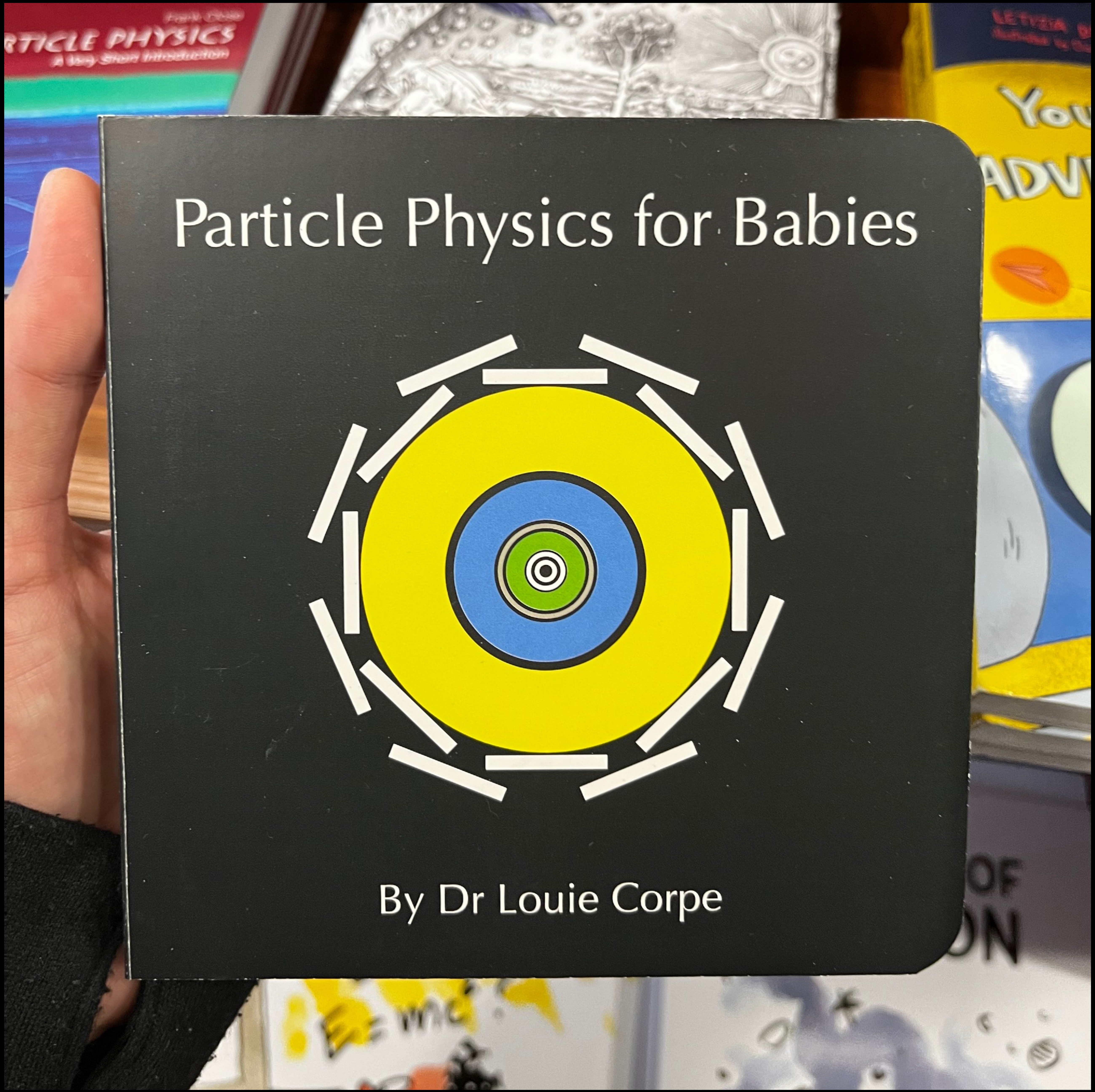


Introduction to CERN and High Energy Particle Physics Programs [Part 2]

N. SRIMANOBHAS,
Chulalongkorn U. (TH), CMS Collaboration
8 Oct 2022, Khon Kaen University

CERN Missions

Research
Seeking and finding answers to questions about the Universe

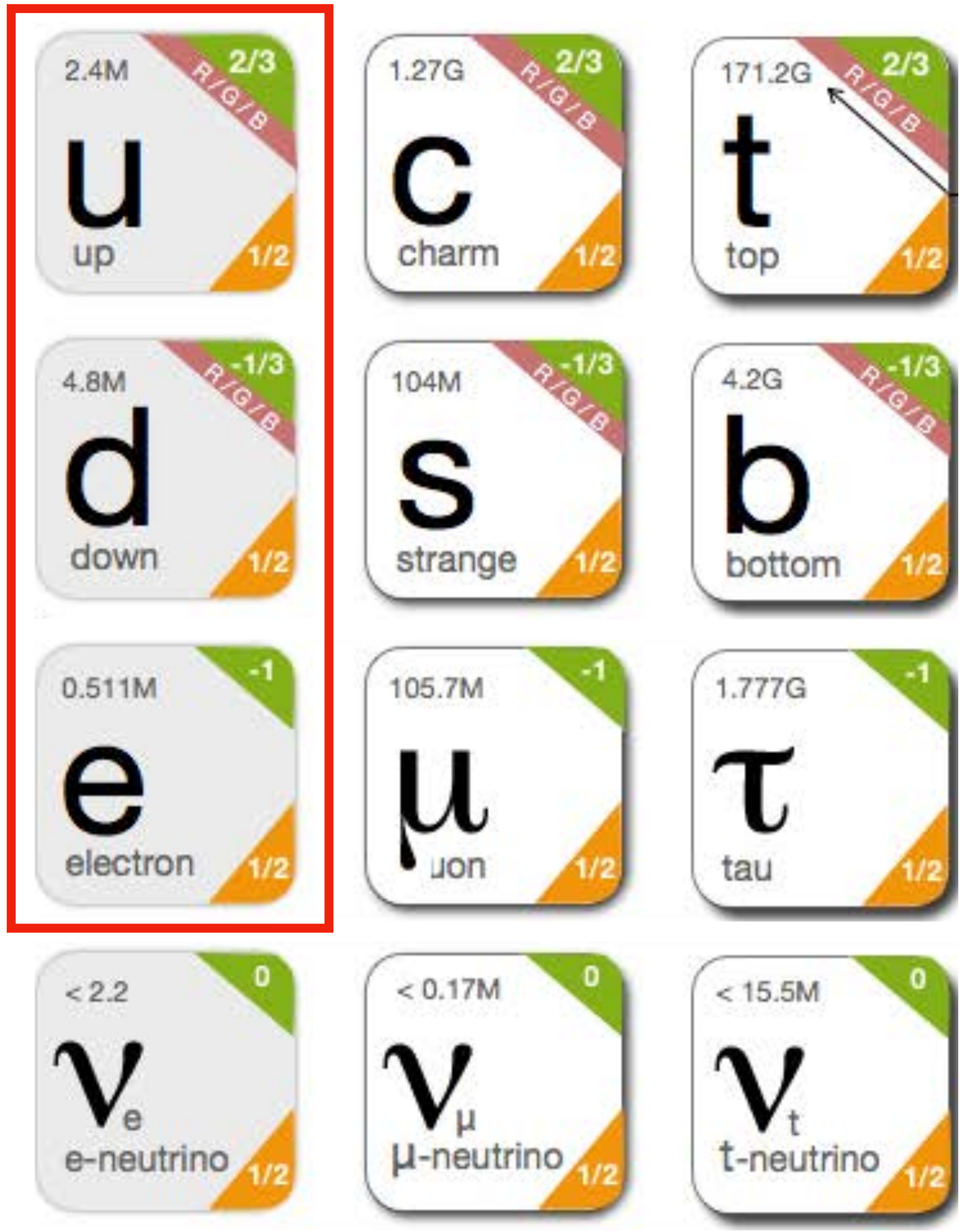
Technology
Advancing the frontiers of technology

Education
Training the scientists of tomorrow

Collaborating
Bringing nations together through science

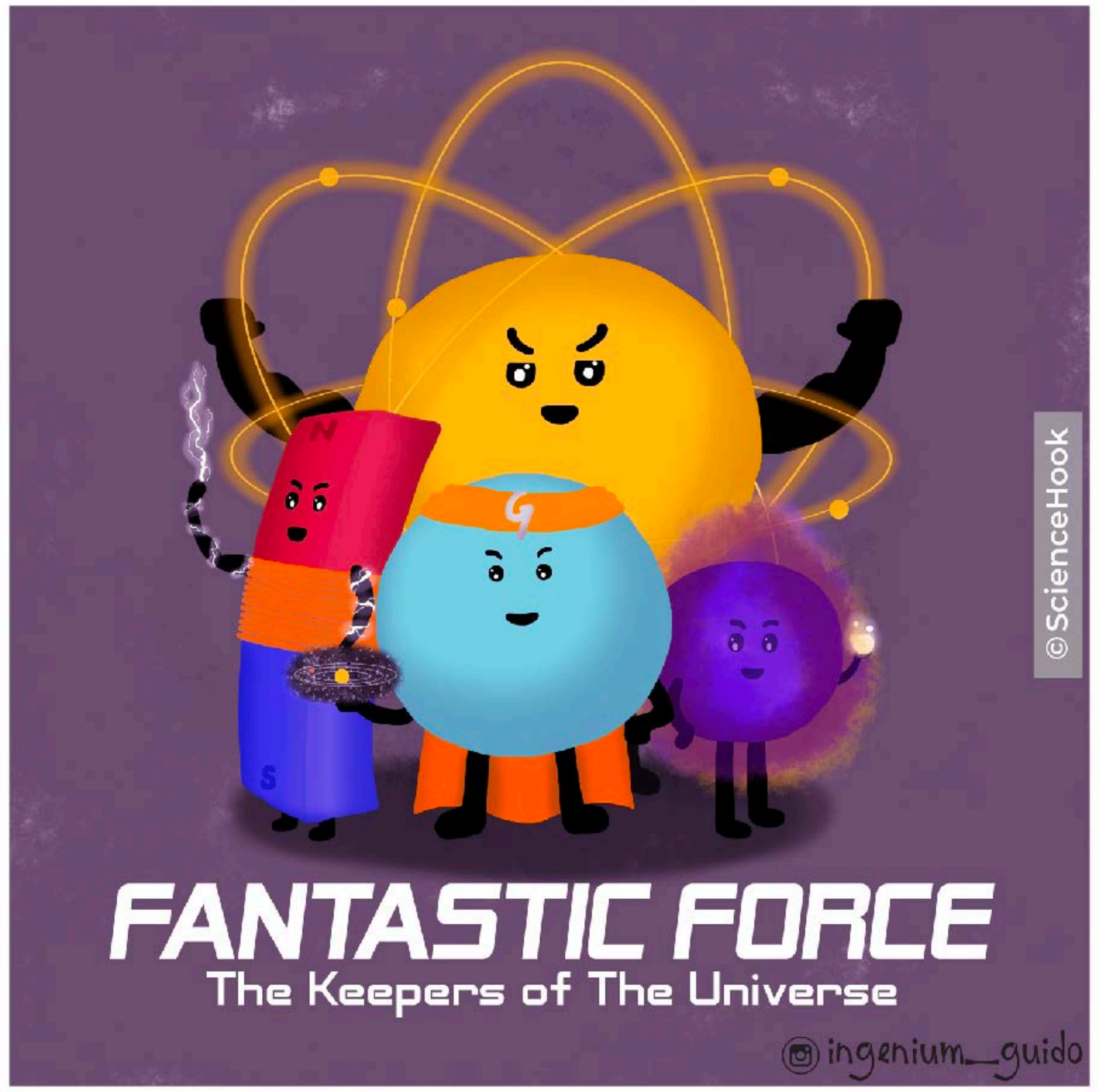
Known universe's ingredients

Known universe's ingredients



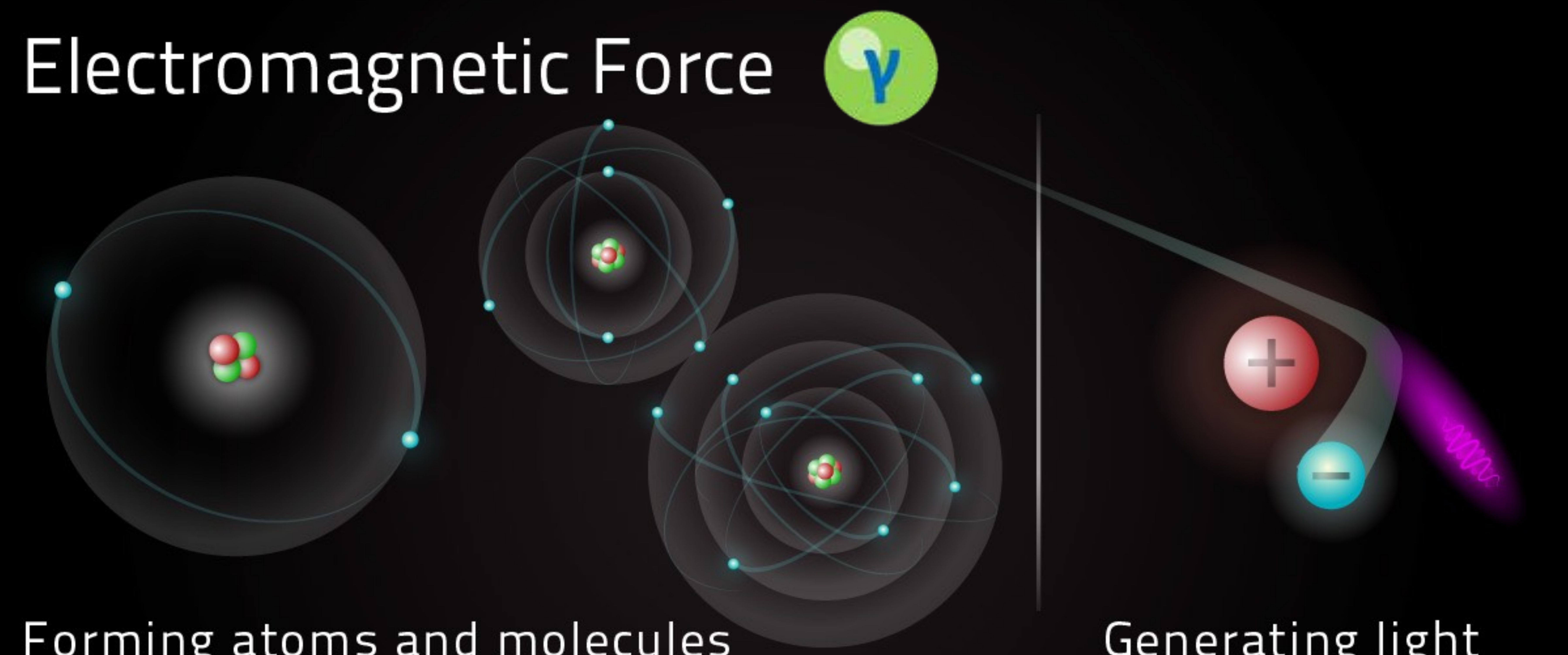
Everything around us (the whole periodic table) is made up of the **first three particles (u-quark, d-quark and electron)**. But somehow nature

- supplies us with two extra families that are very much heavier,
- doesn't allow us to see free quarks (or maybe we don't see it yet),
  - group of 3 quarks: **Baryon** (e.g. proton),
  - quark-antiquark pairs: **Meson** (e.g. pion),
- describes interactions between these particles by **three (out of four) fundamental forces**.



