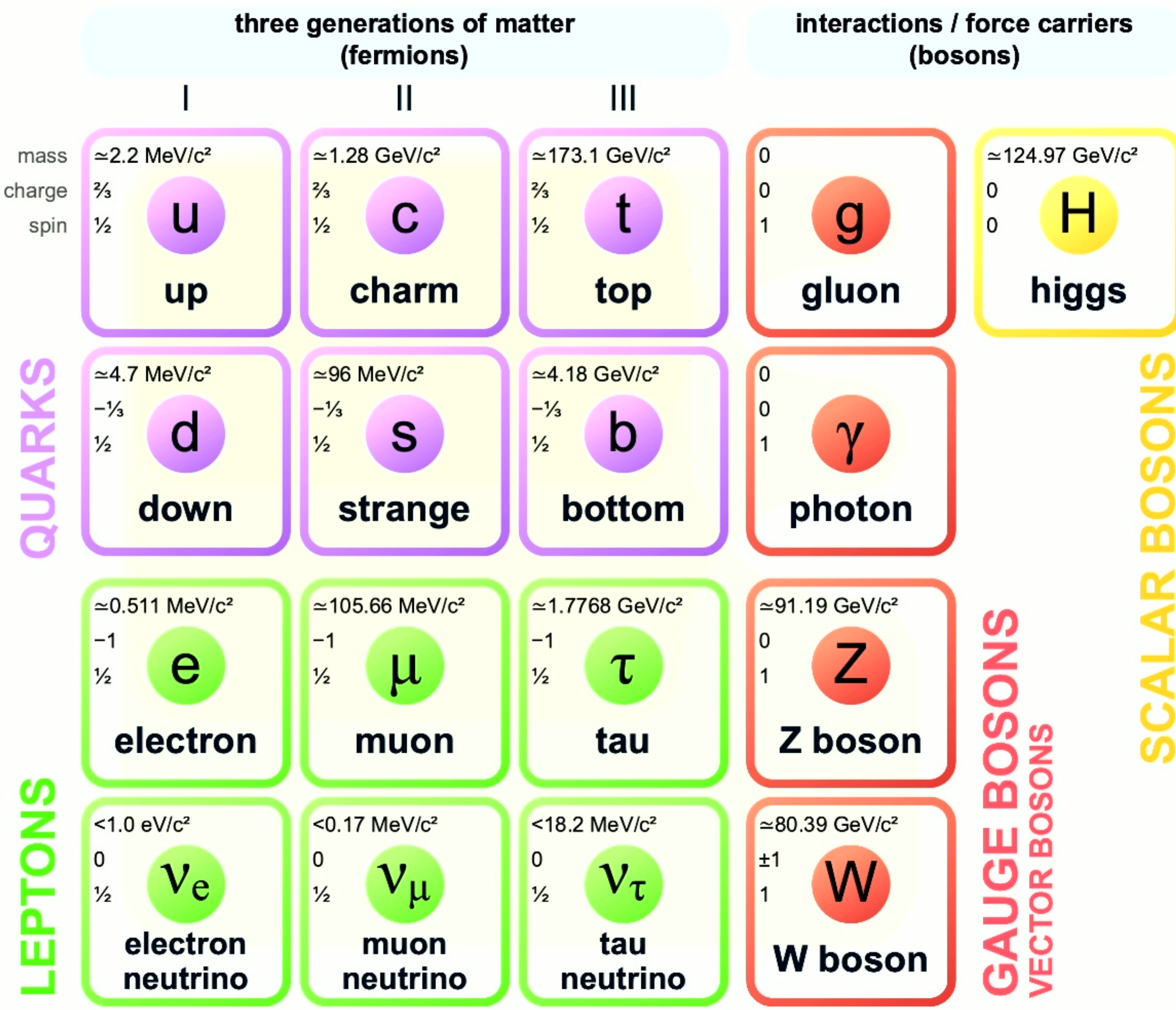



Combined results: the excess
ATLAS Preliminary
2011 + 2012 Data
Expected from SM Higgs at given m_H
5σ
Maximum excess observed at
m_H = 126.5 GeV
Local significance (including energy-scale systematics)
5.0 σ
Probability of background up-fluctuation
3 x 10^{-7}
Expected from SM Higgs m_H=126.5
4.6 σ
Global significance: 4.1-4.3 σ [for LEE over 110-600 or 110-150 GeV]

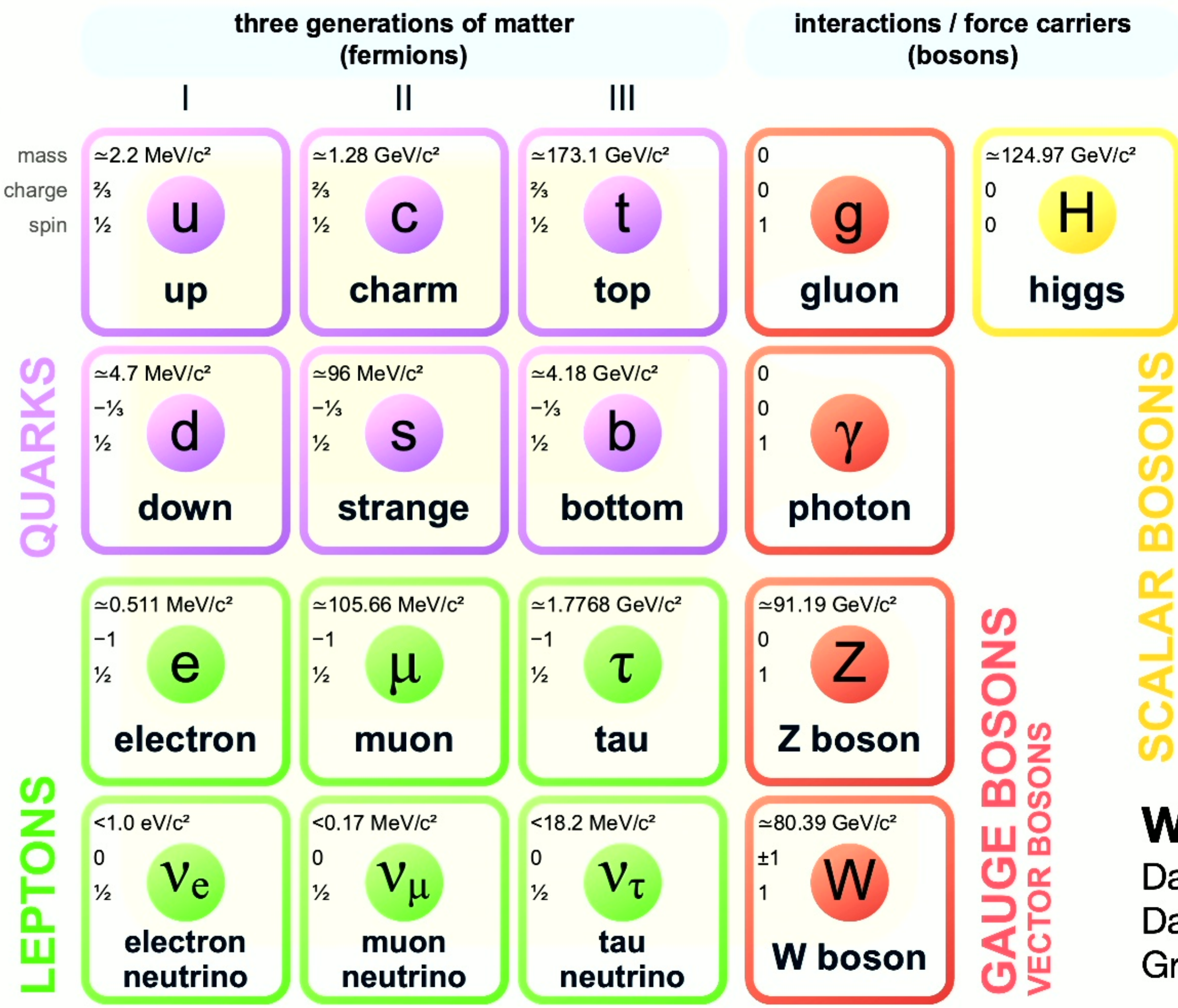
37

The Standard Model (today)



38

The Standard Model (today)

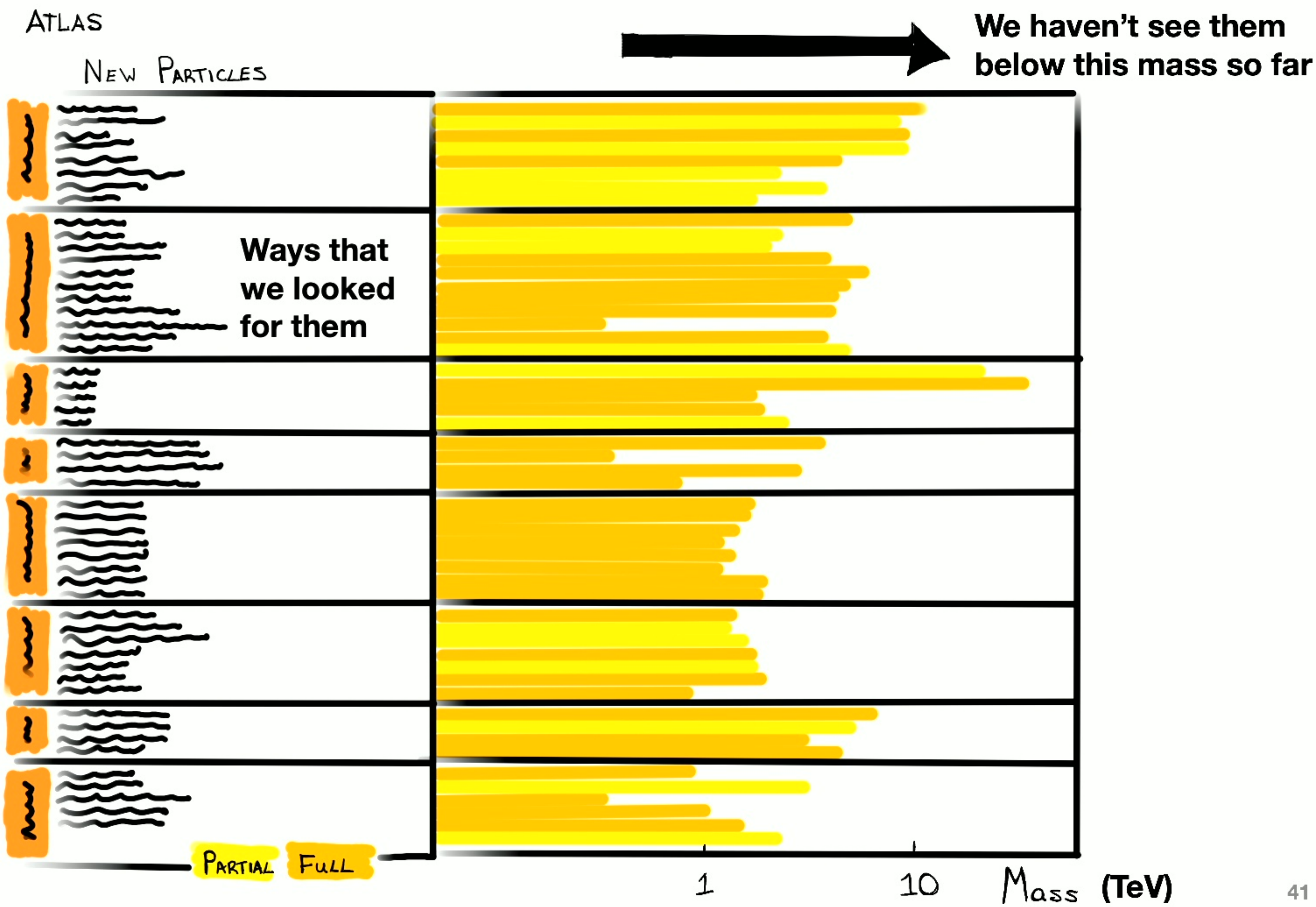


What's missing?