This is so simple, compared to Periodic Table in Chemistry, or Biological taxonomy!

Electromagnetic force



Electromagnetic Force

Forming atoms and molecules

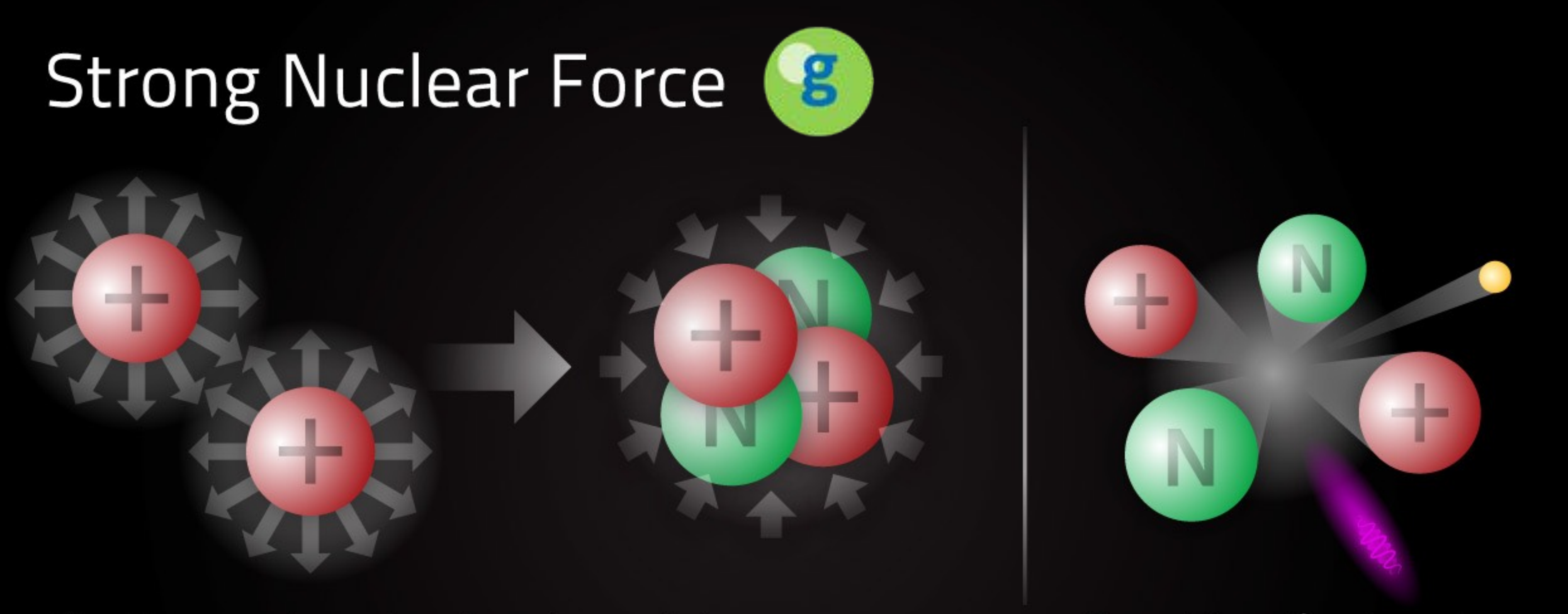
The electromagnetic force pulls negatively charged electrons into bound orbits around positively charged nuclei to form atoms and molecules. As a gas cools, electrons will find their way into the presence of atomic nuclei. Larger nuclei with a greater positve charge pull in more electrons until atoms and molecules have a balance of charges.

Generating light

When a negative electron interacts with a positive proton, the electromagnetic force adds energy to the electron generating a photon.

http://ecuip.lib.uchicago.edu/multiwavelength-astronomy/astrophysics/03.html

Strong nuclear force



Binding protons in atomic nuclei

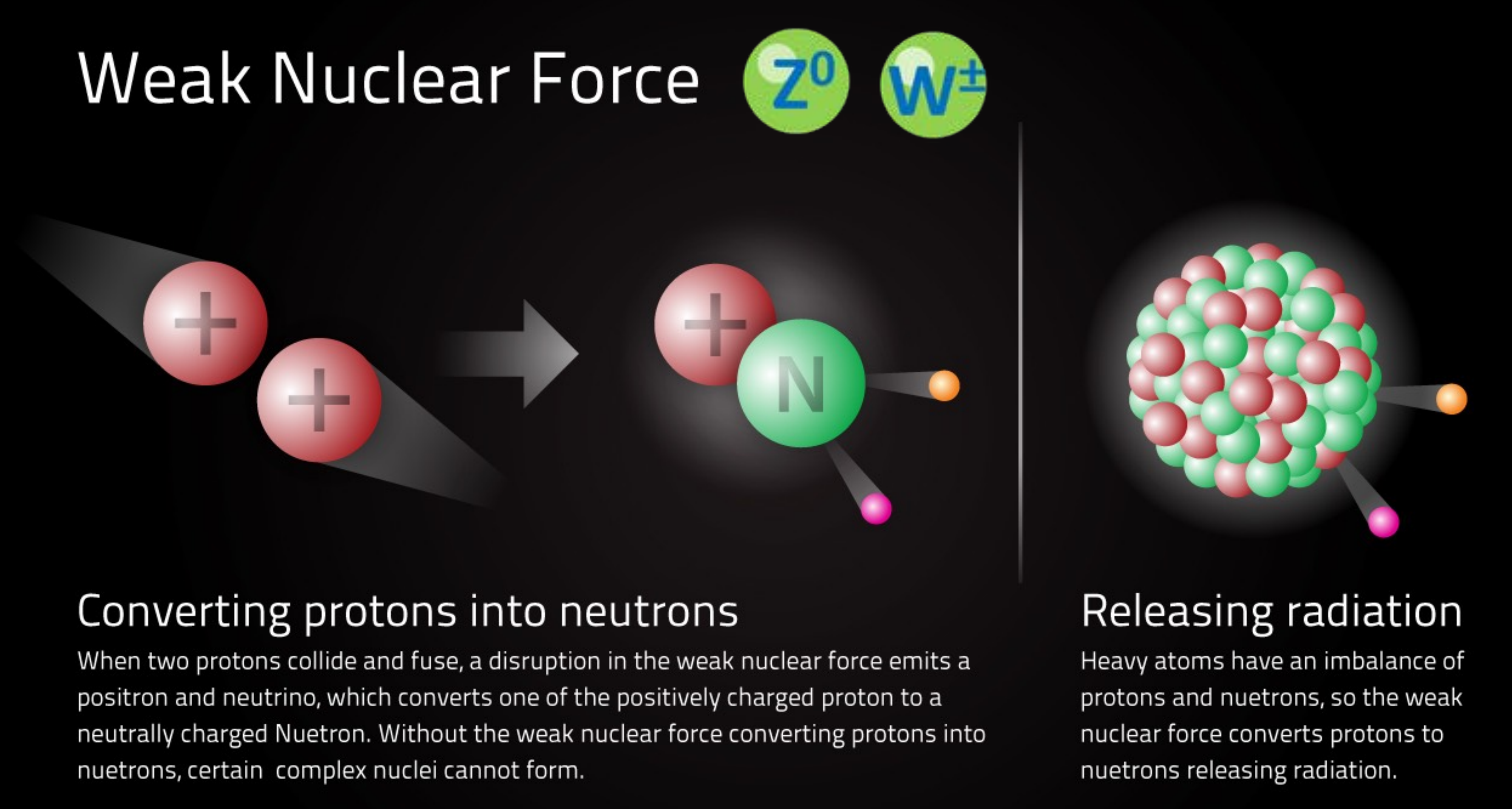
Positively charged particles naturally repel each other, it takes an extreme amount of force to hold protons together. The strong nuclear force overcomes the repulsion between protons to hold together atomic nuclei. Without the strong nuclear force, complex nuclei cannot form.

Breaking the bond

Enormous energy is released as gamma rays and nuetrinos when the strong nuclear force is broken between protons and neutrons.

http://ecuip.lib.uchicago.edu/multiwavelength-astronomy/astrophysics/03.html

Weak nuclear force



Weak Nuclear Force Z^0 $W^\pm$

Converting protons into neutrons

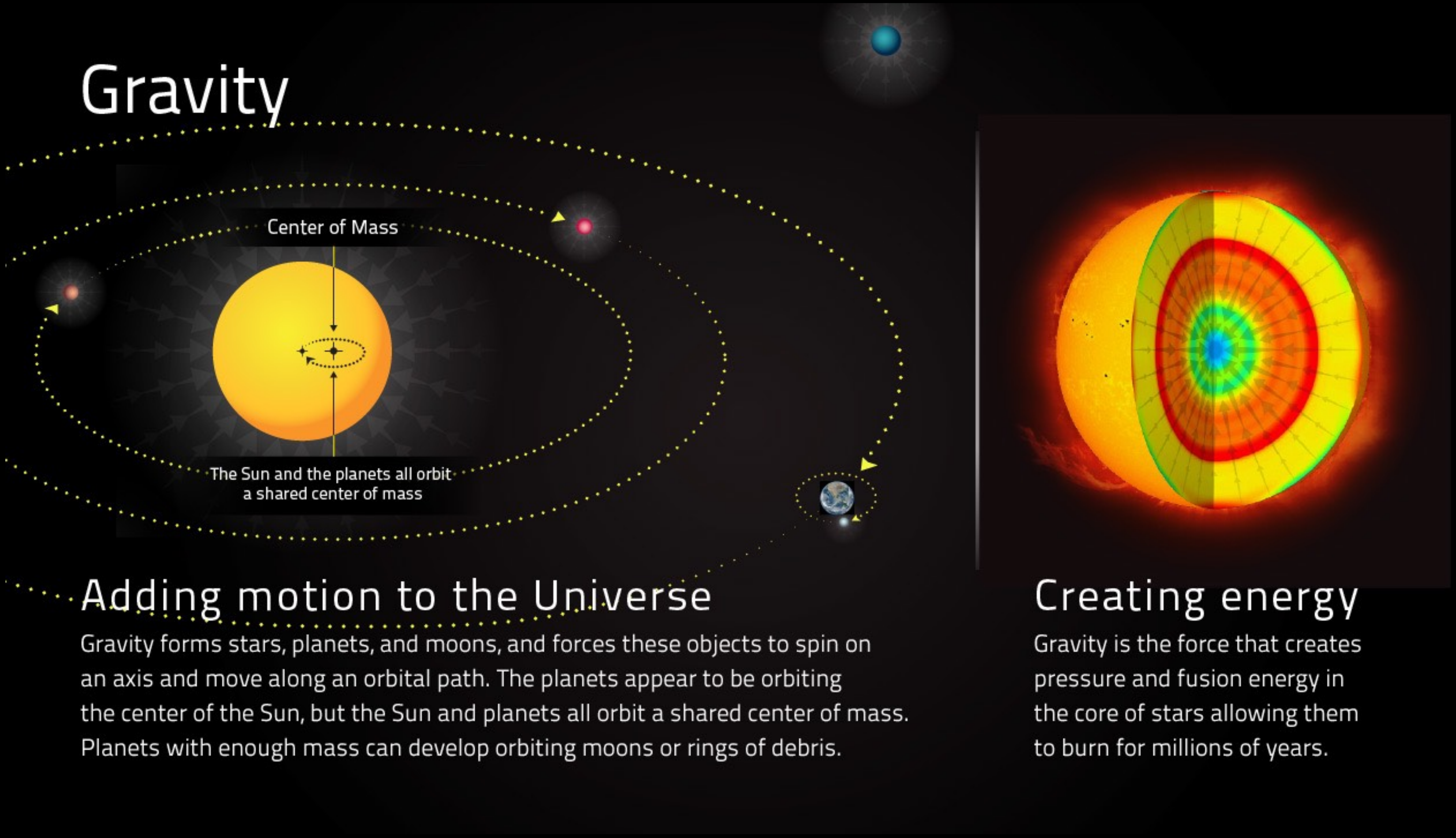
When two protons collide and fuse, a disruption in the weak nuclear force emits a positron and neutrino, which converts one of the positively charged proton to a neutrally charged Nuetron. Without the weak nuclear force converting protons into nuetrons, certain complex nuclei cannot form.

Releasing radiation

Heavy atoms have an imbalance of protons and nuetrons, so the weak nuclear force converts protons to nuetrons releasing radiation.

http://ecuip.lib.uchicago.edu/multiwavelength-astronomy/astrophysics/03.html

Gravity



Gravity

Adding motion to the Universe

Gravity forms stars, planets, and moons, and forces these objects to spin on an axis and move along an orbital path. The planets appear to be orbiting the center of the Sun, but the Sun and planets all orbit a shared center of mass. Planets with enough mass can develop orbiting moons or rings of debris.