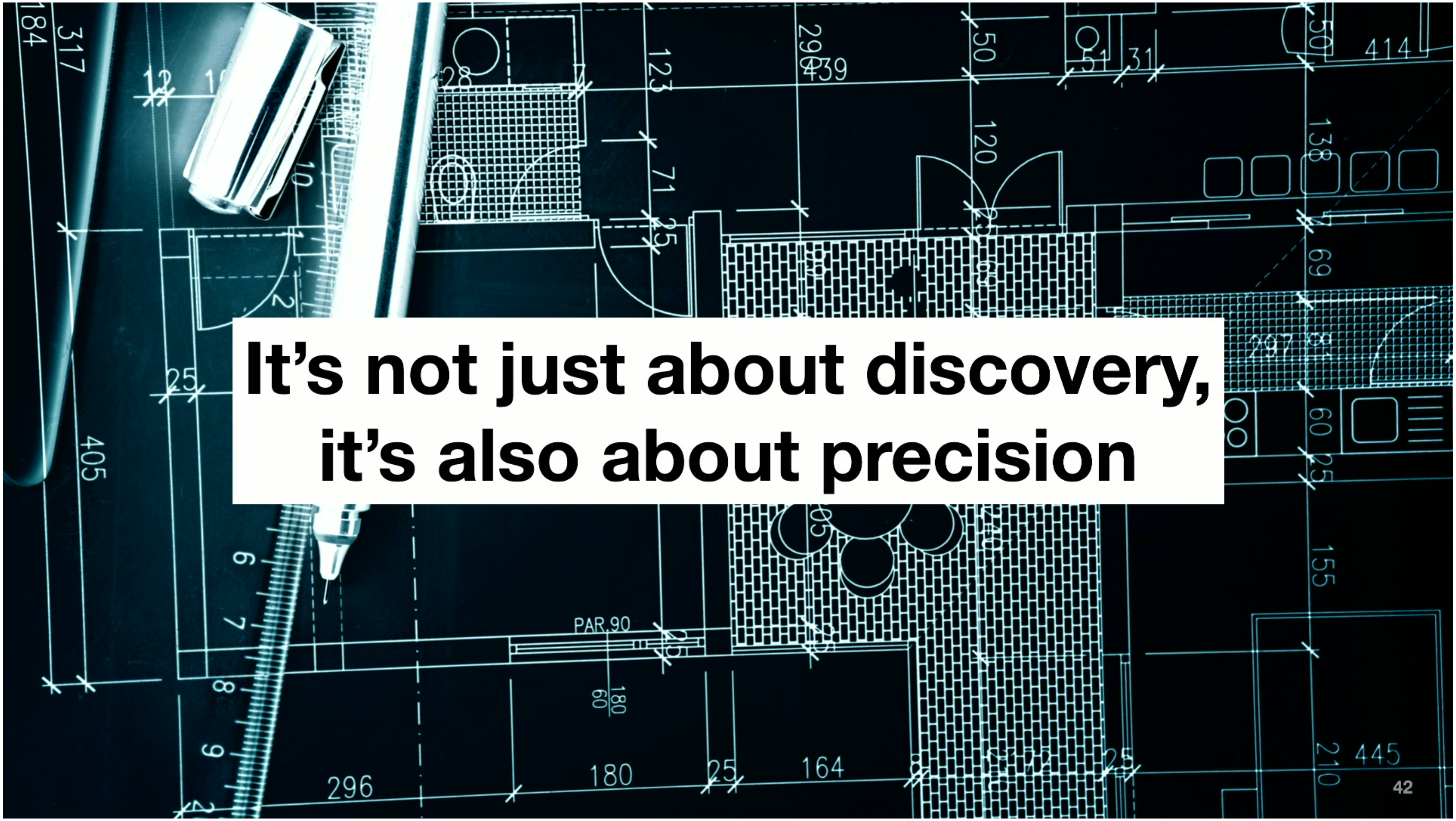
Dark matter
Dark energy
Gravity!

So, we keep searching

Searches



ATLAS
New Particles
Ways that we looked for them
We haven't see them below this mass so far
Partial
Full
1
10
Mass (TeV)

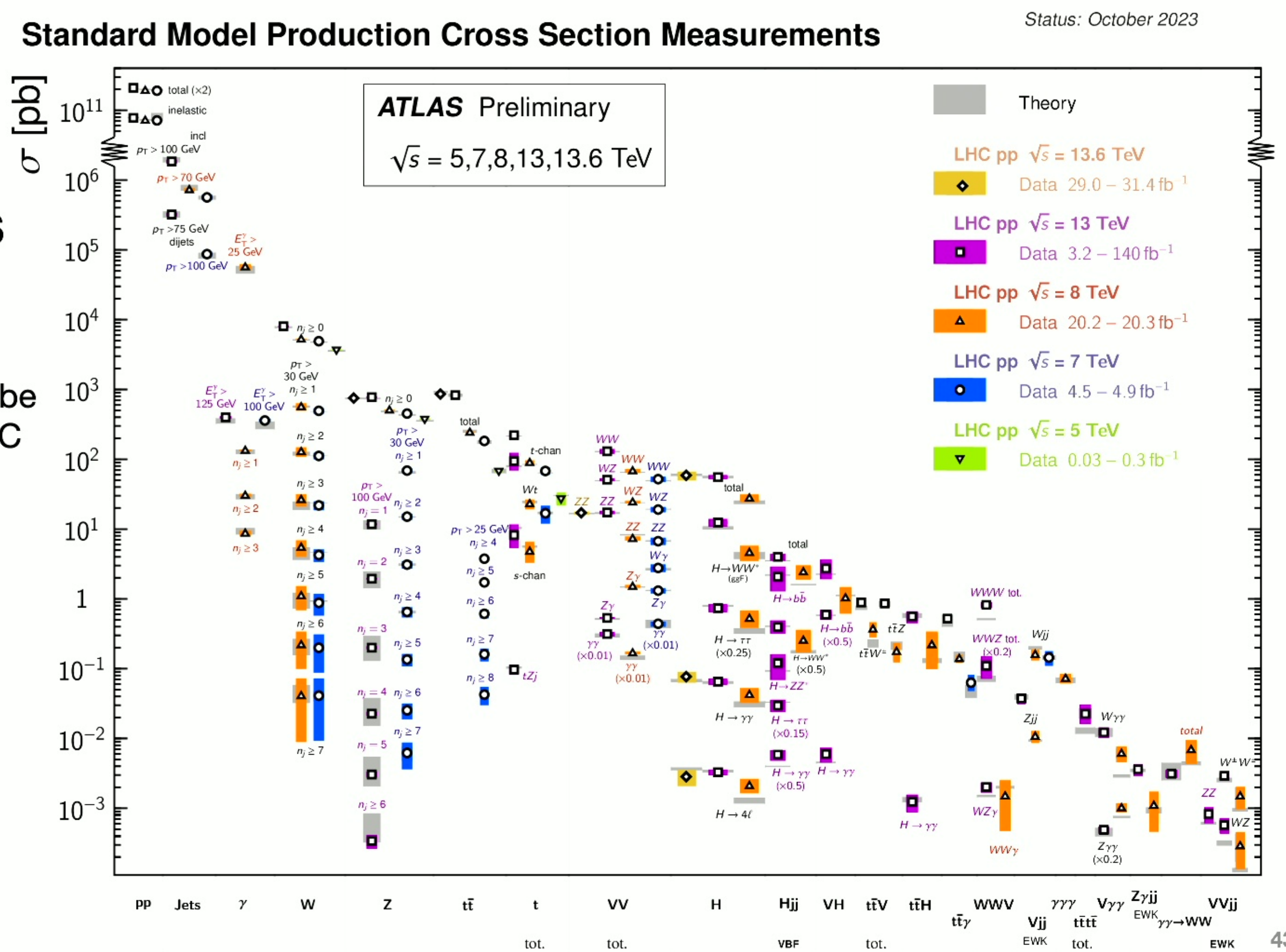


It’s not just about discovery, it’s also about precision

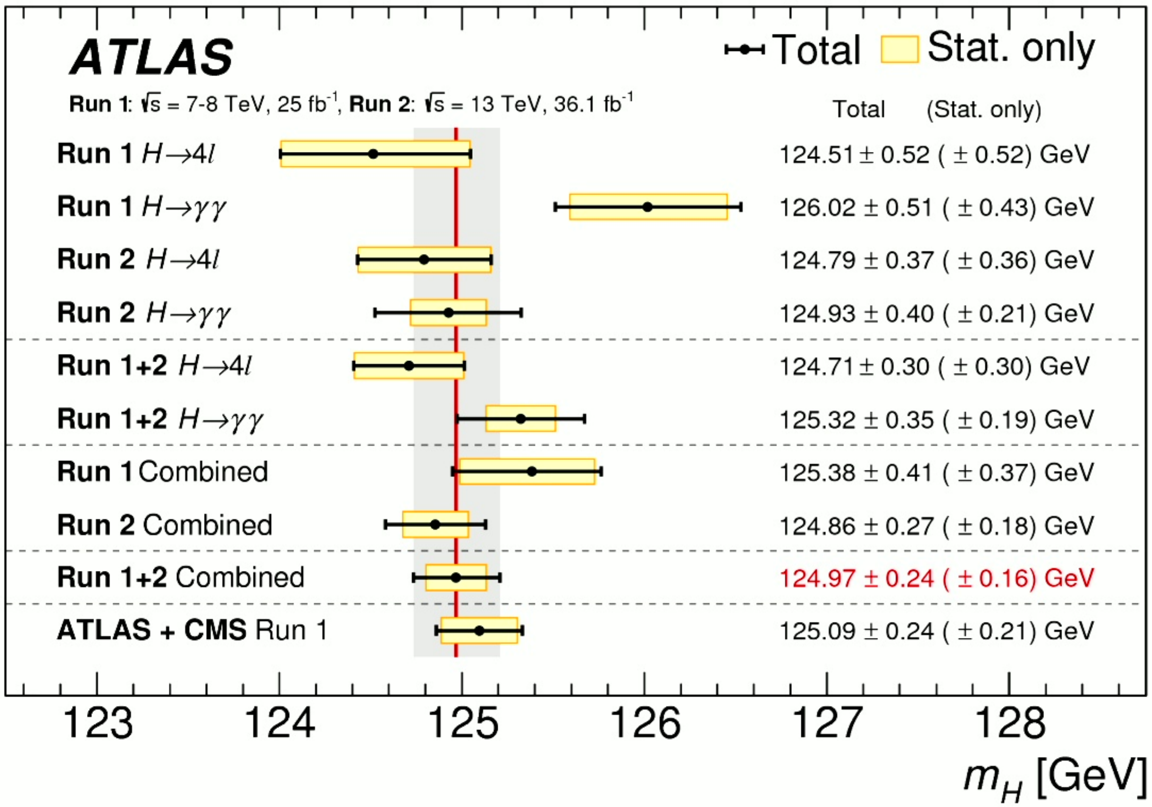
Precision measurements

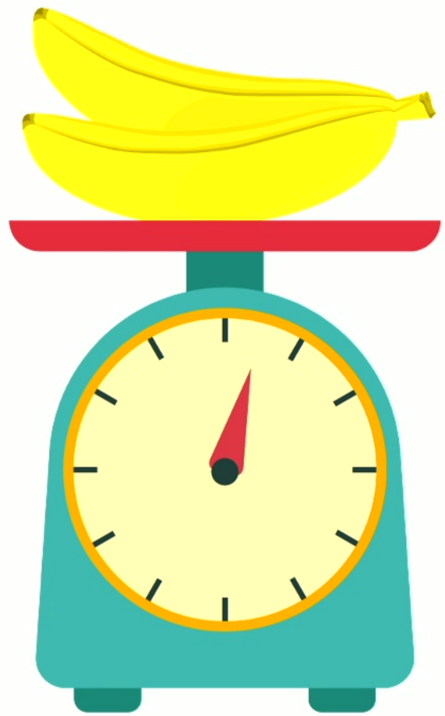
How likely a process is to be created in LHC collisions

A rarer process



Precision Higgs measurements

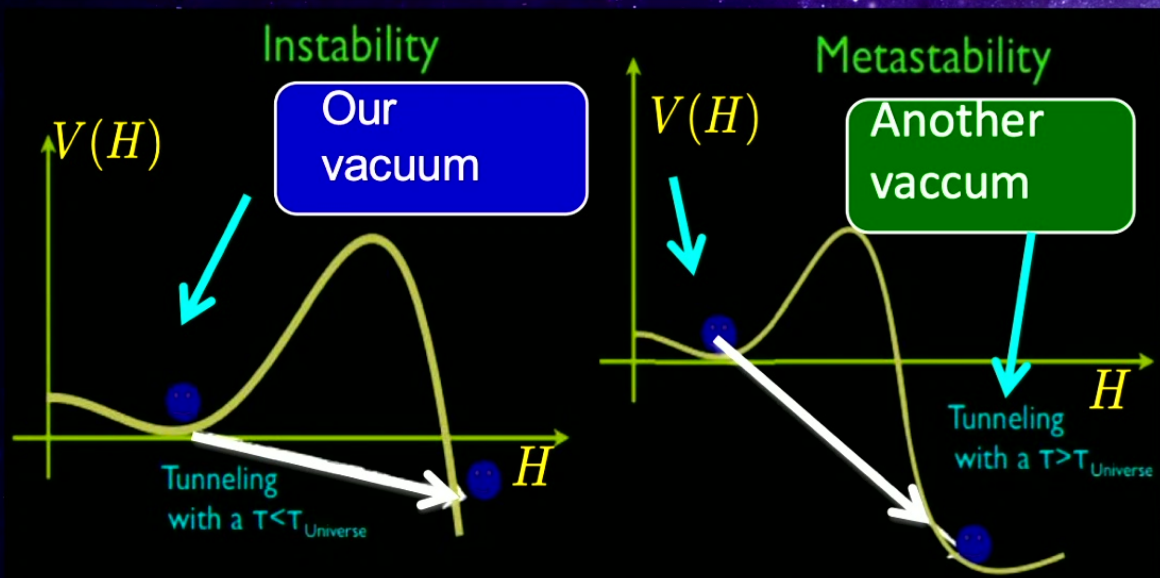


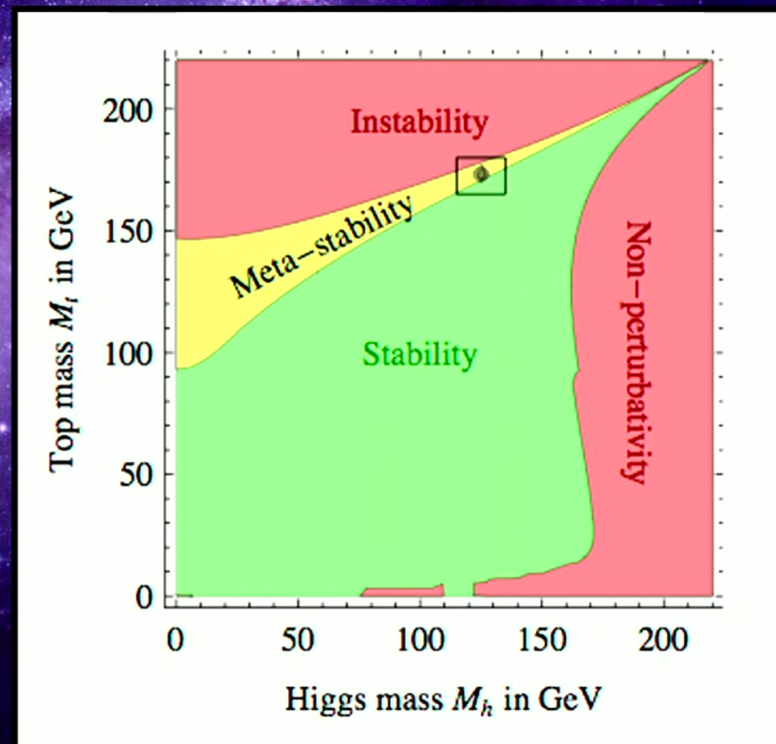


Mass measurements

The stability of the universe depends on it!

(Please note: measuring this doesn't affect the stability. We're a passive observer.)

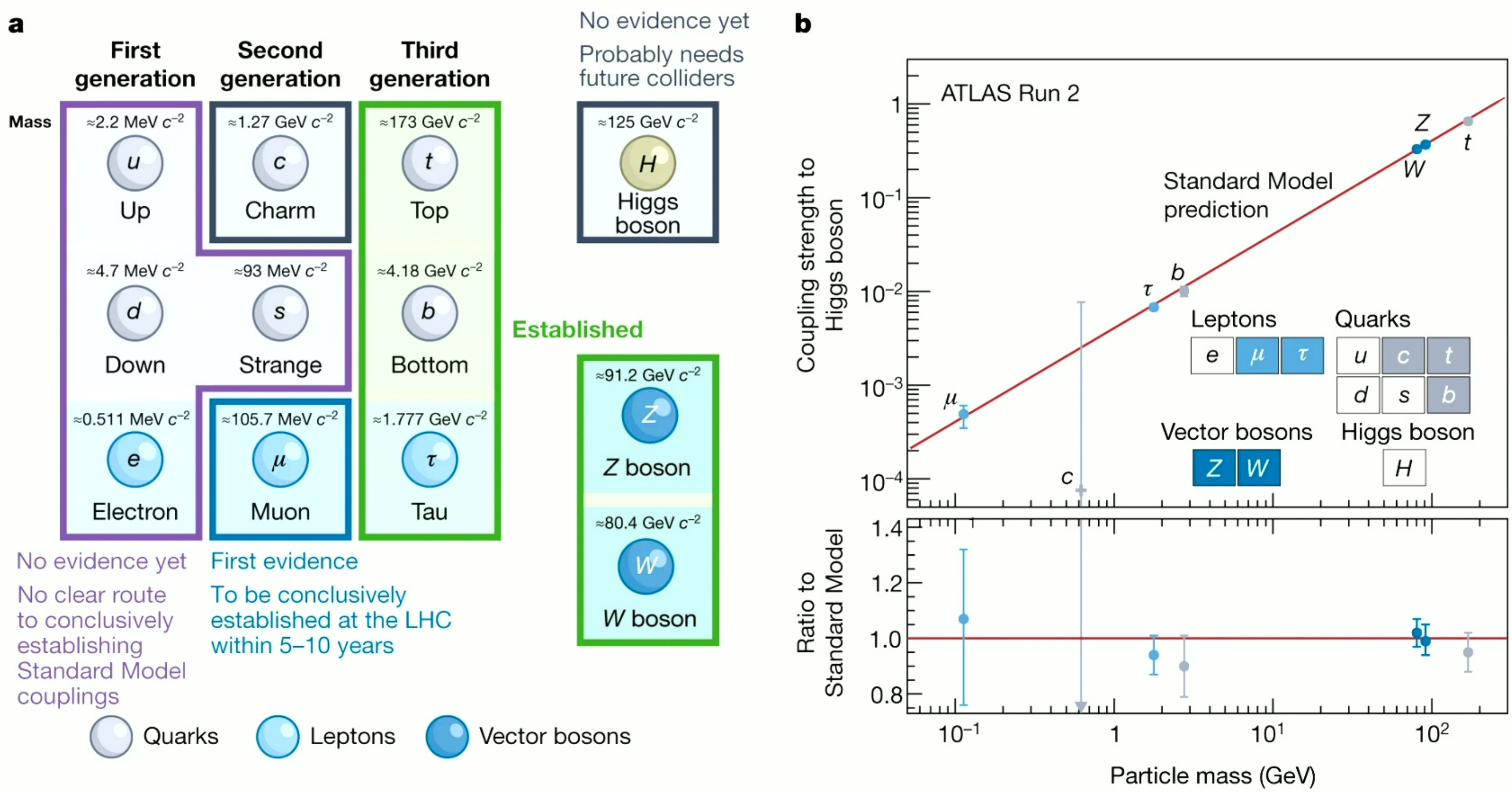




45

Precision Higgs measurements

Nature 607, p41-47 (2022), G. Salam et al.

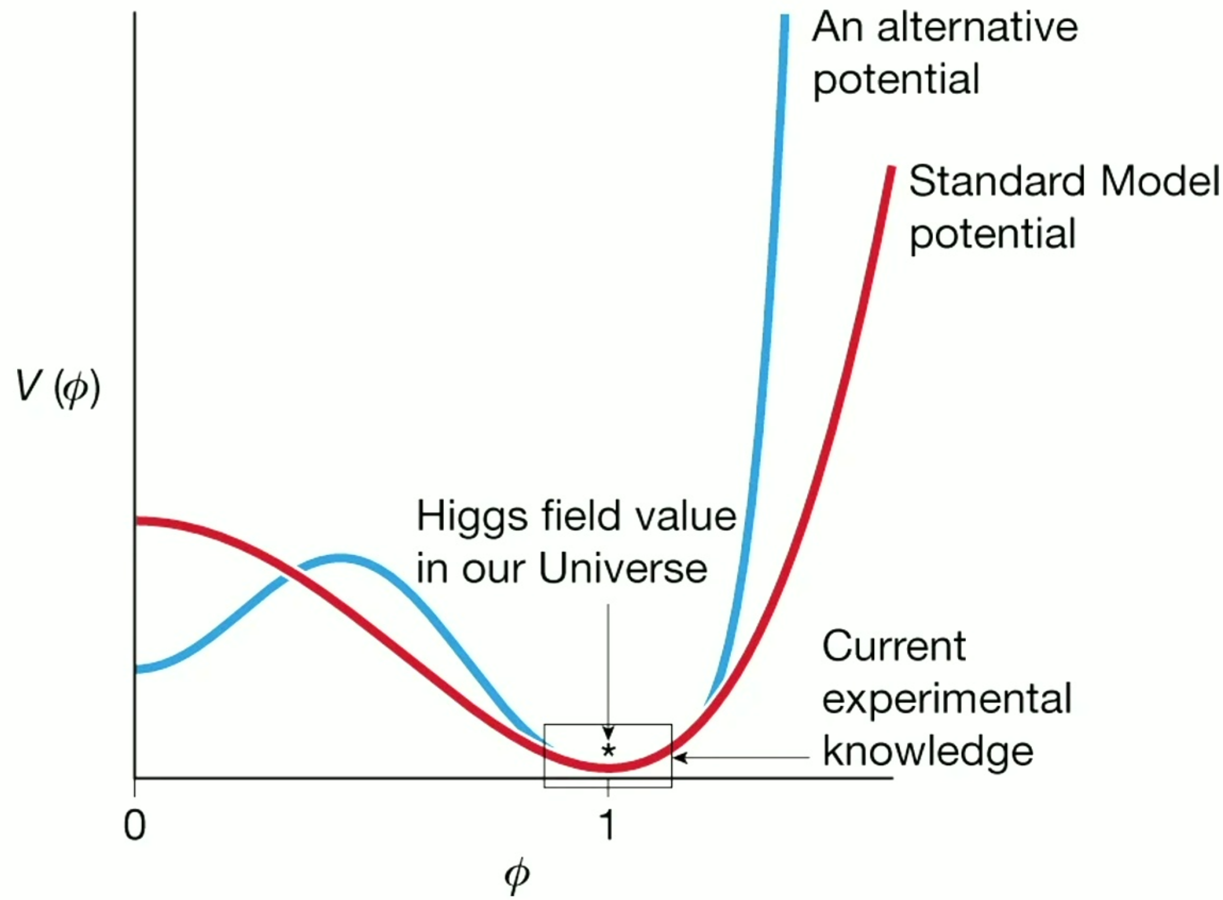


Nature 607, p41-47 (2022), G. Salam et al.