Creating energy

Gravity is the force that creates pressure and fusion energy in the core of stars allowing them to burn for millions of years.

http://ecuip.lib.uchicago.edu/multiwavelength-astronomy/astrophysics/03.html

Goals of today high energy particle physics

The SM is one of the most successful models in physics, but *is it enough?*

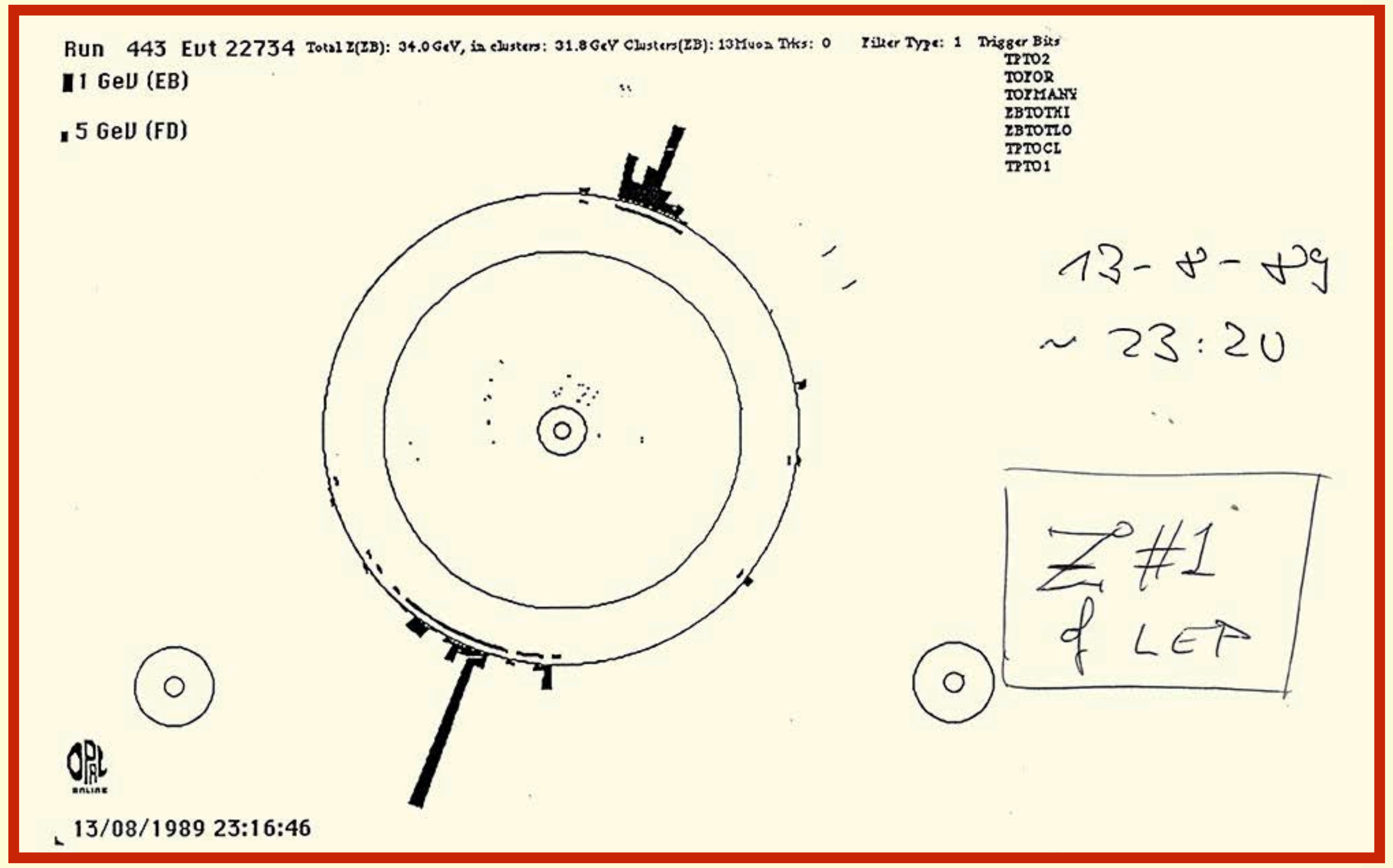
- **SM tells you how, but not why:**
  - Families – 3 families of quark/lepton
  - Number of parameters – 19 free parameters
- **Some phenomenon not explained by the SM:**
  - Gravity – not explained, why so weak?, SM incompatible with general relativity
  - Dark Matter & Dark Energy – accounts for 95% mass of universe but not included in SM
  - Matter/anti-matter asymmetry – SM does not explain the amount of matter/ anti-matter asymmetry at Big Bang

Accelerator is our tool to find answers

Electron mass = 0.511 MeV/c^2

Z-boson mass = 91.18 GeV/c^2

How does very small particle collision create heavy particle?



Run 443 Evt 22734 Total E(EB): 34.0GeV, in clusters: 31.8GeV Clusters(EB): 13Muon Trks: 0 Filter Type: 1 Trigger Bits
TPTO2
TOFOR
TOFMANY
EBTOTHI
EBTOTLO
TPTOCL
TPTO1

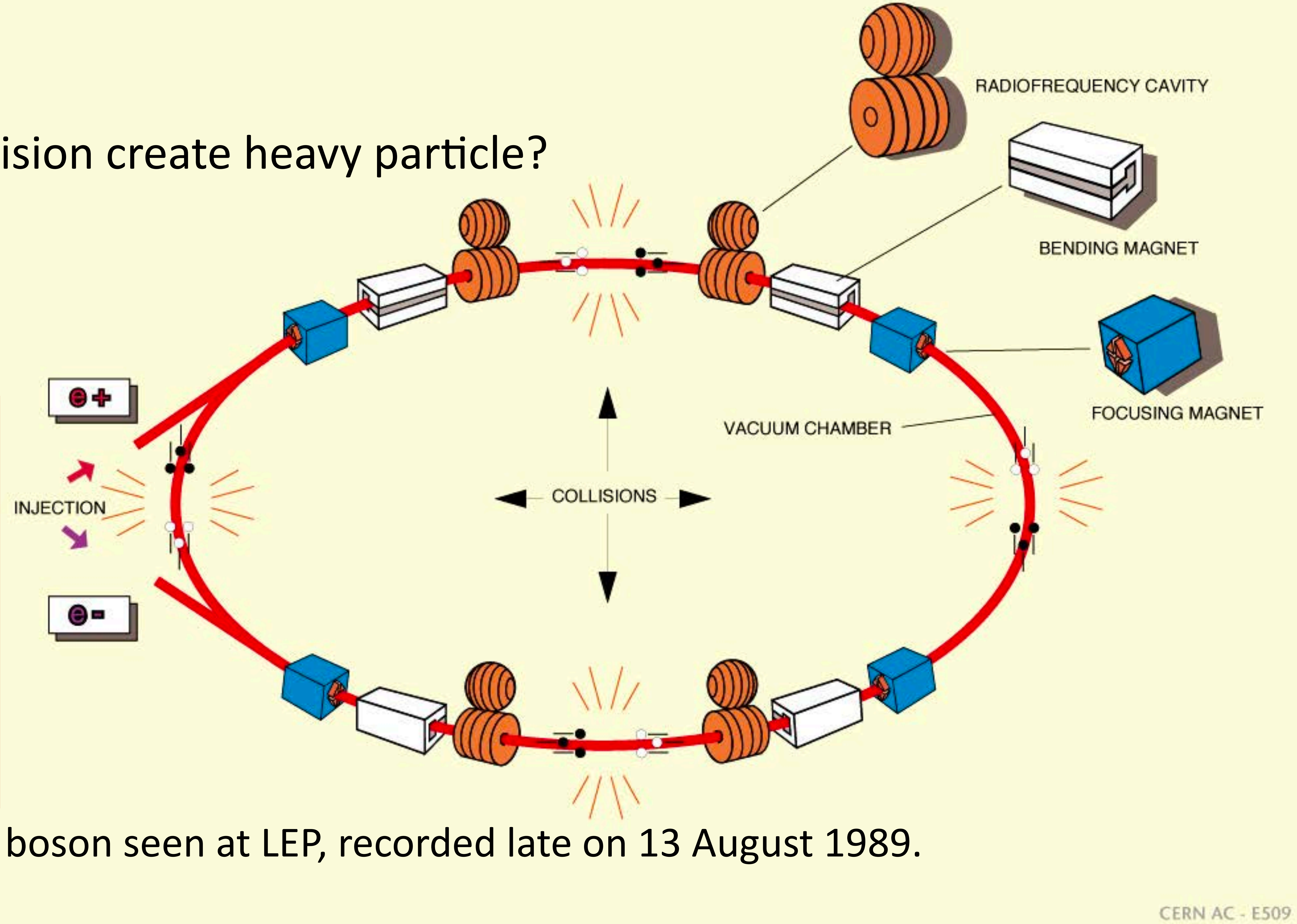
1 GeV (EB)

5 GeV (FD)

13-8-89
~ 23:20

Z #1
of LEP

13/08/1989 23:16:46



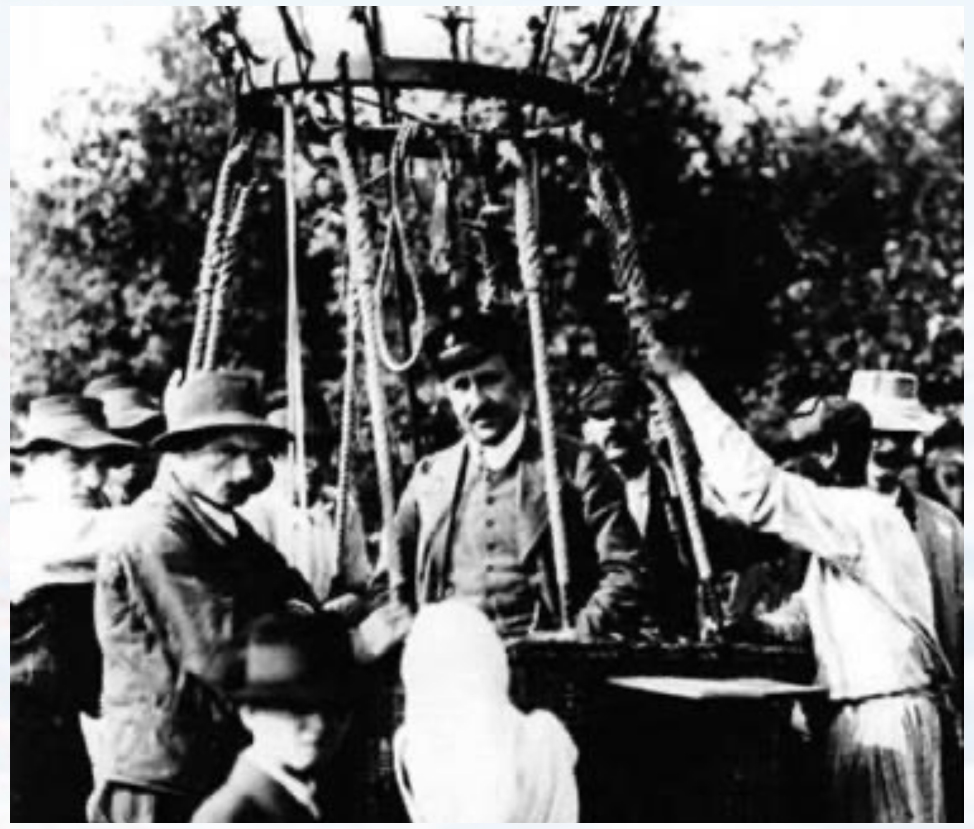
The OPAL logbook entry for the first Z boson seen at LEP, recorded late on 13 August 1989.

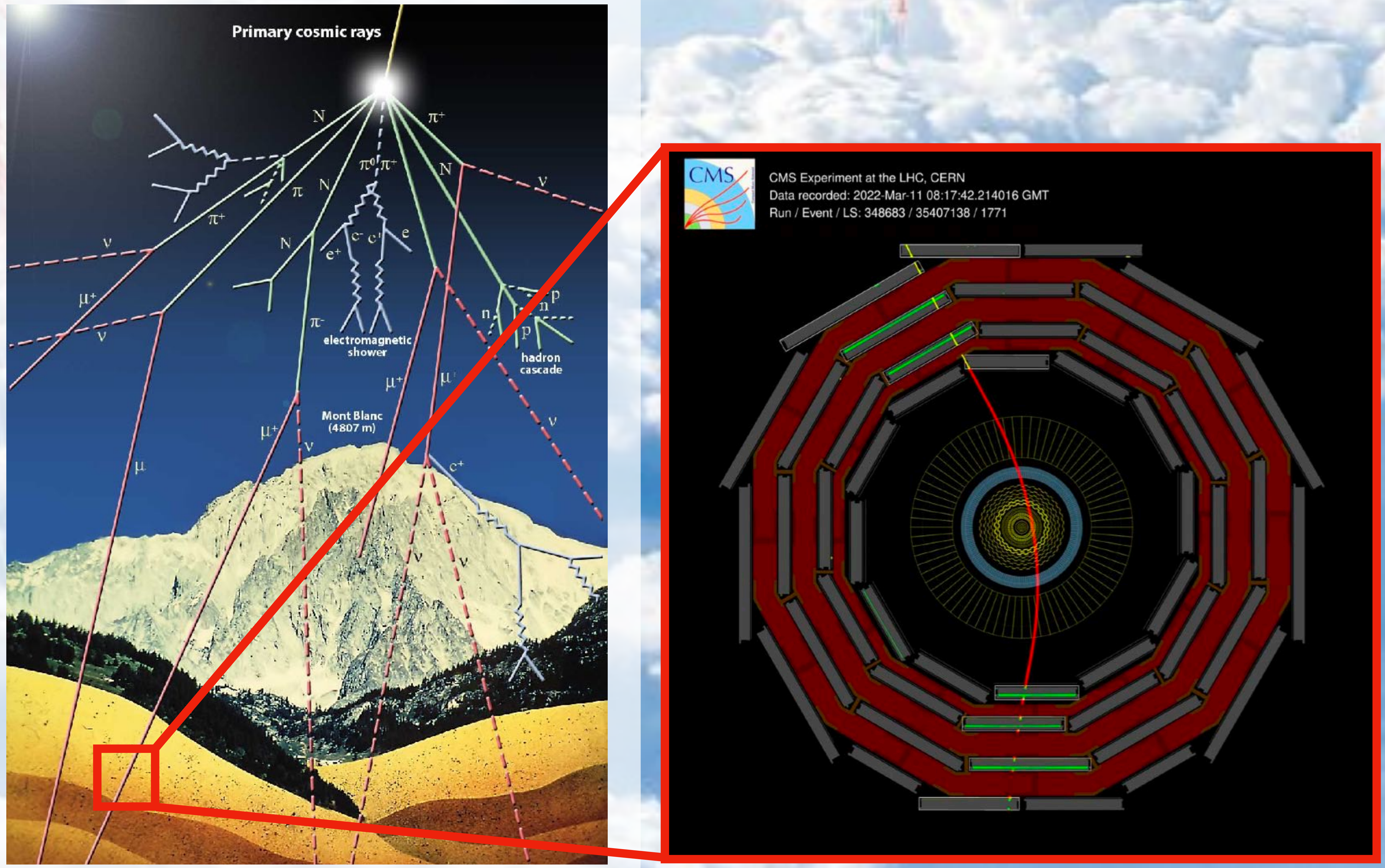
Credit: CERN [Link]

Cosmic rays: Particles from outer space accelerators

In 1912, Austrian physicist **Victor Hess** took an ionization chamber aloft in balloon and measured background radiation. He found that from 2000 meters to 5300 meters the amount of radiation increased, indicating the radiation came from space (Hess ruled out the Sun as the radiation's source by making a balloon ascent during a near-total eclipse). He had discovered "**Cosmic Rays**".