Next step: Higgs self-interaction

Image: Jorge Cham / PhD Comics

Image: Jorge Cham / PhD Comics



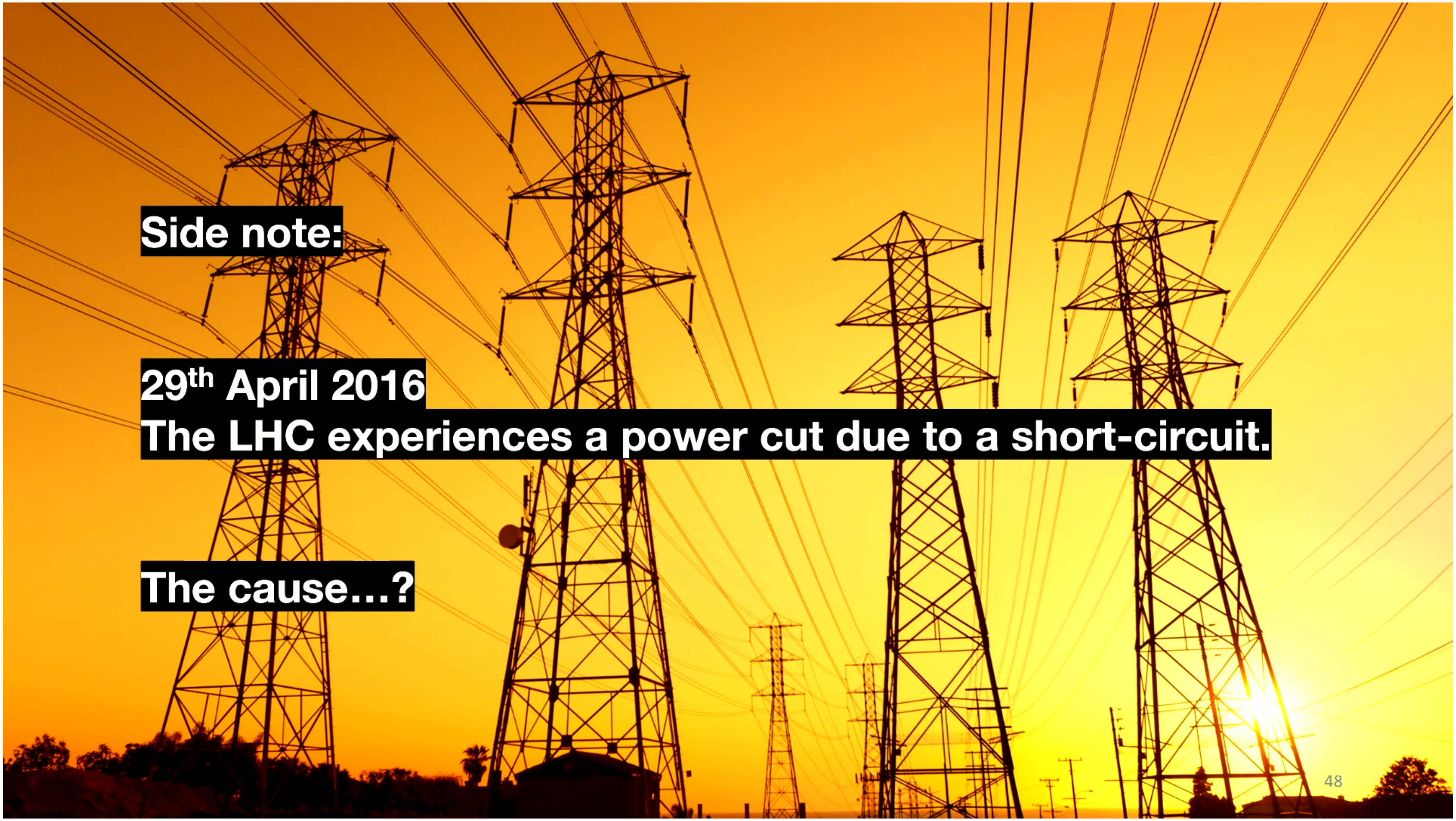

Side note:
29th April 2016
The LHC experiences a power cut due to a short-circuit.
The cause…?
48


Illustration purposes only.

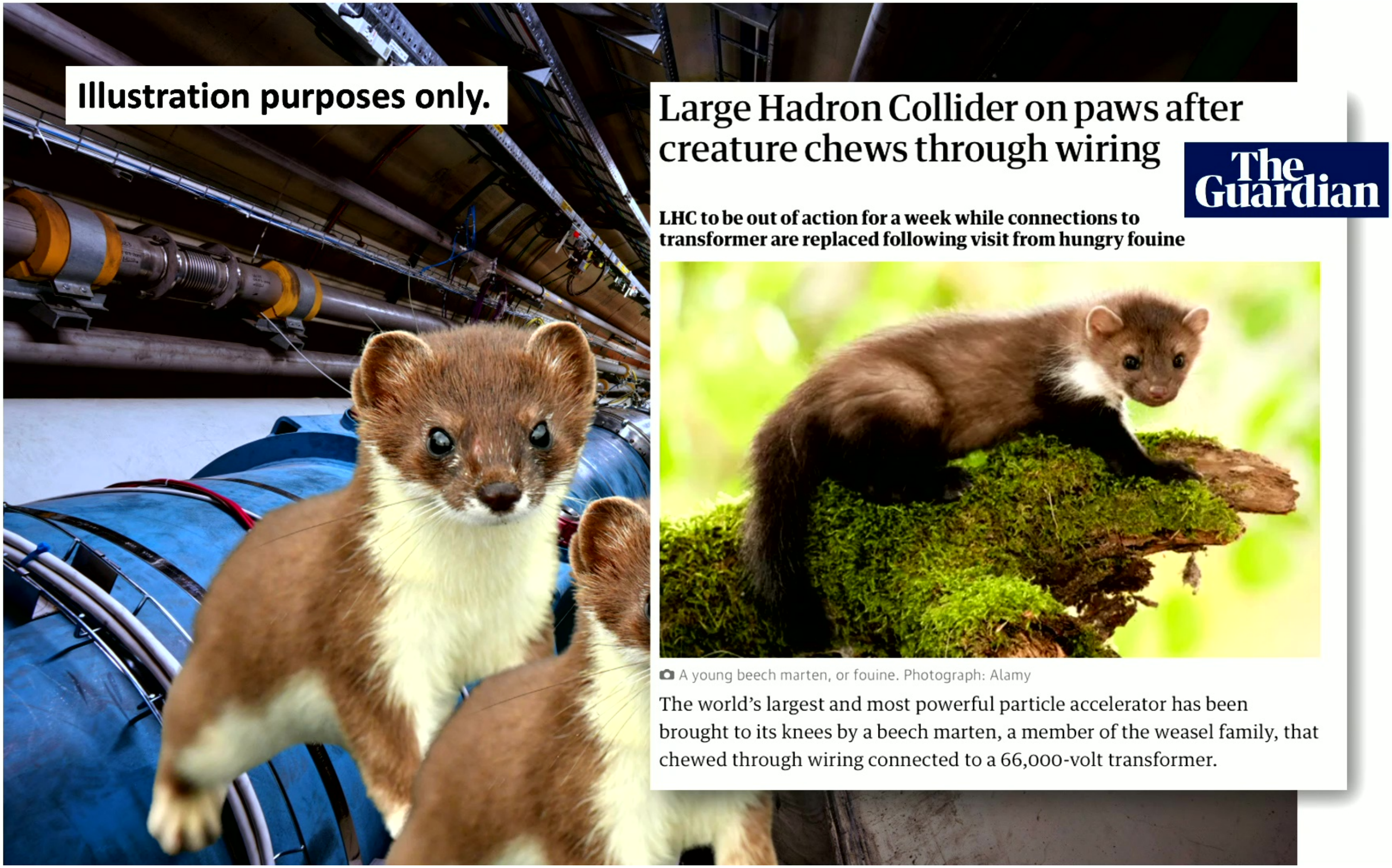
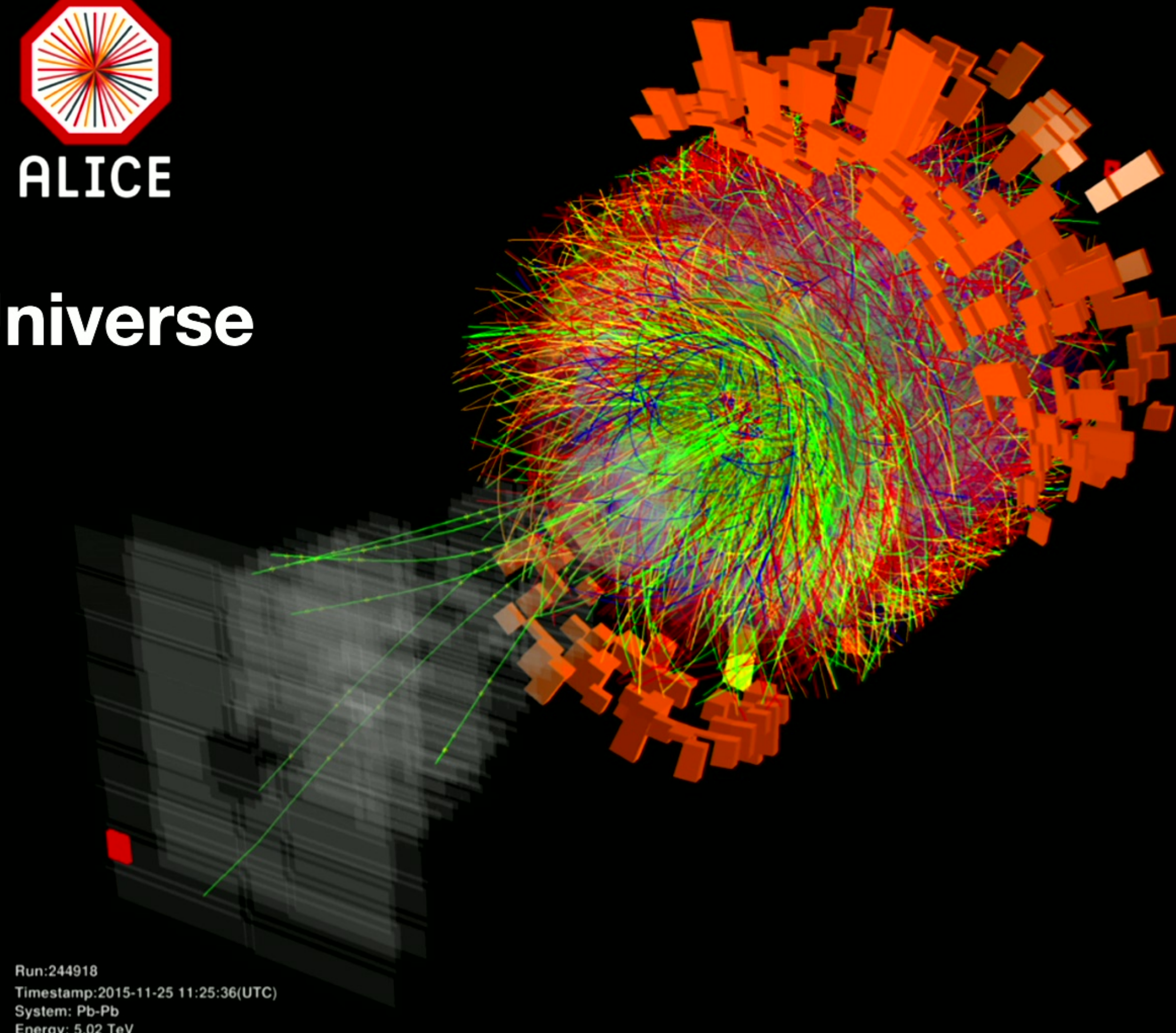


Illustration purposes only.
Large Hadron Collider on paws after creature chews through wiring
The Guardian
LHC to be out of action for a week while connections to transformer are replaced following visit from hungry fouine
A young beech marten, or fouine. Photograph: Alamy
The world's largest and most powerful particle accelerator has been brought to its knees by a beech marten, a member of the weasel family, that chewed through wiring connected to a 66,000-volt transformer.

ALICE

The Very Early Universe

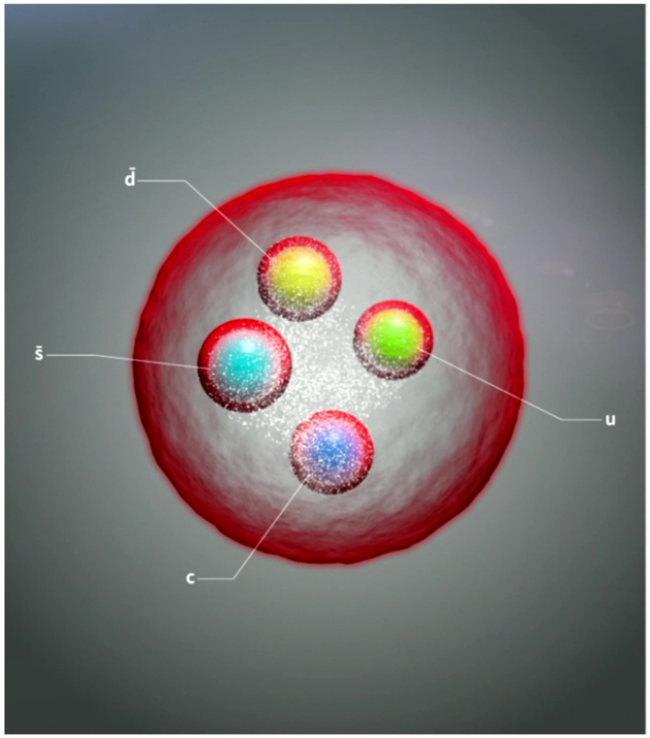
ALICE studies the quark gluon plasma, created in heavy ion collisions, and gives us a better understanding of this special state of matter.

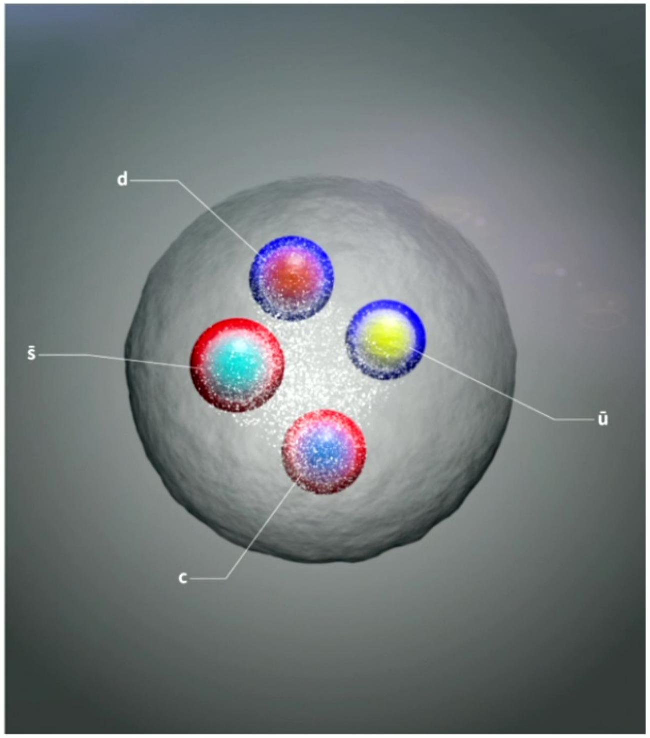


2022

LHCb pentaquarks and tetraquarks

LHC creates many new states, including new (fleeting) exotic forms of matter

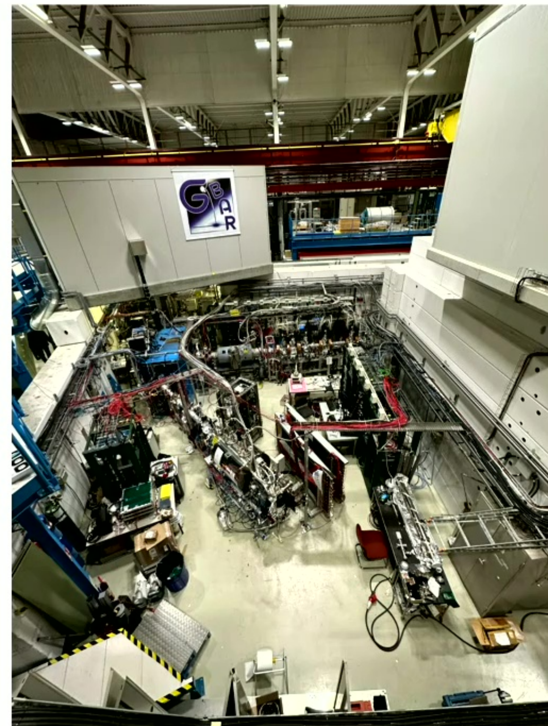




2023

The Antimatter Factory

Create and store antimatter to study its properties

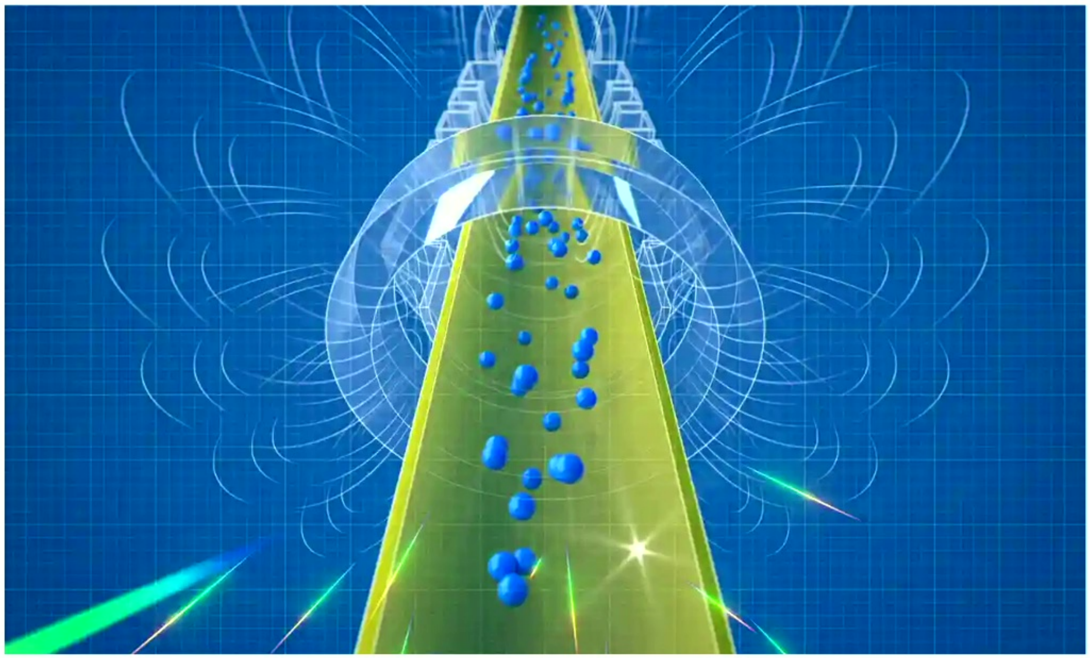


2023

The Antima

Scientists find antimatter is subject to gravity

Tests at Cern refute suggestion that antigravity might apply to antimatter, showing instead it also falls downwards



Scientists have struggled to preserve antimatter long enough to carry out experiments on it. Illustration: US National Science Foundation/AFP/Getty Images