Hess shared the 1936 Nobel prize in physics for his discovery, and cosmic rays have proved useful in physics experiments – including several at CERN – since. Cosmic-ray showers were found to contain many different types of particles. Accelerators study these particles in detail.



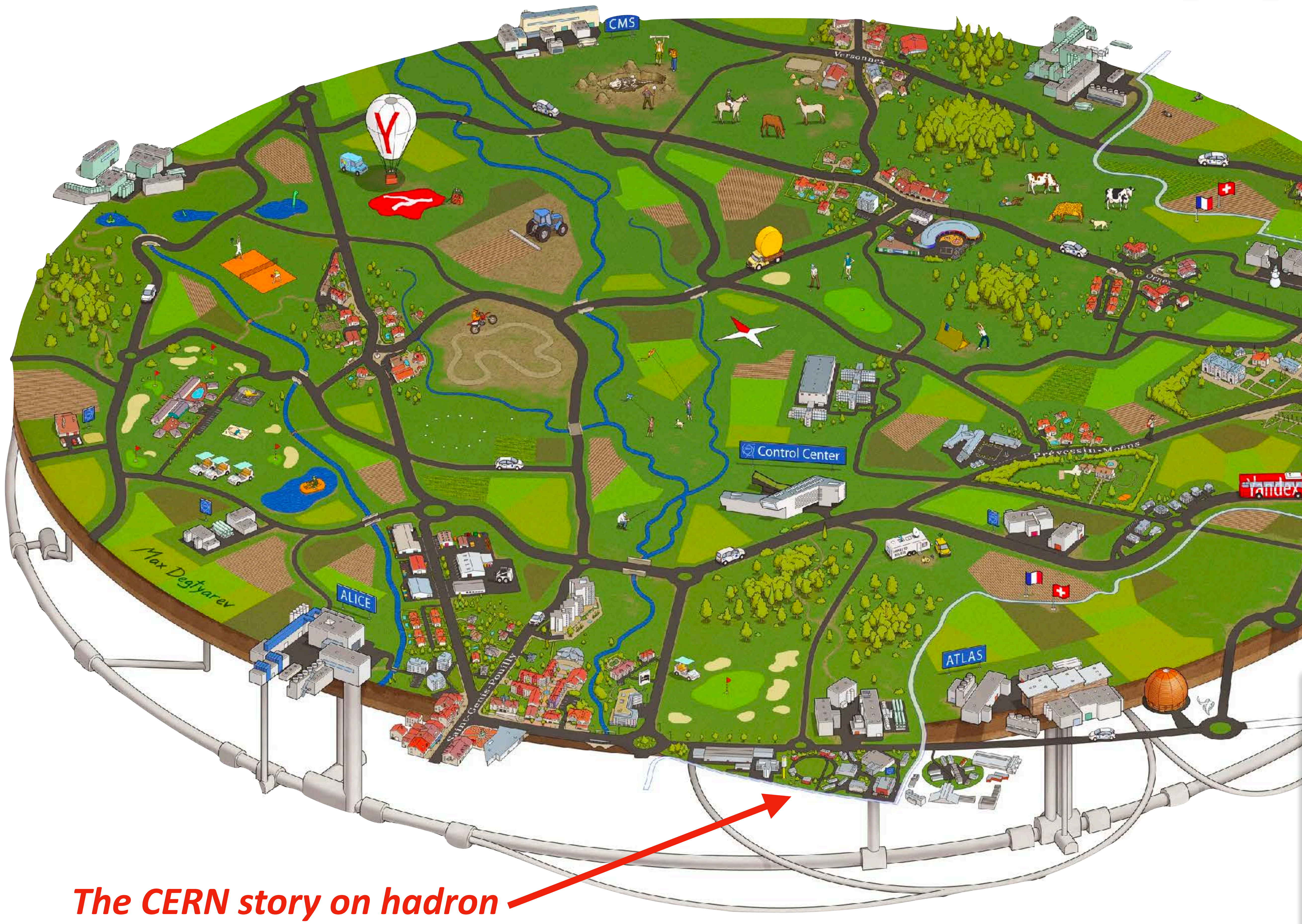


27 Jan 1971 … the era of hadron collider has begun

A vacuum chamber where the proton beams collide in the ISR

http://cds.cern.ch/record/41966

https://www.reddit.com/r/CERN/comments/8xnwz1/the_map_of_cern_and_cutaway_illustration_of_lhcb/

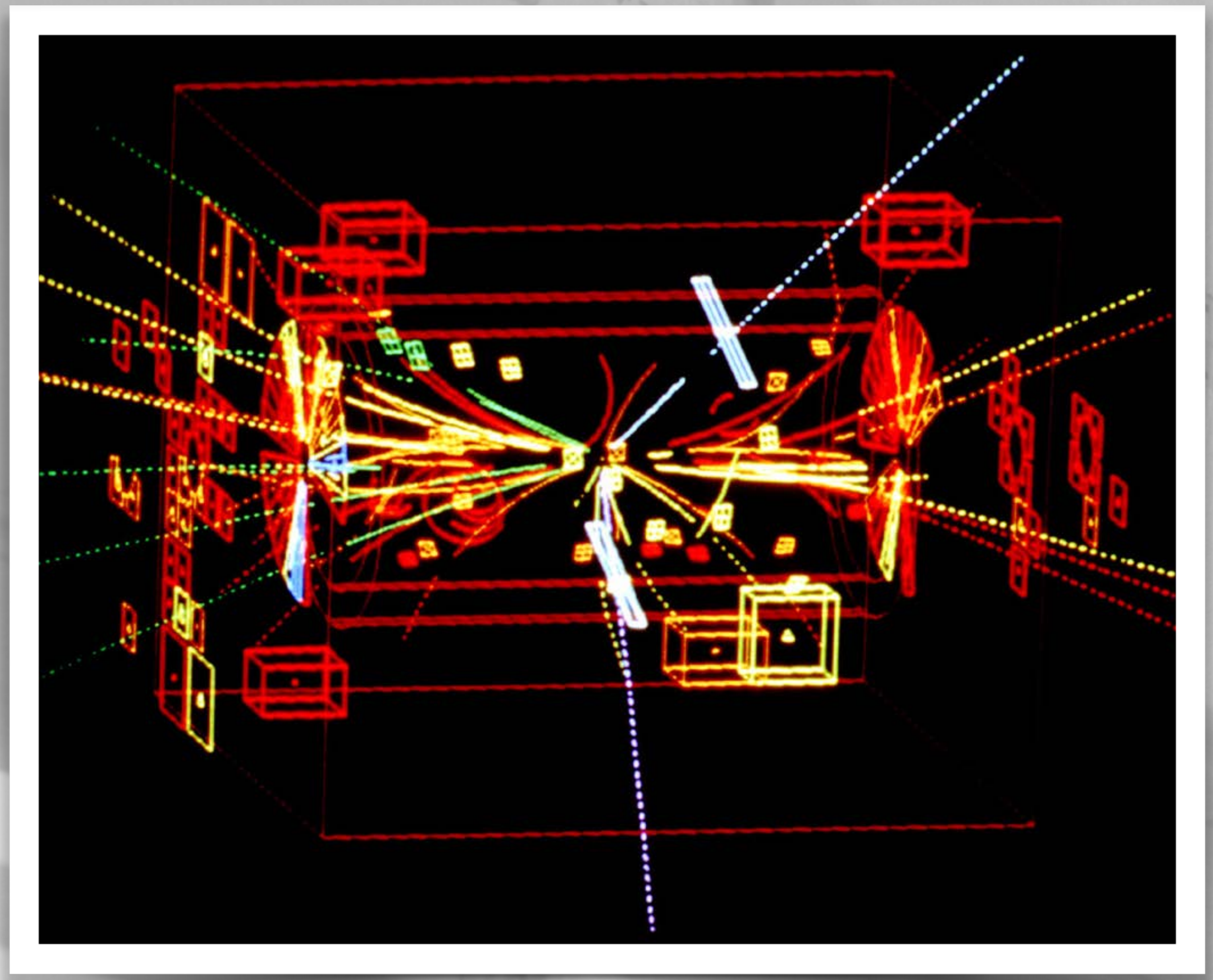


The CERN story on hadron collider started from here

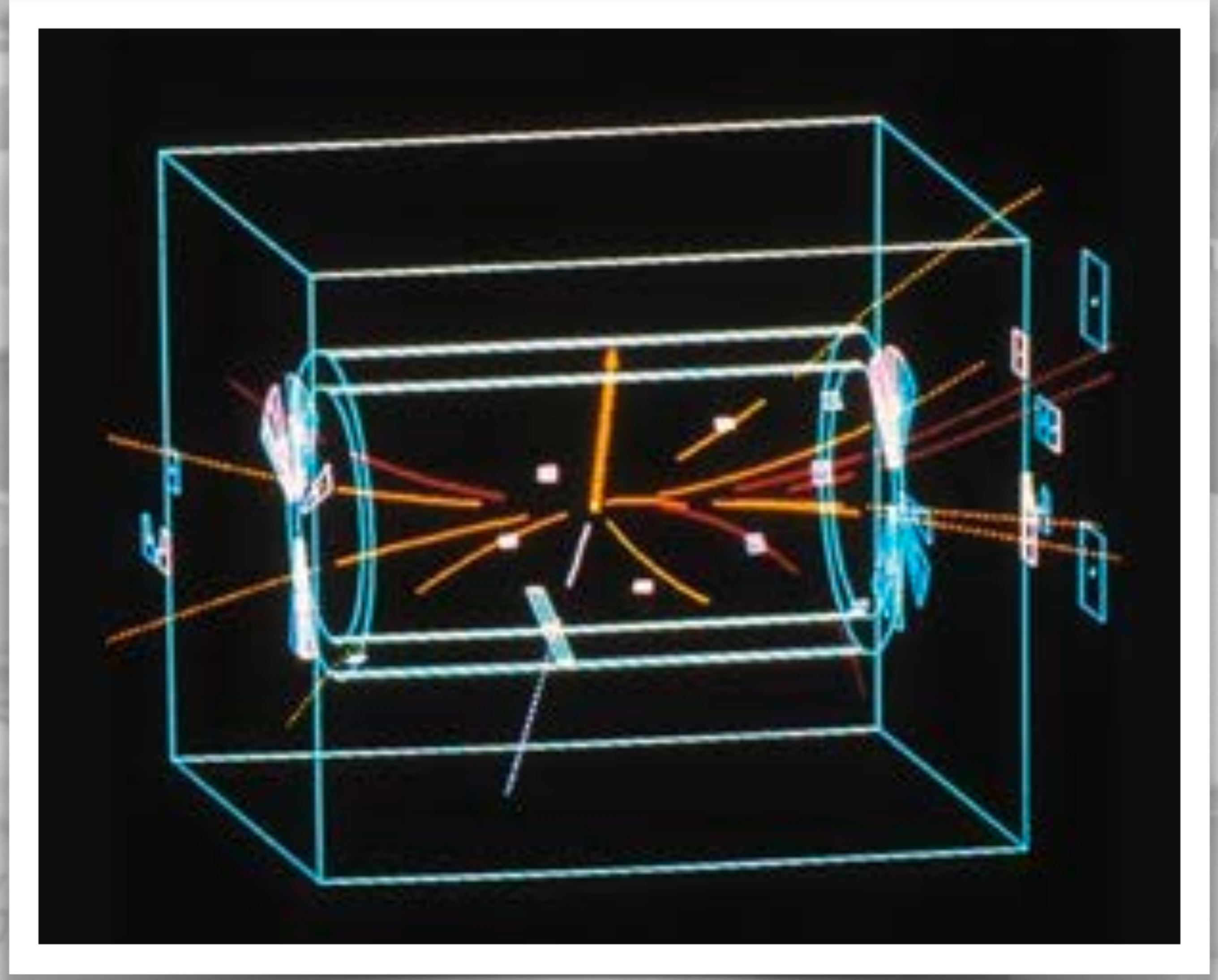
On 27 January 1971, Kjell Johnsen, who led the construction team which built the Intersecting Storage Rings (ISR), announced that the first ever interactions from colliding protons had been recorded.