ore antimatter
operties

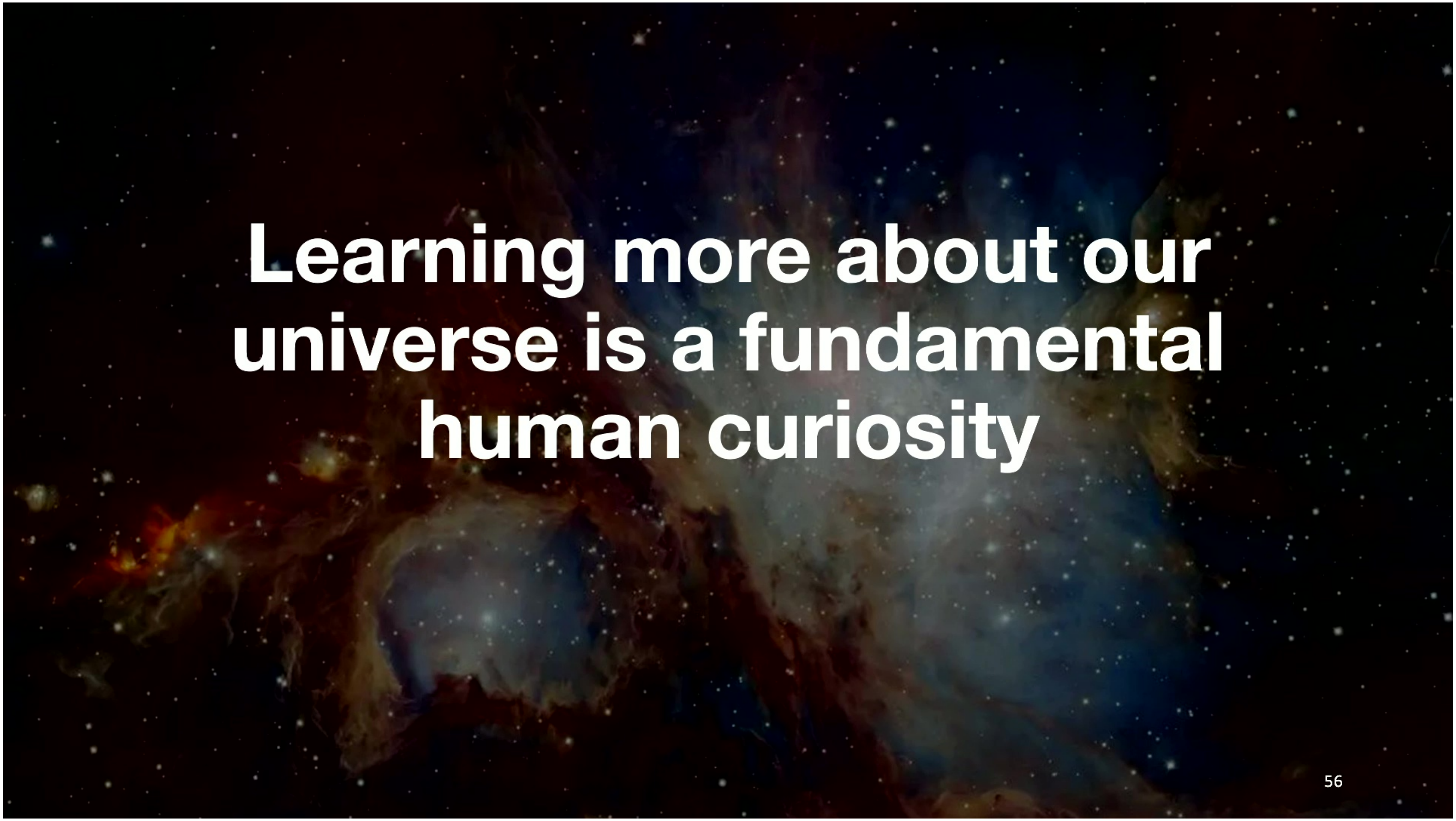
53

2023

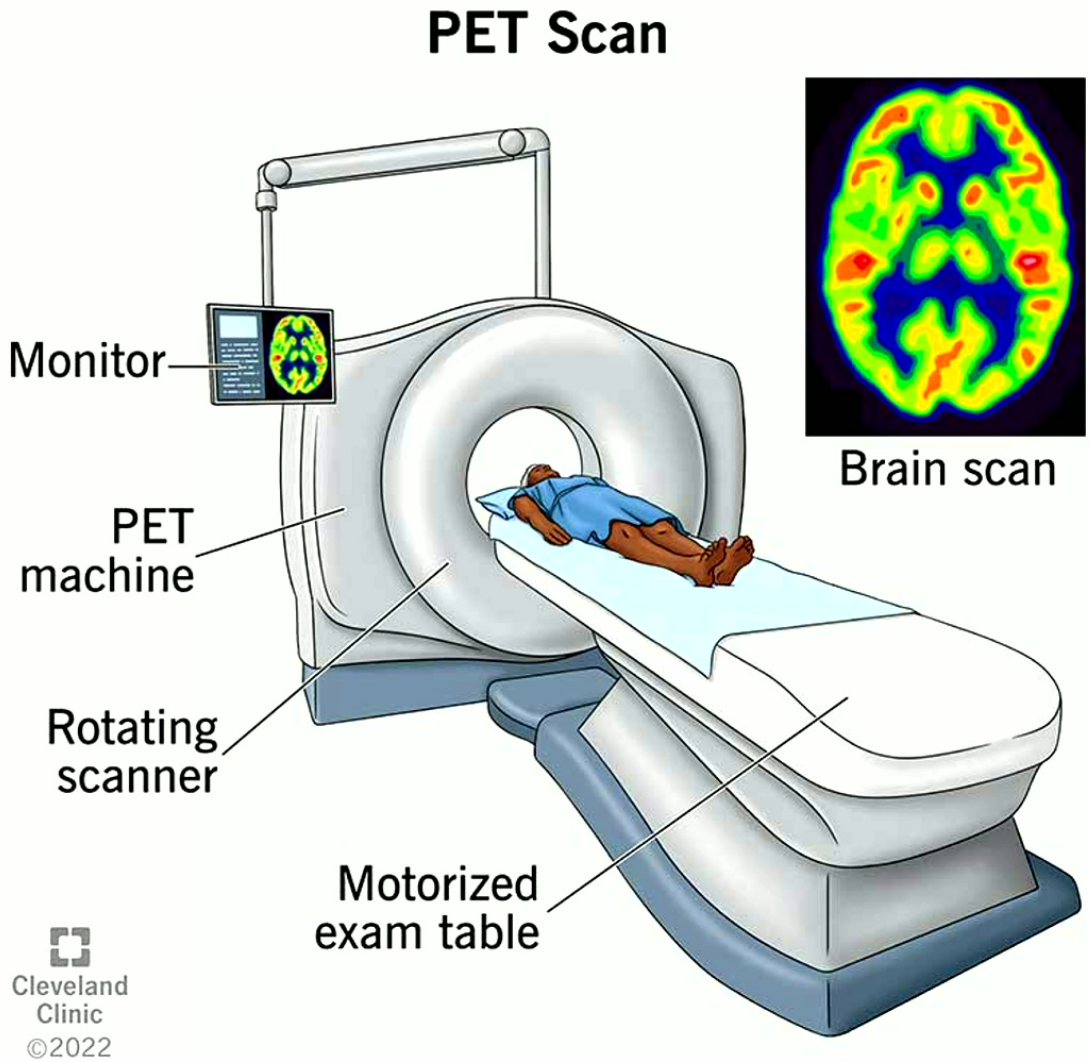
Highest energy observation of quantum entanglement, looking at top quarks in the ATLAS Experiment

54

How does this affect you?


Learning more about our universe is a fundamental human curiosity
56

Doing difficult things gives us better technology that improves our lives and tells us interesting things right now!



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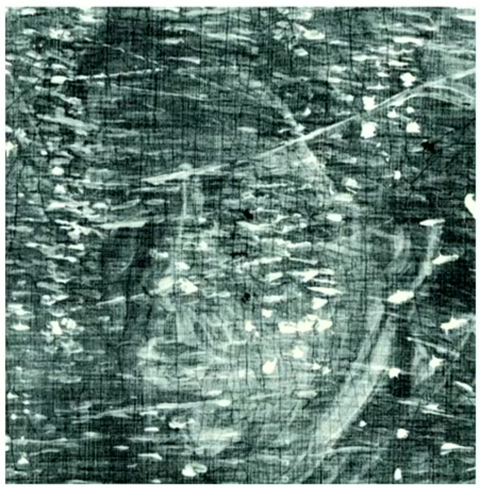
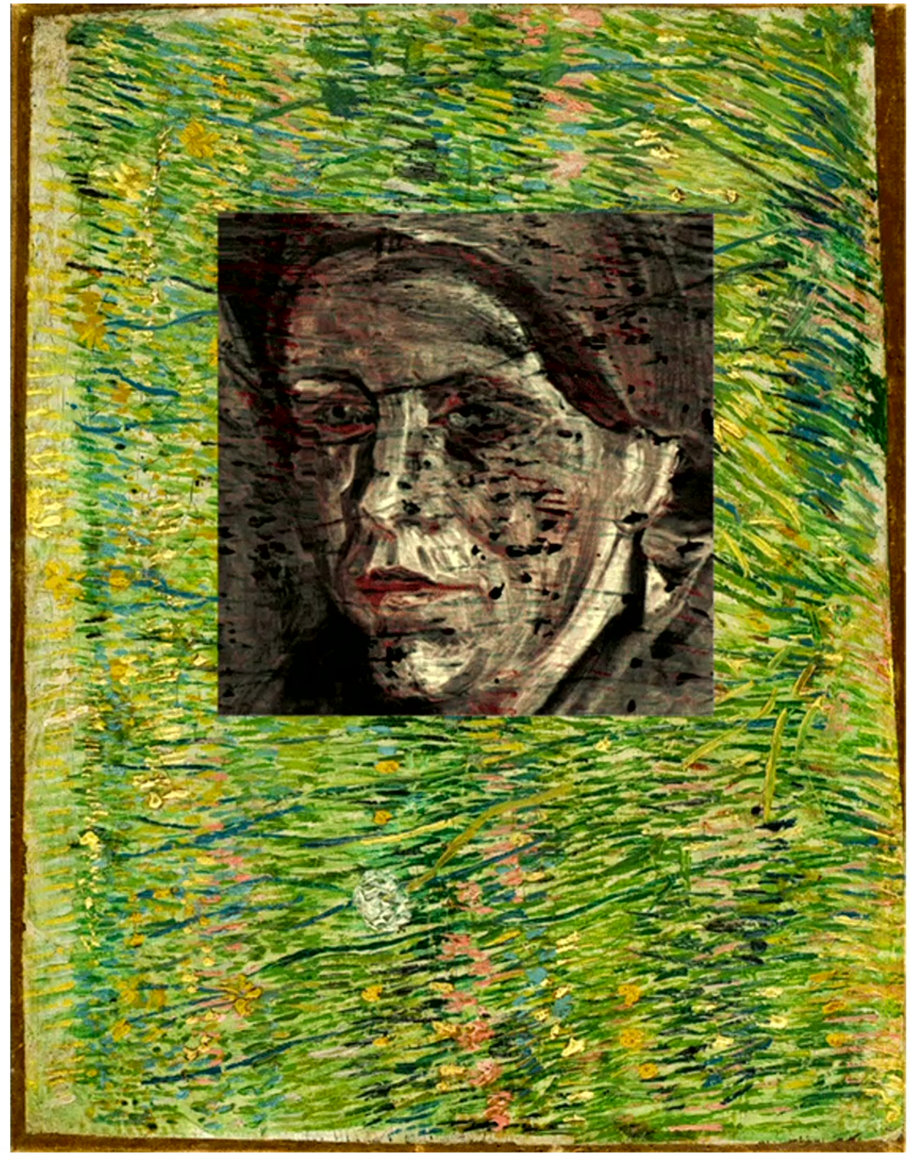
Synchrotron Radiation Based X-ray Fluorescence Elemental Mapping