http://cds.cern.ch/record/39571

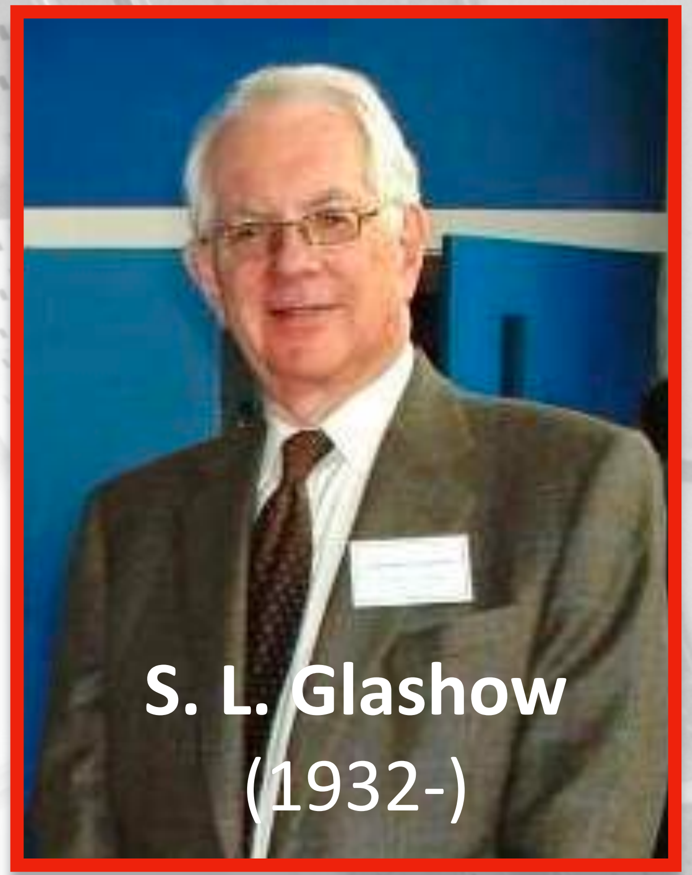
17 June 1976, SPS ... plan changed to $p\bar{p}$ collider ... discovery



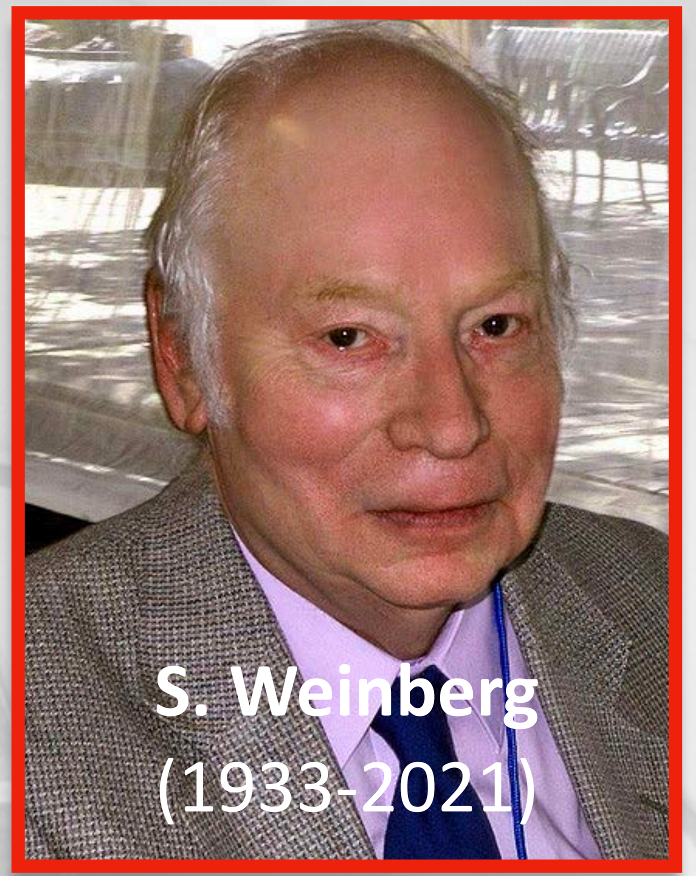
30 April 1983, Image taken by the UA1 which later confirmed to be Z candidate decays to electron-positron pair



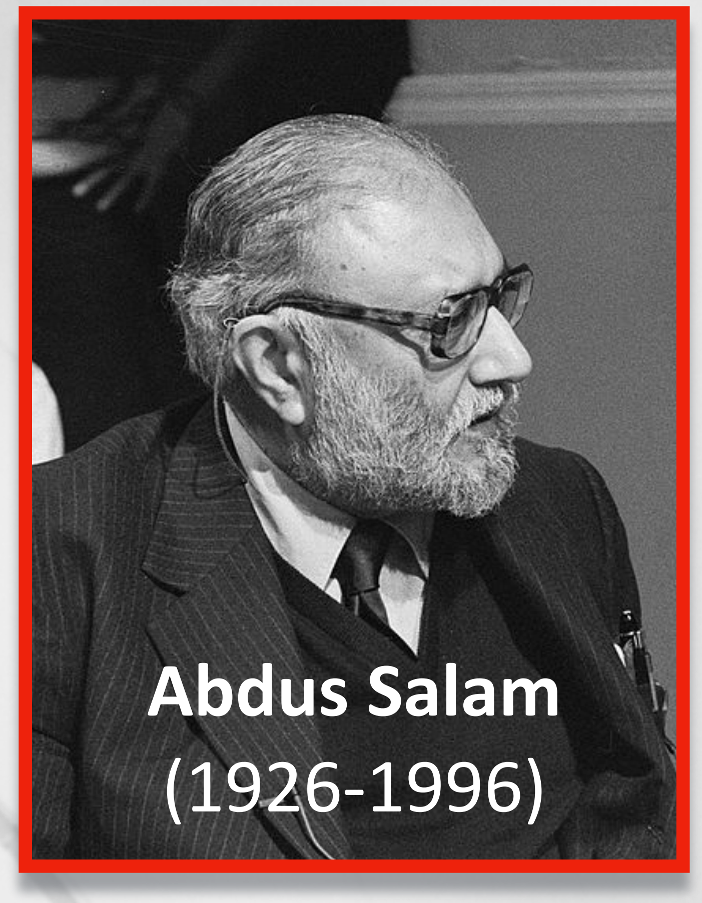
UA1 detected the W candidate event with electron and high missing energy



S. L. Glashow
(1932-)



S. Weinberg
(1933-2021)



Abdus Salam
(1926-1996)

Around 1968, theorists came up with the electroweak theory, which unified electromagnetism and weak interactions. The theory postulated the existence of W and Z bosons. CERN decided to modify SPS to SppS.

W mass is still in discussion.

Large Hadron Collider

Large Hadron Collider by numbers

27KM (16 MILES)
IN CIRCUMFERENCE

1 PETABYTE-PER-SECOND
IN RAW DATA GENERATED BY LHC EXPERIMENTS

1 BILLION COLLISIONS
OCCUR PER SECOND

100K TIMES HOTTER THAN THE SUN'S CORE,
HEAT GENERATED BY COLLISIONS

99.99999999%
SPEED OF LIGHT
ACHIEVED BY PARTICLES

1.9 KELVIN (-271.3 DEGREES CELSIUS)
INTERNAL OPERATING TEMPERATURE

120,000 CORES RUNNING
CERN'S OPENSTACK CLOUD ACROSS TWO DATA CENTERS

http://www.intelfreepress.com/news/cern-upgrades-data-center-and-restarts-large-hadron-collider/9819/

Parton - Proton

http://www.fnal.gov/pub/today/archive/archive_2012/today12-05-04_NutshellReadMore.html

Parton

- **1964**, **Murray Gell-Mann** and **George Zweig** independently proposed that the proton (and also the neutron) consisted of three smaller particles. We now use Gell-Mann's name for them: **quarks**. They were still theoretical.
- **1968**, SLAC use electron to probe the structure of the proton. However initially it was impossible to show that these proton constituents were quarks. **Richard Feynman** called them as **parton** in **1969**.
- Referred today as quarks and gluons.

Parton - Proton

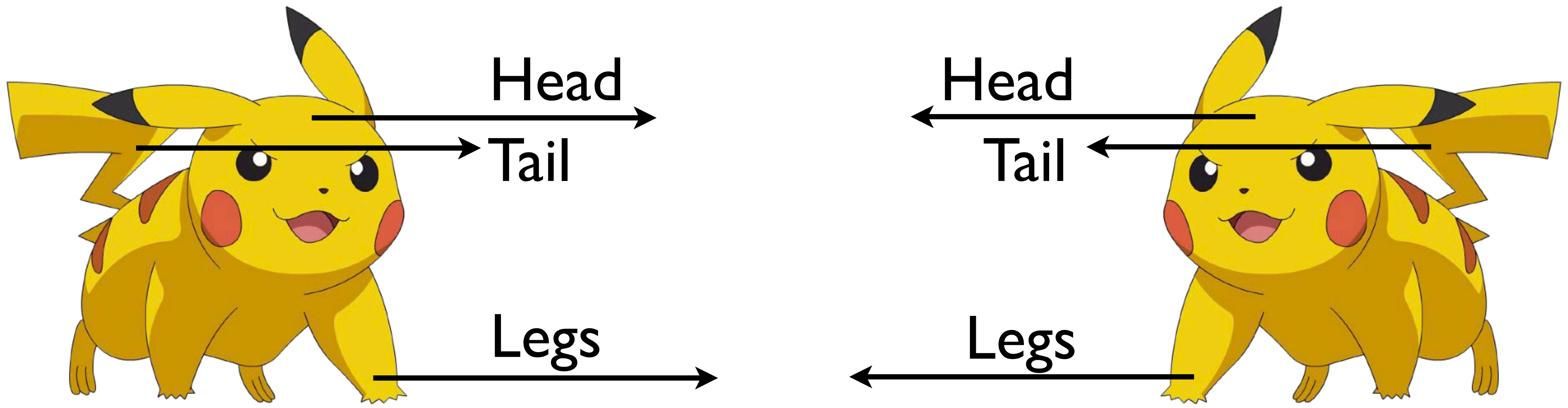
http://www.fnal.gov/pub/today/archive/archive_2012/today12-05-04_NutshellReadMore.html

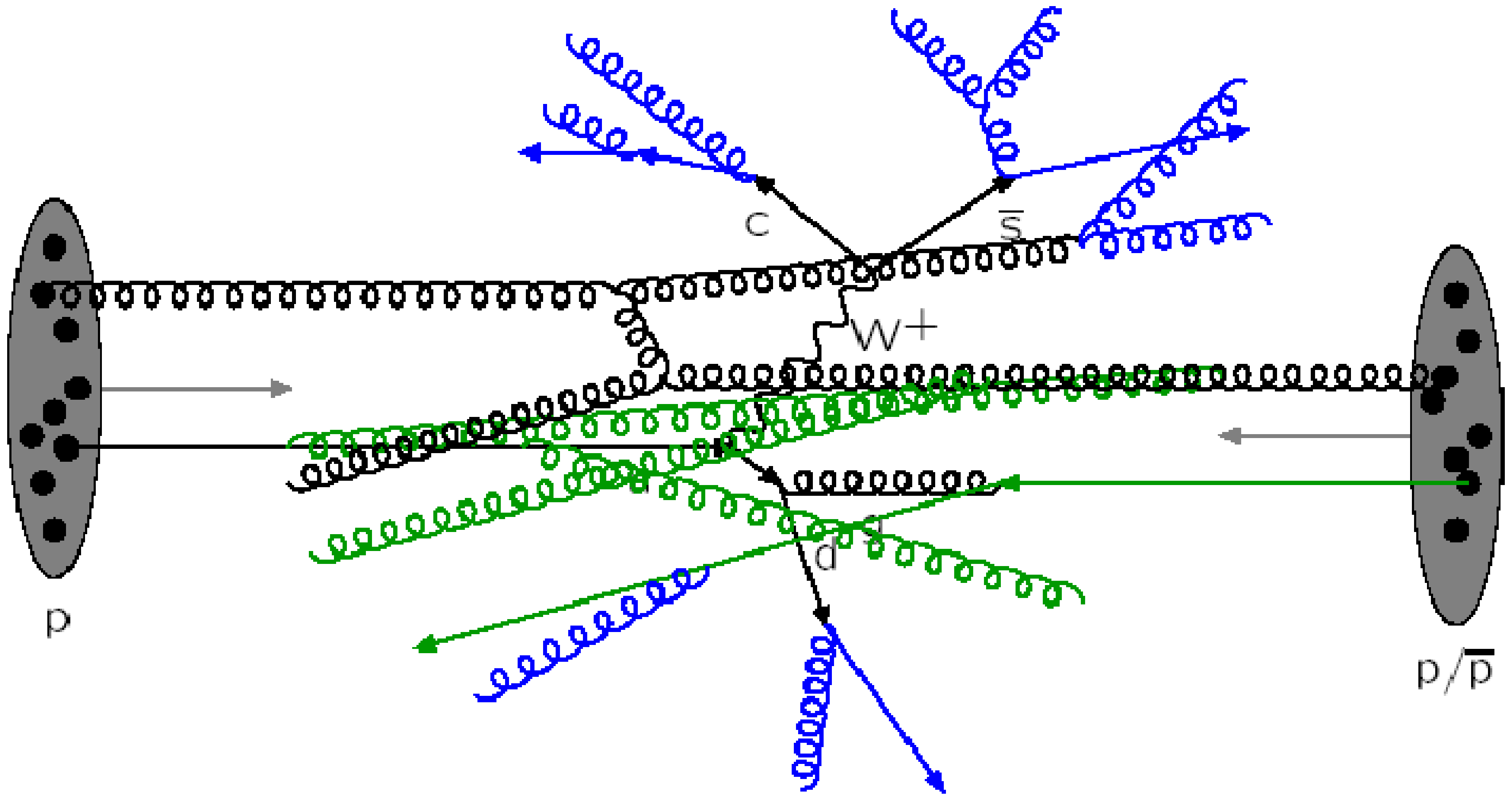
Proton

- Attempts to understand partons inside the proton led to the generation of the current theory of strong force interactions, called quantum chromodynamics, or QCD. This theory postulated that there would be additional particles in the proton called **gluons**. Gluons were observed at the HERA accelerator in Germany in 1979.
- Current model: valence quarks are imbedded in a sea of virtual quark-antiquark pairs generated by the gluons which hold the quarks together in the proton.

Proton collision

When “You” watch Pikachu fighting, you watch one-by-one interaction, i.e. Head-vs-Head, Tail-vs-Head, Head-vs-Leg, and then you are looking for the final result. This is the same case as proton interaction.





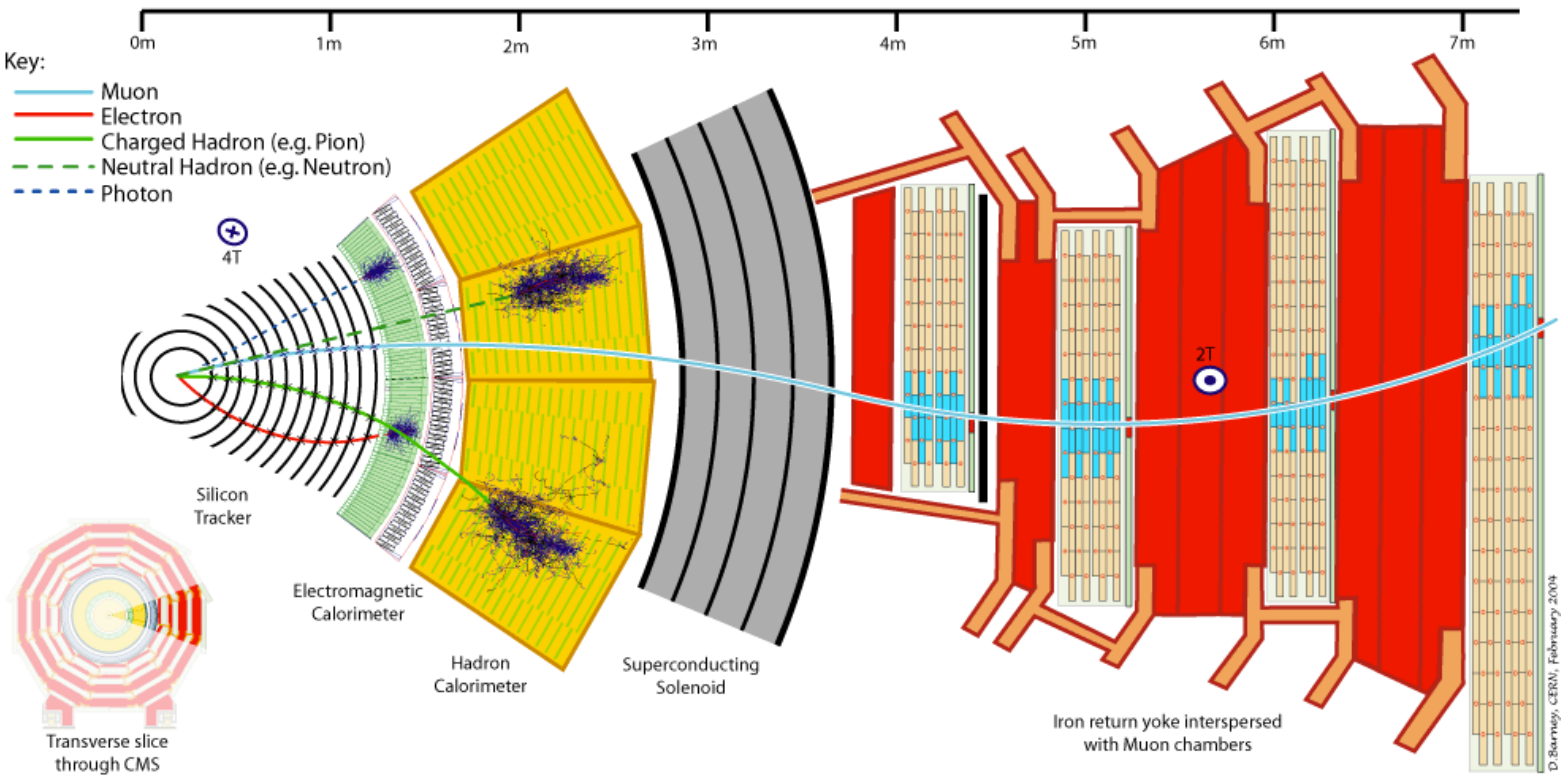
Particle detection

In experimental physics, a particle detector or radiation detector is an instrument used to detect, to track and to identify elementary particles by measuring one or more properties of them.

Particle detectors are devices producing an observable signal when they are crossed by a particle. Usually they are made by an active element (such that there is some interaction with the particle) and by a readout system ("forming" the signal and sending it to the data acquisition chain)

Aim: to detect as many of the stable and long-lived particles produced in a particle collision.

Need to measure: charge, mass, energy, direction.



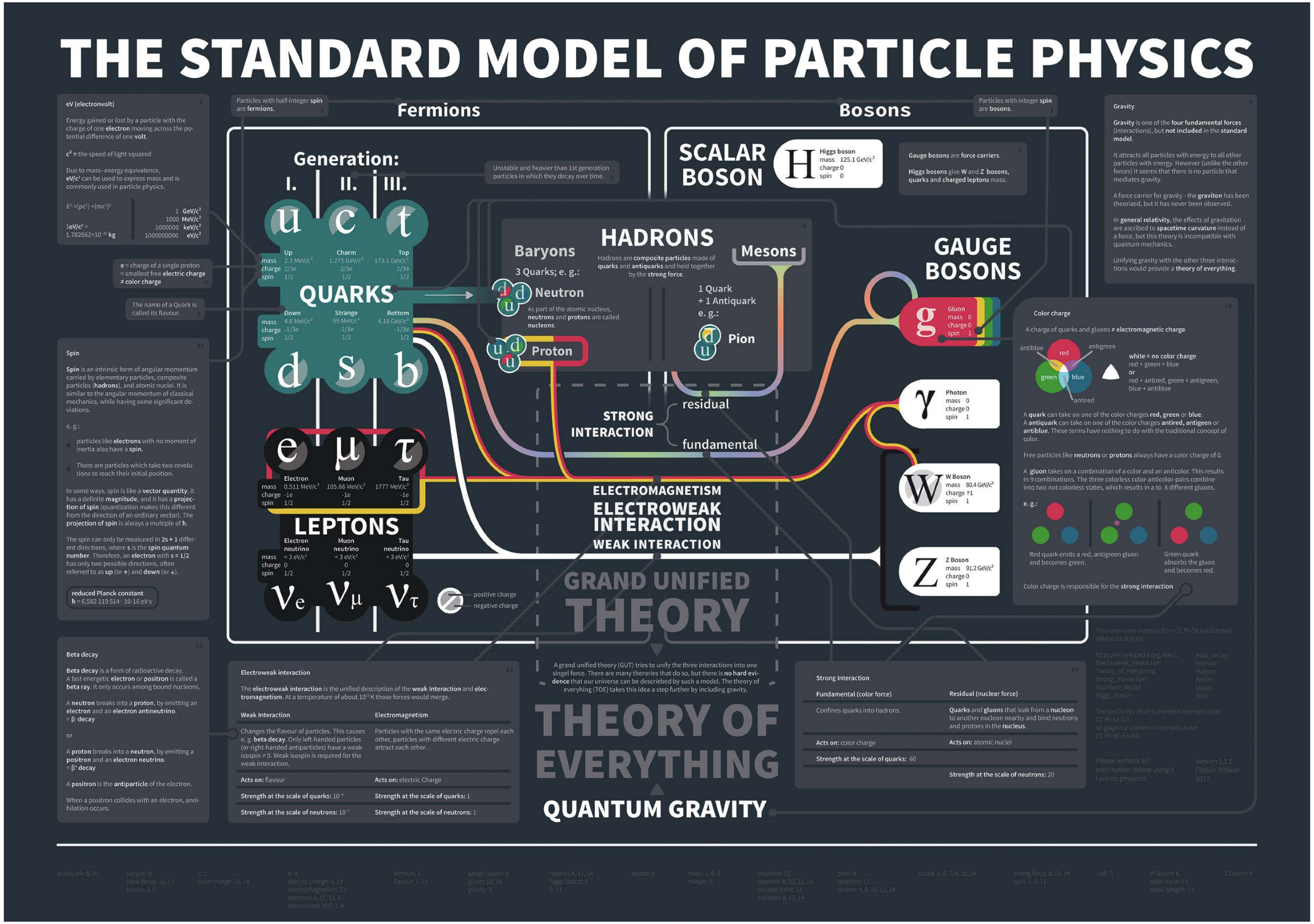
Standard Model

The Standard Model (SM) of particle physics is the theory describing three of the four known fundamental forces (the electromagnetic, weak, and strong interactions, and not including the gravitational force) in the universe, as well as classifying all known elementary particles.

Steven Weinberg

Sheldon Glashow

Abdus Salam



THE STANDARD MODEL OF PARTICLE PHYSICS

eV (electronvolt)

Energy gained or lost by a particle with the charge of one **electron** moving across the potential difference of one **volt**.

c^2 = the speed of light squared

Due to mass–energy equivalence, eV/c^2 can be used to express mass and is commonly used in particle physics.

$E^2=(pc^2)+(mc^2)^2$

$1eV/c^2 = 1.782662\times10^{-36}$ kg

1 GeV/c^2
1000 MeV/c^2
1000000 keV/c^2
1000000000 eV/c^2

e = charge of a single proton
= smallest free **electric charge**
≠ **color charge**

The name of a Quark is called its flavour.

Spin

Spin is an intrinsic form of angular momentum carried by elementary particles, composite particles (**hadrons**), and atomic nuclei. It is similar to the angular momentum of classical mechanics, while having some significant deviations.

e. g.:

- particles like **electrons** with no moment of inertia also have a **spin**.
- There are particles which take two revolutions to reach their initial position.

In some ways, spin is like a **vector quantity**; it has a definite **magnitude**, and it has a **projection of spin** (quantization makes this different from the direction of an ordinary vector). The **projection of spin** is always a multiple of **ħ**.

The spin can only be measured in **2s + 1** different directions, where **s** is the **spin quantum number**. Therefore, an **electron** with **s = 1/2** has only two possible directions, often referred to as **up** (or ↑) and **down** (or ↓).

reduced Planck constant
ħ = 6,582 119 514 · 10-16 eV s

Beta decay

Beta decay is a form of radioactive decay. A fast energetic **electron** or **positron** is called a **beta ray**. It only occurs among bound nucleons.

A **neutron** breaks into a **proton**, by emitting an **electron** and an **electron antineutrino**.
= β^- **decay**

or

A **proton** breaks into a **neutron**, by emitting a **positron** and an **electron neutrino**.
= β^+ **decay**

A **positron** is the **antiparticle** of the electron.

When a positron collides with an electron, annihilation occurs.

Particles with half-integer **spin** are **fermions**.

Fermions

Generation: I. II. III.

Unstable and heavier than 1st generation particles in which they decay over time.

QUARKS

	Up	Charm	Top
mass	2.3 MeV/c^2	1.275 GeV/c^2	173.1 GeV/c^2
charge	2/3e	2/3e	2/3e
spin	1/2	1/2	1/2

	Down	Strange	Bottom
mass	4.8 MeV/c^2	95 MeV/c^2	4.18 GeV/c^2
charge	-1/3e	-1/3e	-1/3e
spin	1/2	1/2	1/2

LEPTONS

	Electron	Muon	Tau
mass	0.511 MeV/c^2	105.66 MeV/c^2	1777 MeV/c^2
charge	-1e	-1e	-1e
spin	1/2	1/2	1/2

	Electron neutrino	Muon neutrino	Tau neutrino
mass	< 3 eV/c^2	< 3 eV/c^2	< 3 eV/c^2
charge	0	0	0
spin	1/2	1/2	1/2

HADRONS

Hadrons are **composite particles** made of **quarks** and **antiquarks** and held together by the **strong force**.

Baryons

3 Quarks; e. g.:

Neutron

As part of the atomic nucleus, **neutrons** and **protons** are called **nucleons**.

Proton

Mesons

1 Quark
+ 1 Antiquark
e. g.:

Pion

STRONG INTERACTION

residual

fundamental

ELECTROMAGNETISM

ELECTROWEAK INTERACTION

WEAK INTERACTION

GRAND UNIFIED THEORY

A grand unified theory (GUT) tries to unify the three interactions into one singel force. There are many therories that do so, but there is **no hard evidence** that our universe can be descriebed by such a model. The theory of everyhing (TOE) takes this idea a step further by including gravity.

THEORY OF EVERYTHING

QUANTUM GRAVITY

Bosons

Particles with integer **spin** are **bosons**.

SCALAR BOSON

Higgs boson
mass 125.1 GeV/c^2
charge 0
spin 0

Gauge bosons are **force carriers**.

Higgs bosons give **W** and **Z bosons**, **quarks** and **charged leptons** mass.

GAUGE BOSONS

	Gluon	Photon	W Boson	Z Boson
mass	0	0	80.4 GeV/c^2	91.2 GeV/c^2
charge	0	0	±1	0
spin	1	1	1	1

Gravity

Gravity is one of the **four fundamental forces** (interactions), but **not included** in the **standard model**.

It attracts all particles with energy to all other particles with energy. However (unlike the other forces) it seems that there is no particle that mediates gravity.

A force carrier for gravity - the **graviton** has been theorized, but it has never been observed.

In **general relativity**, the effects of gravitation are ascribed to **spacetime curvature** instead of a force, but this theory is incompatible with quantum mechanics.

Unifying gravity with the other three interactions would provide a **theory of everything**.

Color charge

A charge of quarks and gluons ≠ **electromagnetic charge**.

white = no color charge
red + green + blue
or
red + antired, green + antigreen, blue + antiblue

A **quark** can take on one of the color charges **red, green** or **blue**. A **antiquark** can take on one of the color charges **antired, antigeen** or **antiblue**. These terms have nothing to do with the traditional concept of color.

Free particles like **neutrons** or **protons** always have a color charge of 0.

A **gluon** takes on a combination of a color and an anticolor. This results in 9 combinations. The three colorless color-anticolor-pairs combine into two not colorless states, which results in a to 8 different gluons.

e. g.:

Red quark emits a red, antigreen gluon and becomes green.

Green quark absorbs the gluon and becomes red.

Color charge is responsible for the **strong interaction**

Electroweak interaction

The **electroweak interaction** is the unified description of the **weak Interaction** and **electromagnetism**. At a temperature of about 10^{15} K those forces would merge.