Synchrotron Radiation Based X-ray Fluorescence Elemental Mapping

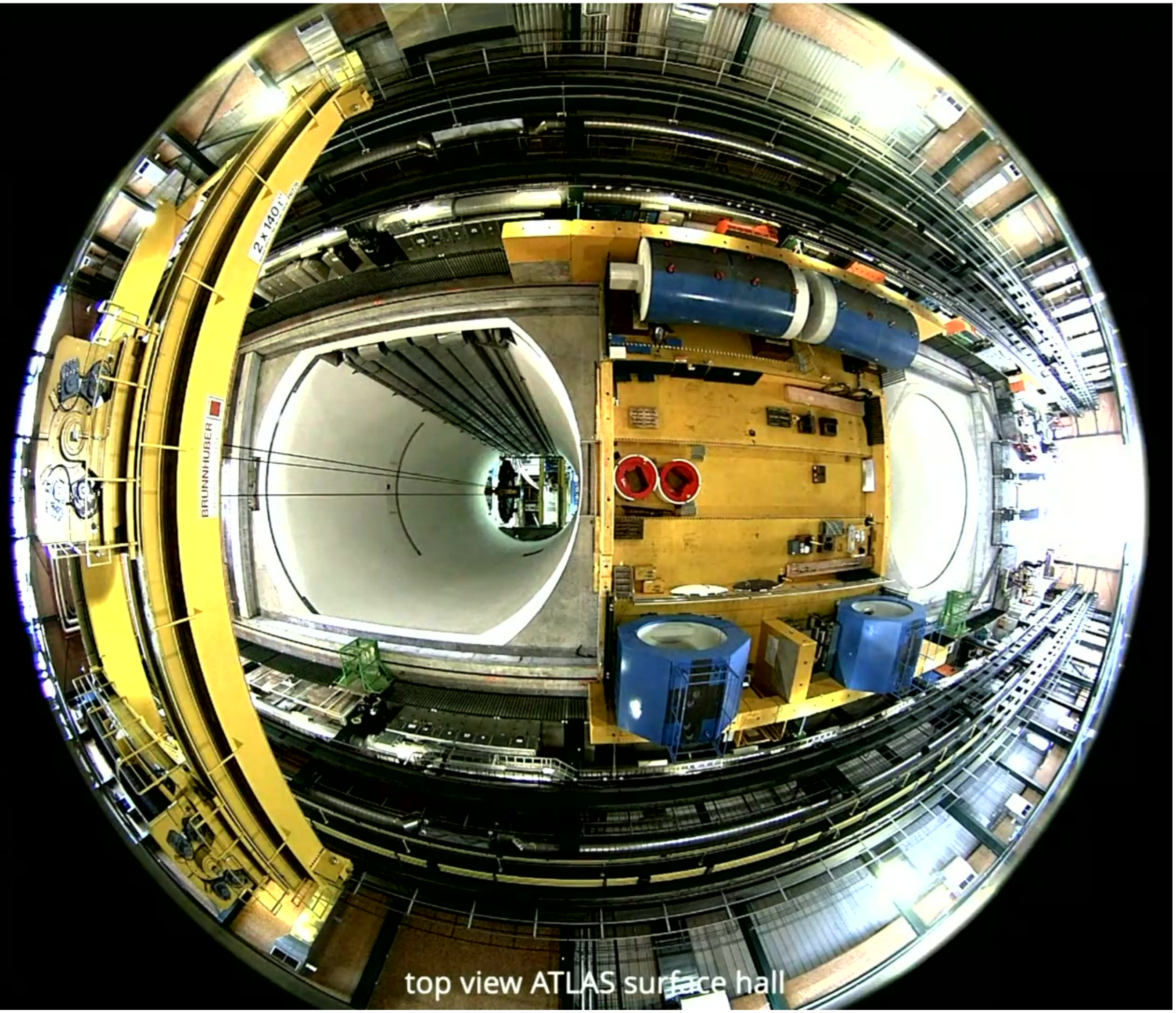


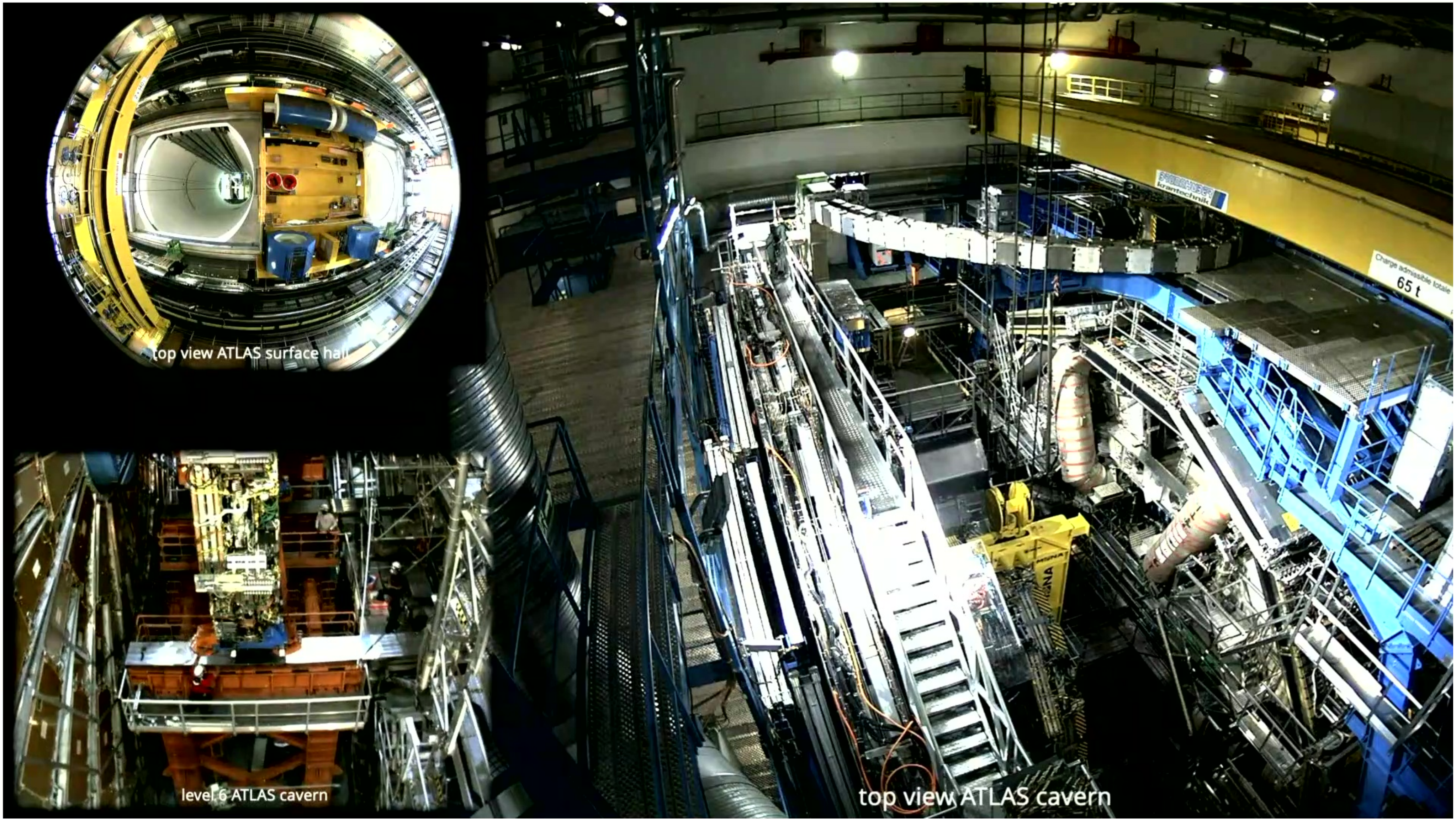


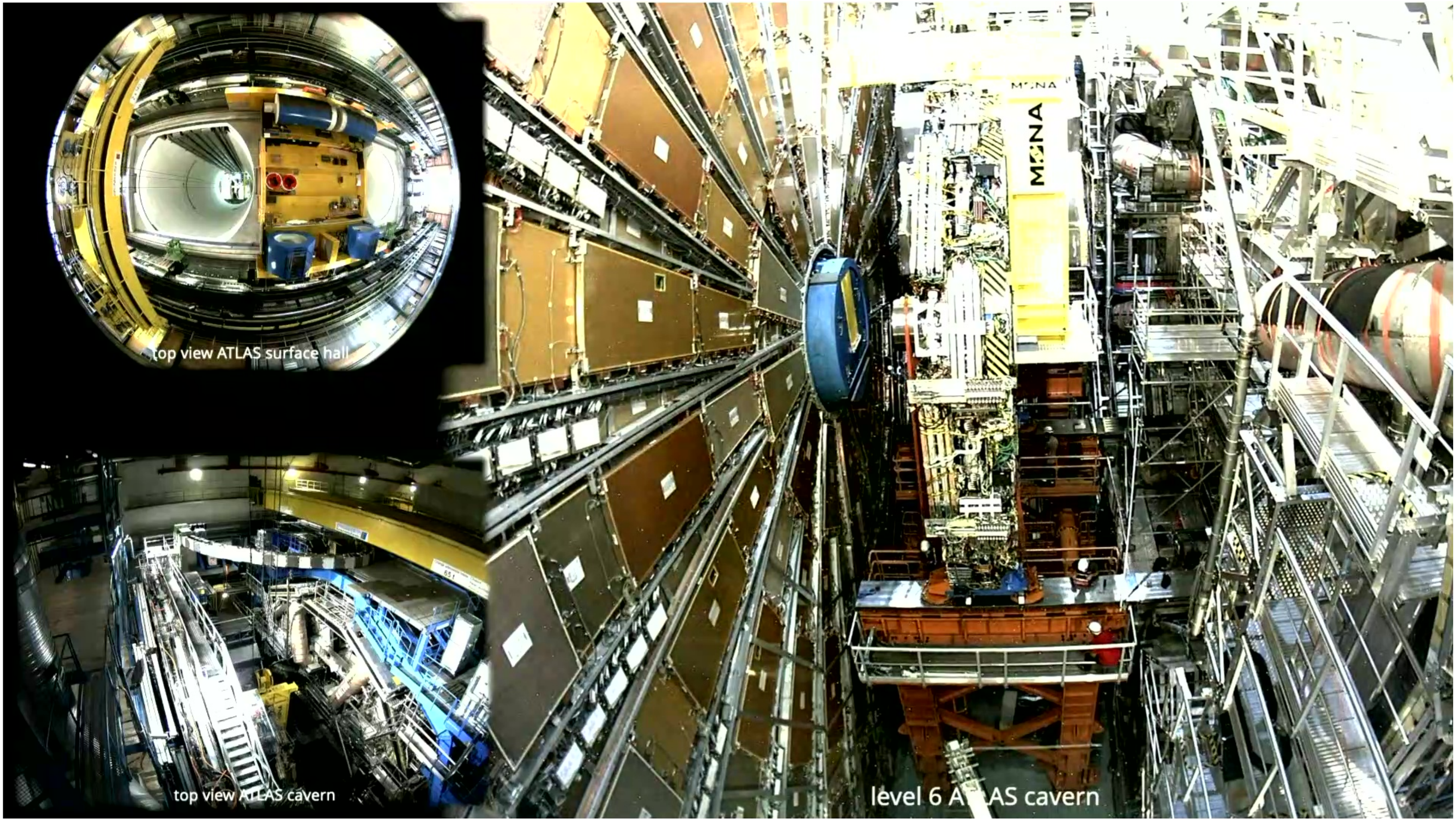
Muon tomography for pyramids

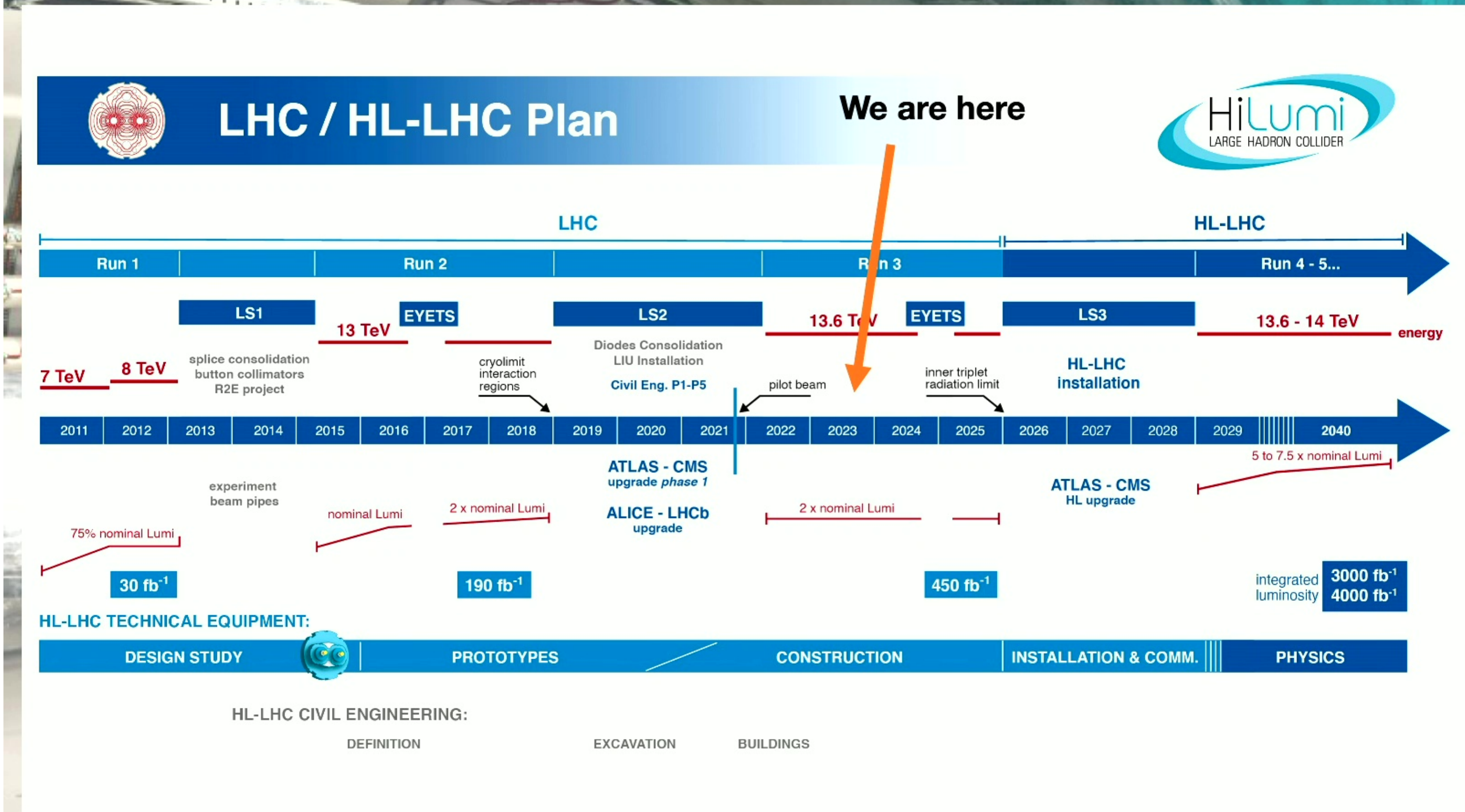

top view ATLAS cavern


level 6 ATLAS cavern


BRUNNHUBER
top view ATLAS surface hall


top view ATLAS surface hall
level 6 ATLAS cavern
top view ATLAS cavern
Charge admissible totale
65 t