Weak Interaction	Electromagnetism
Changes the flavour of particles. This causes e. g. **beta decay**. Only left-handed particles (or right-handed antiparticles) have a weak isospin ≠ 0. Weak isospin is required for the weak interaction.	Particles with the same electric charge repel each other, particles with different electric charge attract each other.
Acts on: flavour	**Acts on:** electric Charge
Strength at the scale of quarks: 10^{-4}	**Strength at the scale of quarks:** 1
Strength at the scale of neutrons: 10^{-7}	**Strength at the scale of neutrons:** 1

Strong Interaction

Fundamental (color force)	Residual (nuclear force)
Confines quarks into hadrons.	**Quarks** and **gluons** that leak from a **nucleon** to another nucleon nearby and bind neutrons and protons in the **nucleus**.
Acts on: color charge	**Acts on:** atomic nuclei
Strength at the scale of quarks: 60	
	Strength at the scale of neutrons: 20

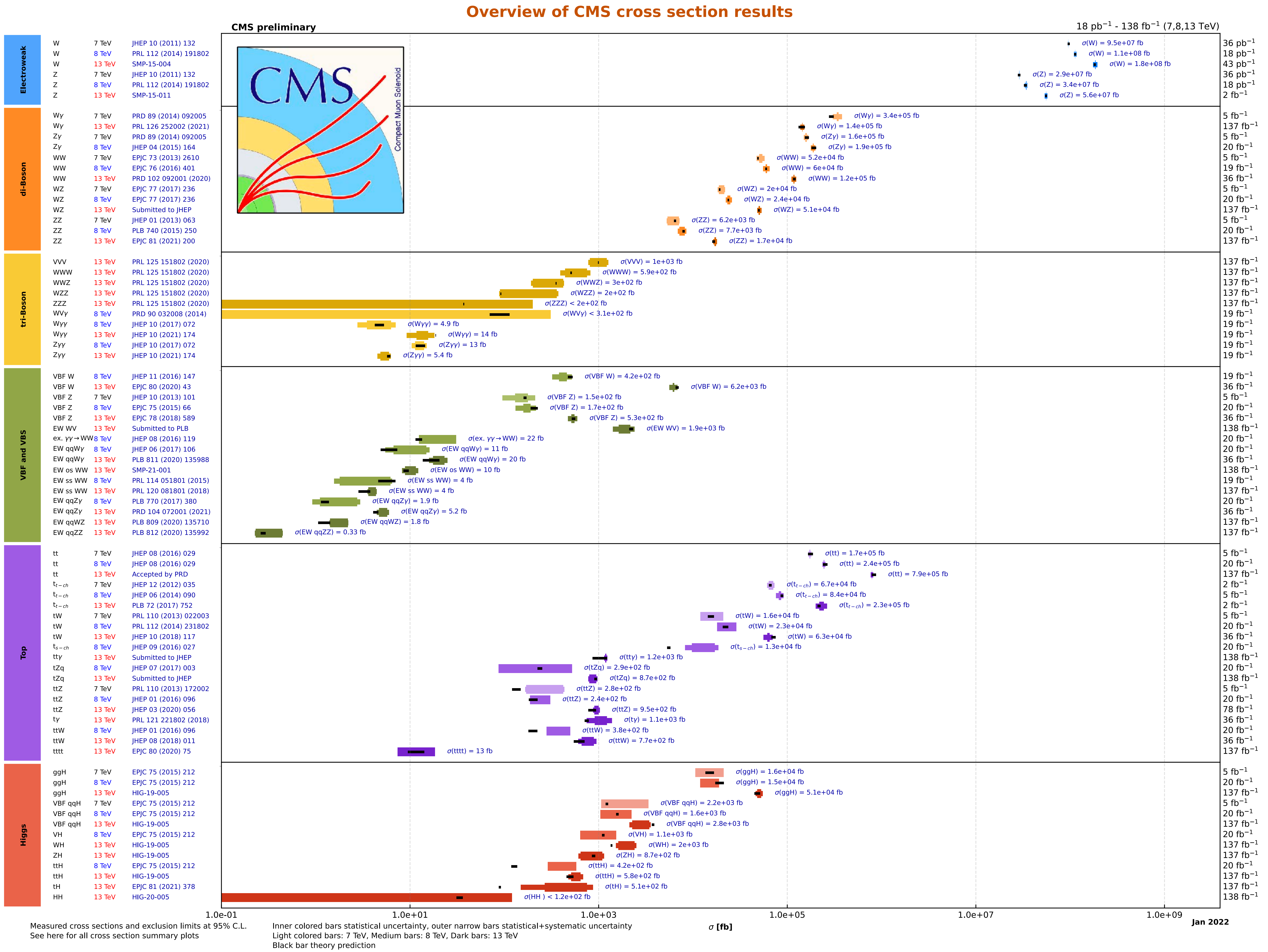
Please recheck all information before using it. I am no physicist.

Version 1.1.1
Florian Winkler
2017

LHC with Standard Model

Since the 7 TeV data collection started in 2011, until now, LHC physics program shows that SM (still) works very well and Higgs (with mass 125 GeV) is there. However, one need to remember than studying known processes is very challenging:

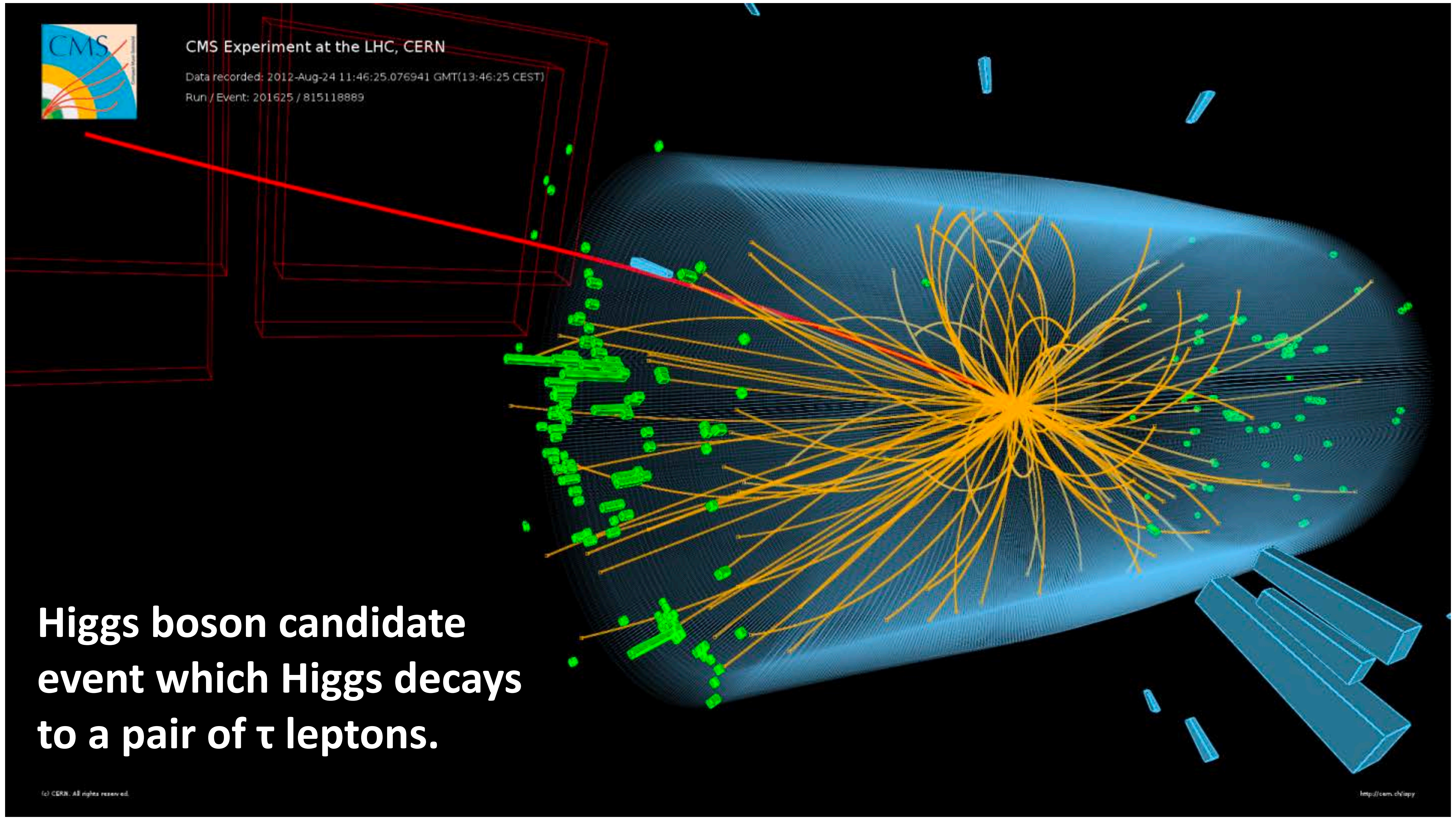
- Excellent performance and calibration
- Probe uncovered parameter space
- Try new techniques to enhance Signal/ Background separation, i.e. new machine learning techniques



Mass of elementary particles?

One missing piece was the way to explain masses of elementary particles. In the mid 1960s, the mechanism to explain the mass generation came out by three independent groups,

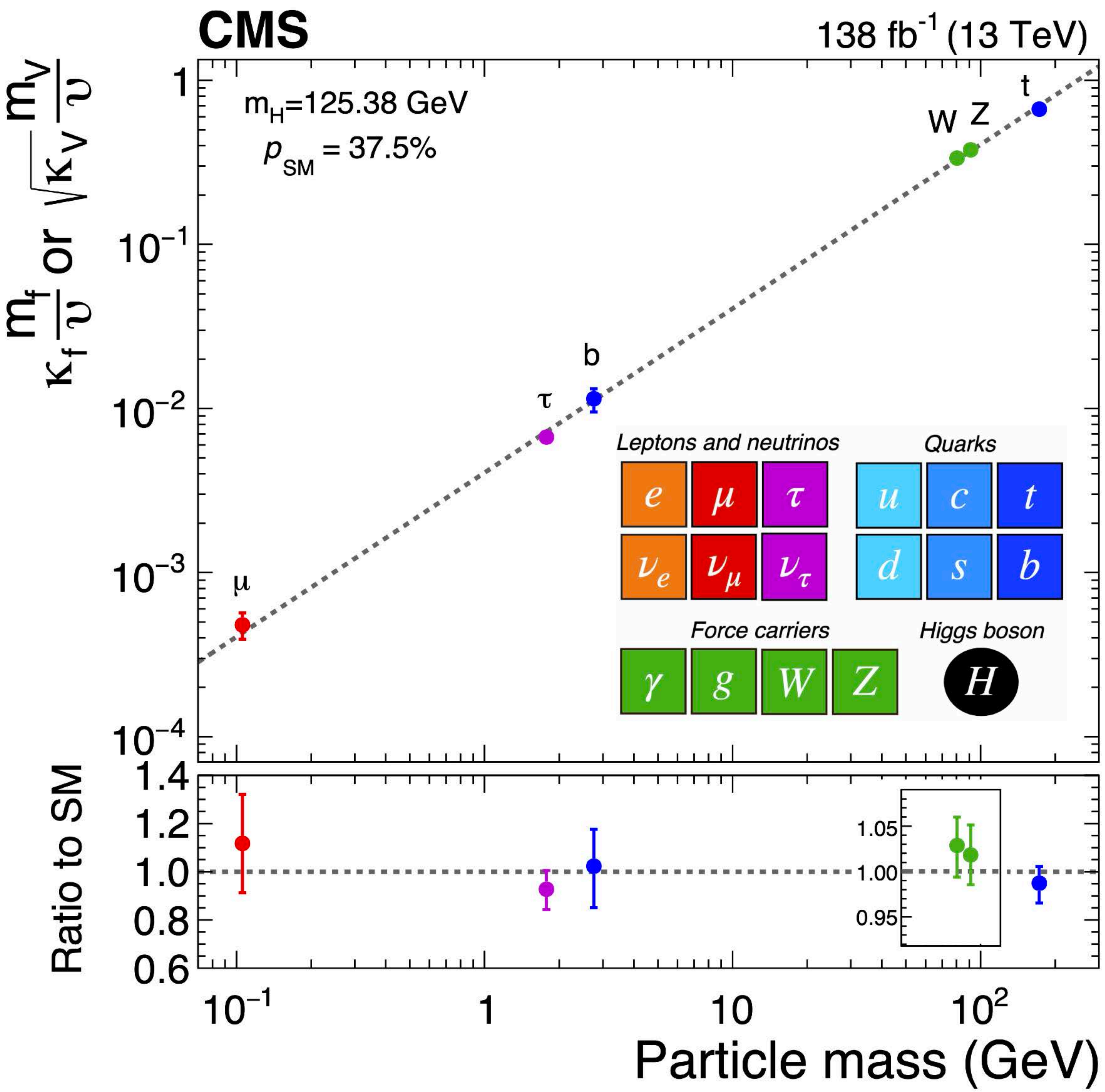
- by **Robert Brout** and **François Englert** [Phys. Rev. Lett. 13, 321];
- by **Peter Higgs** [Phys. Rev. Lett. 13, 508];
- by **Gerald Guralnik**, **C. R. Hagen**, and **Tom Kibble** [Phys. Rev. Lett. 13, 585].



Higgs boson candidate event which Higgs decays to a pair of τ leptons.

July 2012, Announcement for the discovery of what could be the long-sought Higgs boson!!

Mass of elementary particles?