top view ATLAS surface hall
top view ATLAS cavern
level 6 A LAS cavern

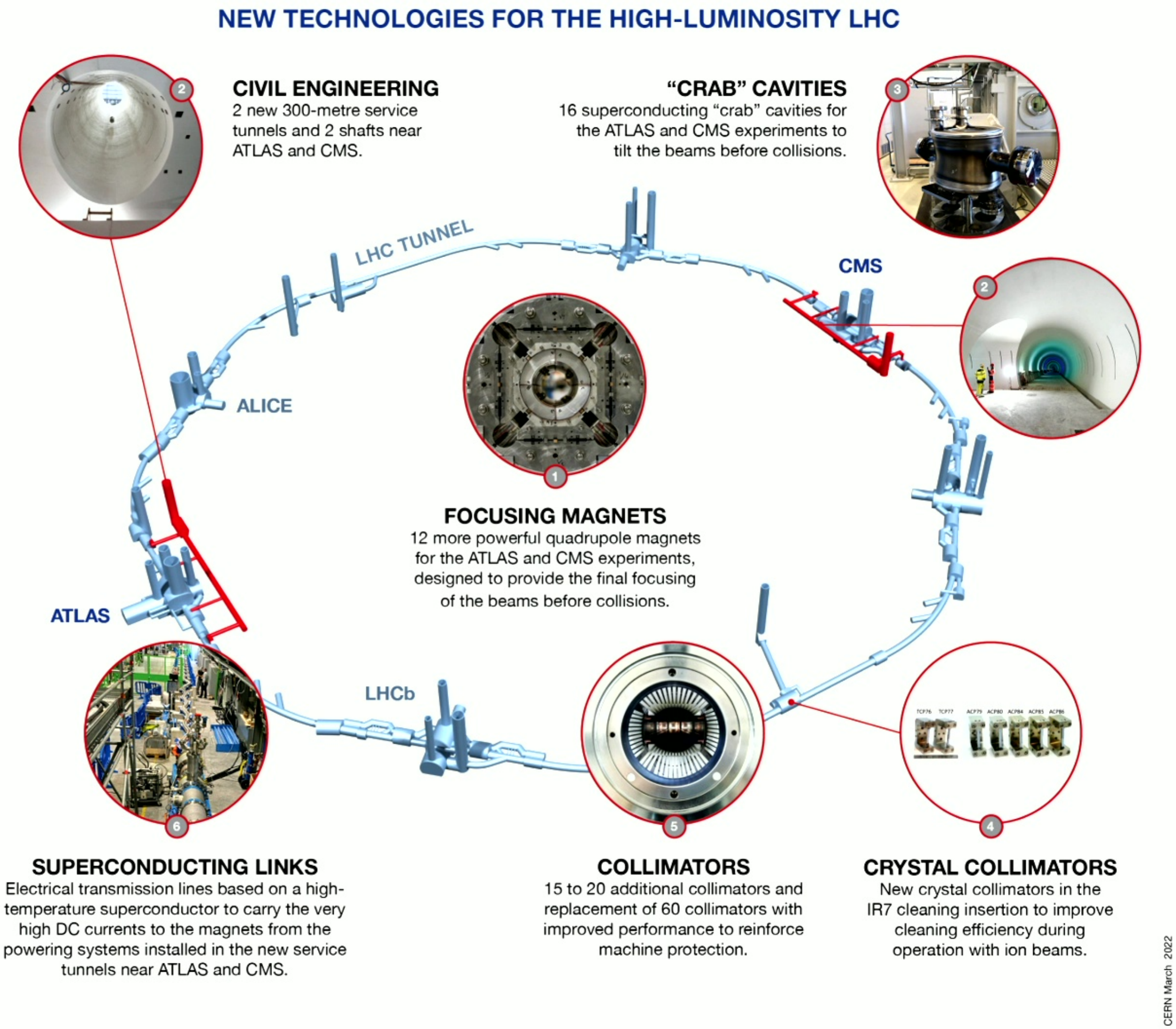


Have only taken ~ 7% of planned data so far

62

2026

A new LHC Towards high luminosity



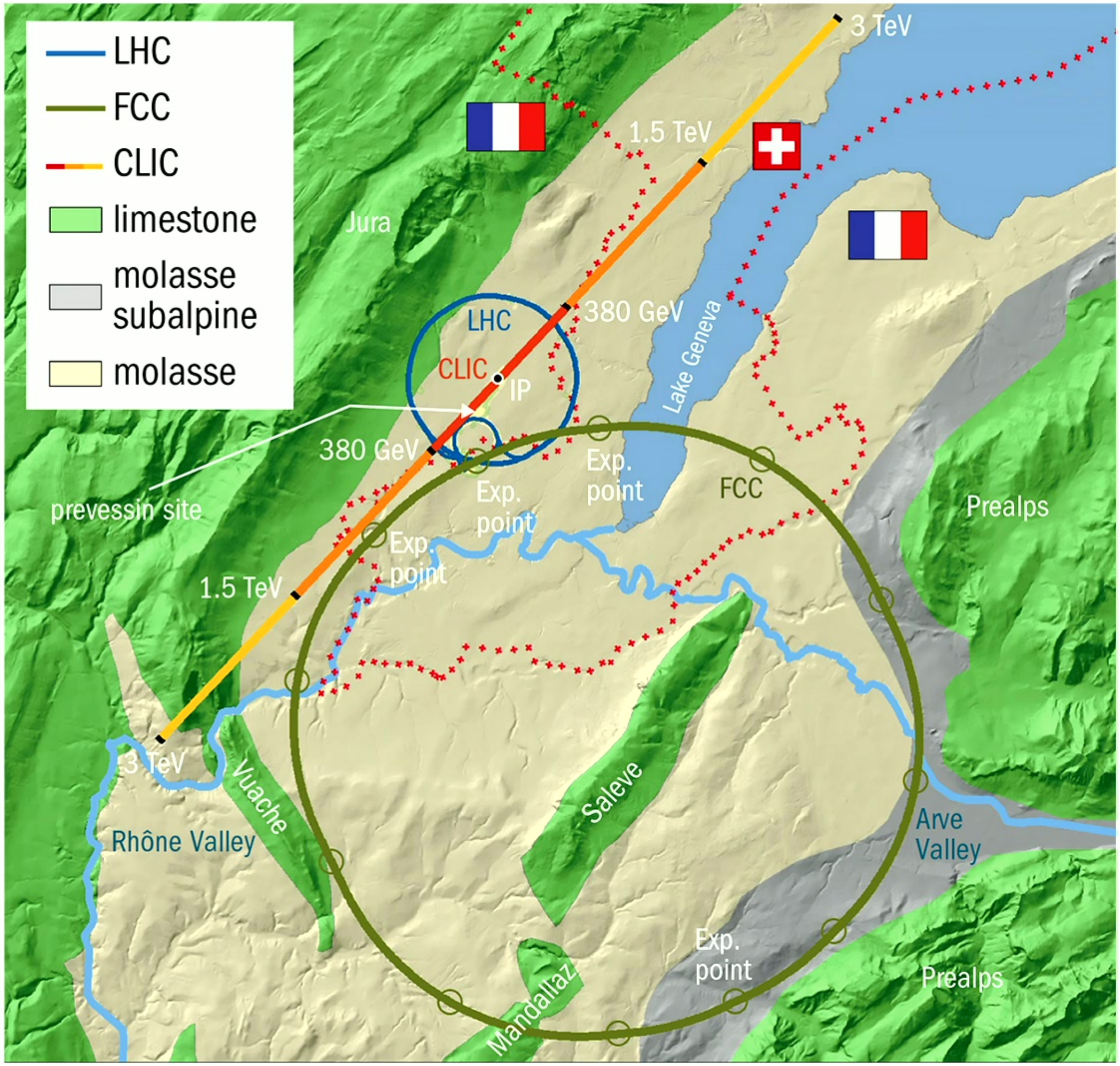
63

2040 and after

The future

What's beyond the HL-LHC?

Linear collider?



Circular collider?

64

2040 and after

The future

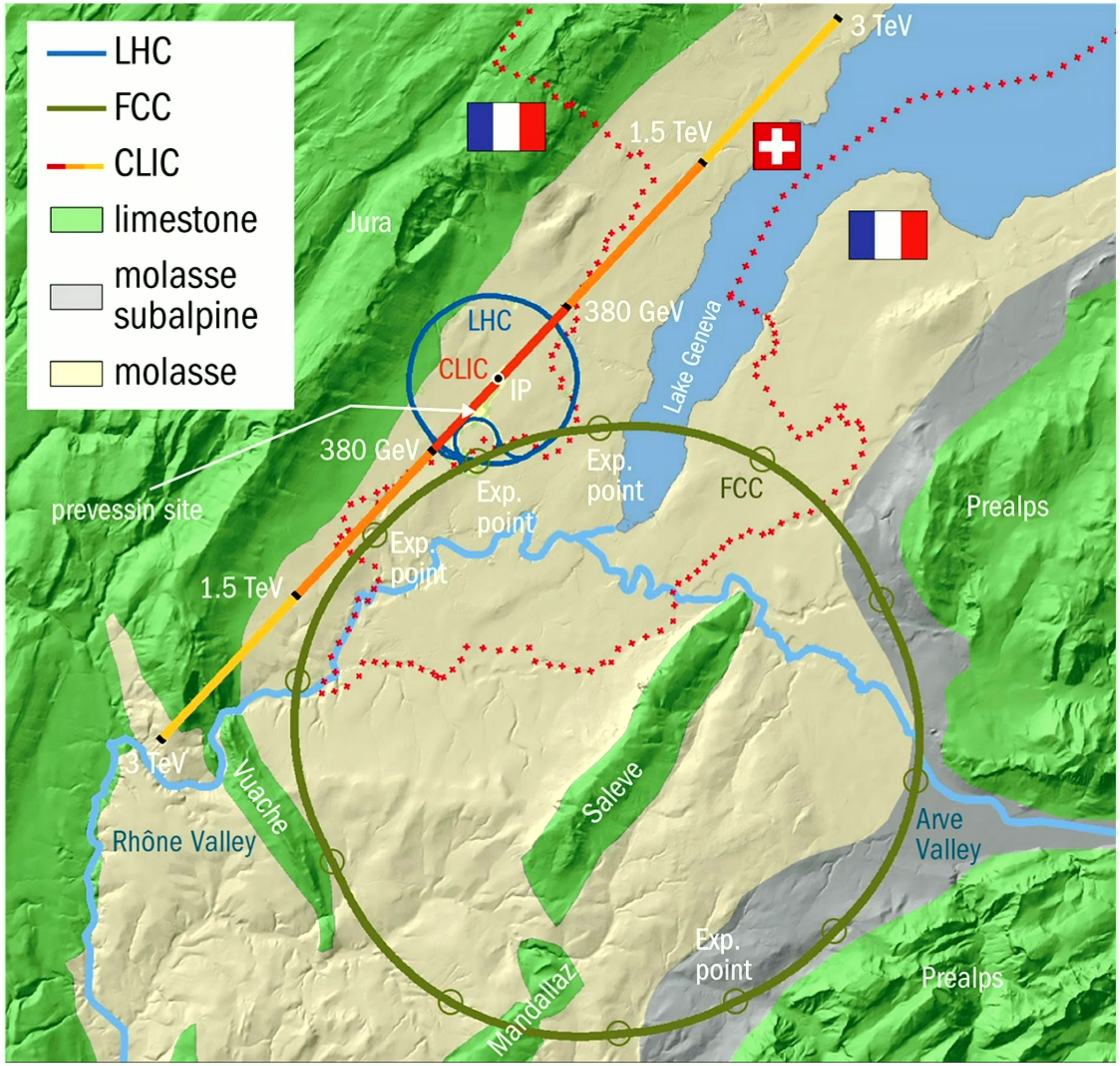
What's beyond the HL-LHC?

For the FCC we need magnets with strength of 16 T

- We don't have this yet
- Need R&D!

Also, muon colliders, plasma wakefield accelerators…

Linear collider?



Circular collider?

thank you!