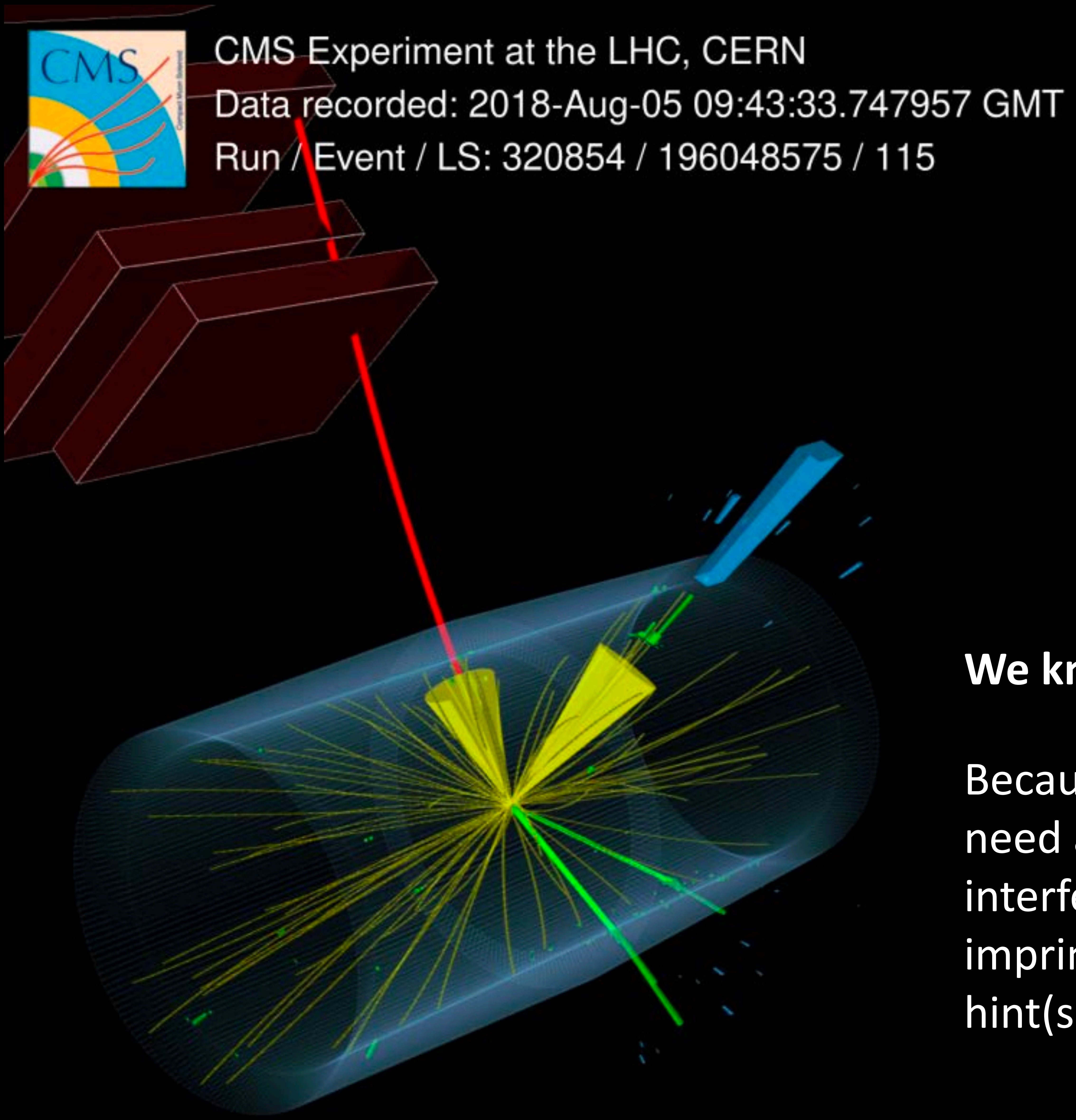
CERN 10 years HIGGS boson discovery

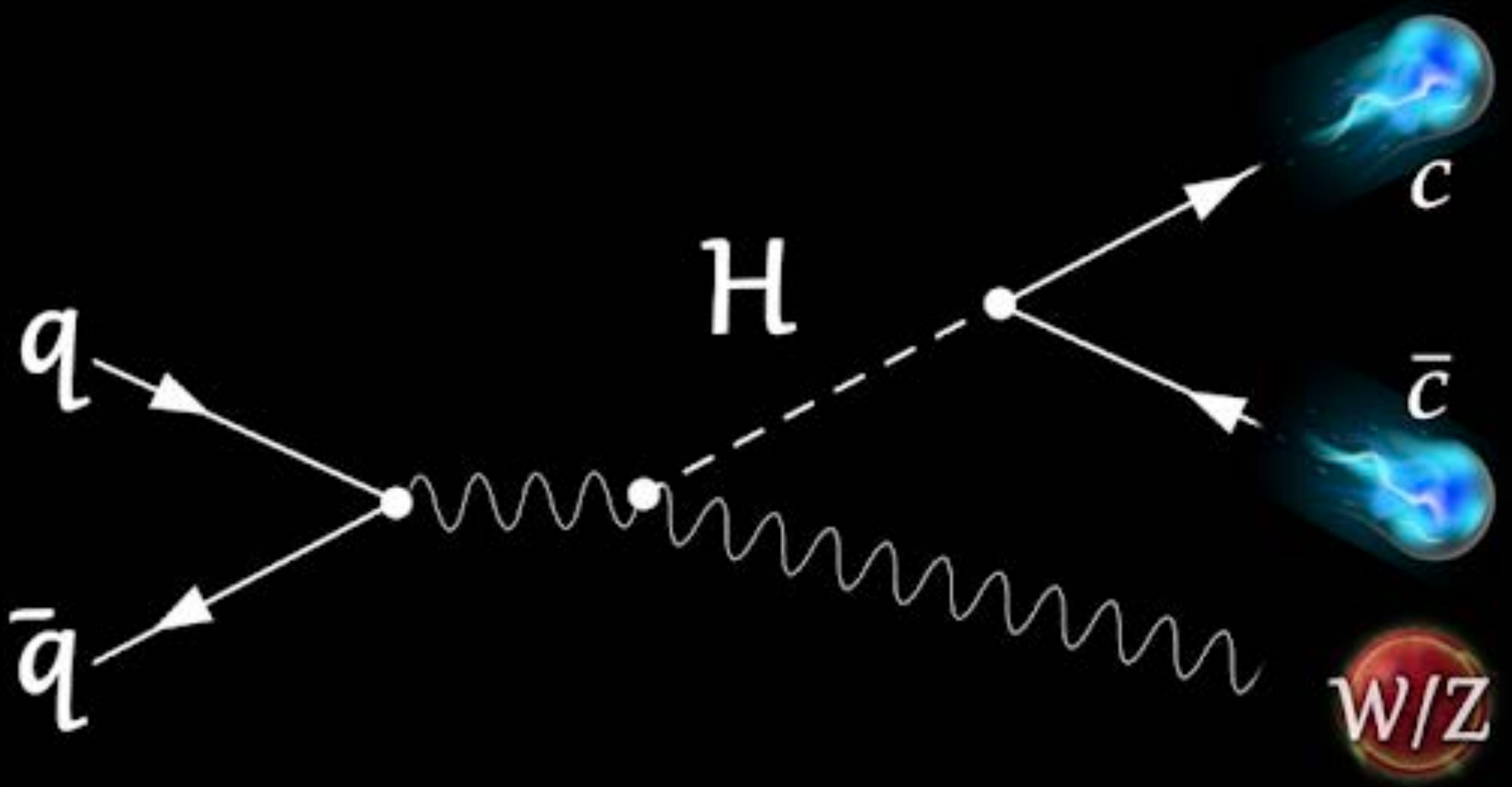
The Higgs boson is predicted to couple to particles (or decay into them) with a strength depending on their masses in a well-defined way: the higher the mass, the stronger the coupling. The measurement of the many ways this Higgs boson decays and the measurement of its couplings to different particles, shown in the figure, provide a crucial test of the validity of existing theories.

All the measurements of the properties of the Higgs boson presently agree with the theoretical predictions within the measurement and prediction uncertainties.

[Link]

Higgs ... from *search* to *precision measurement*

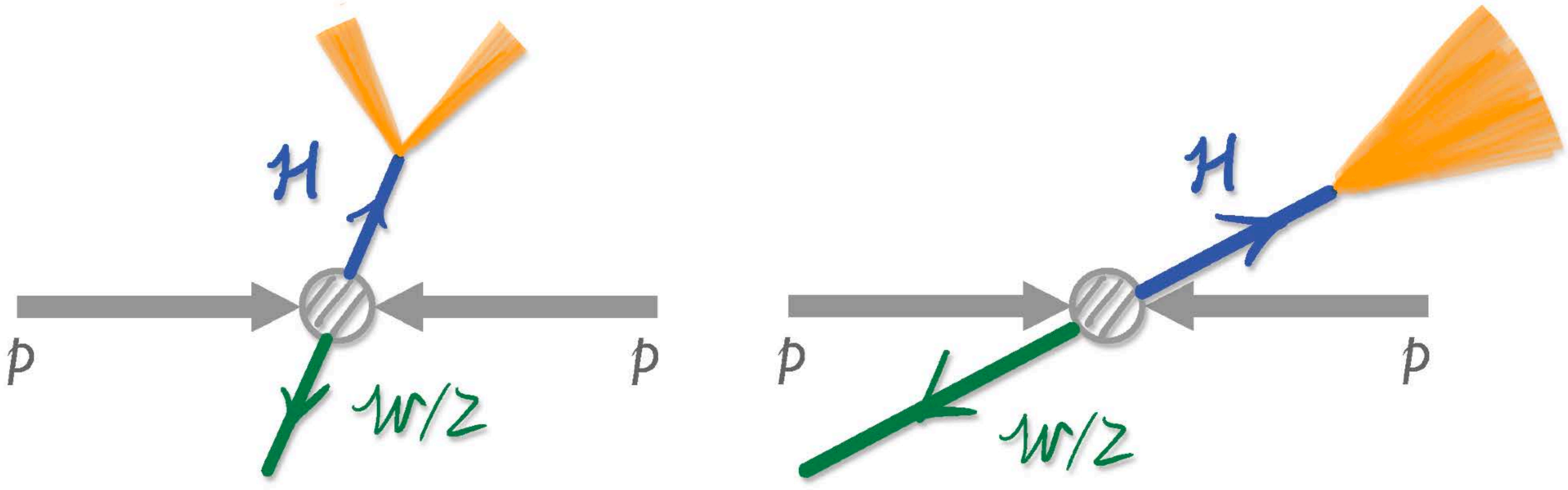




We know that Higgs is there, why do we need precise measurements?

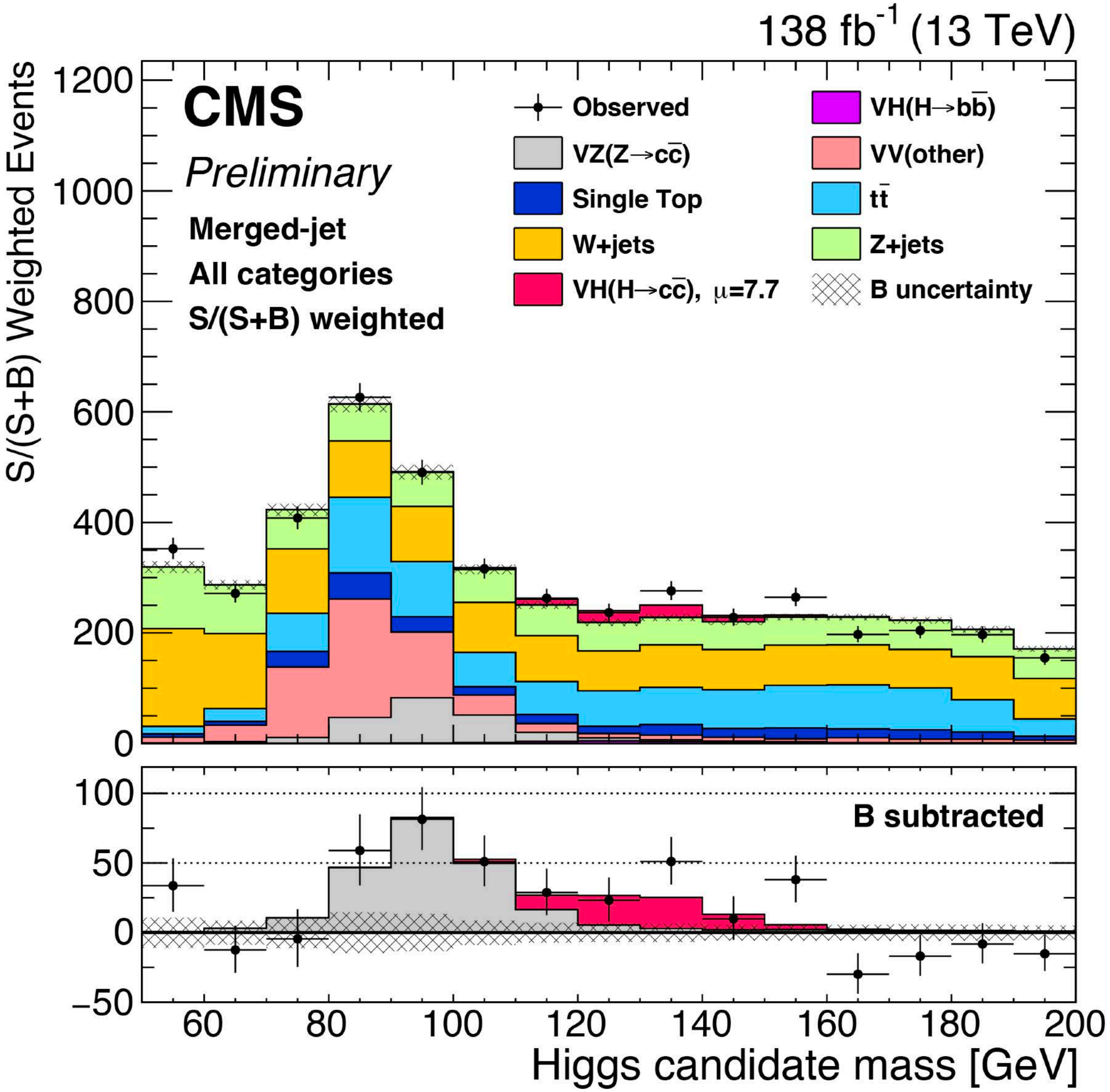
Because the lack of direct observations of new particles at the LHC!, we need an alternative approach which we consider that BSM physics interfere with standard model particles and subsequently leave an imprint on their properties. With precise measurement, we may see hint(s) of new physics.

Higgs … from *search* to *precision measurement*



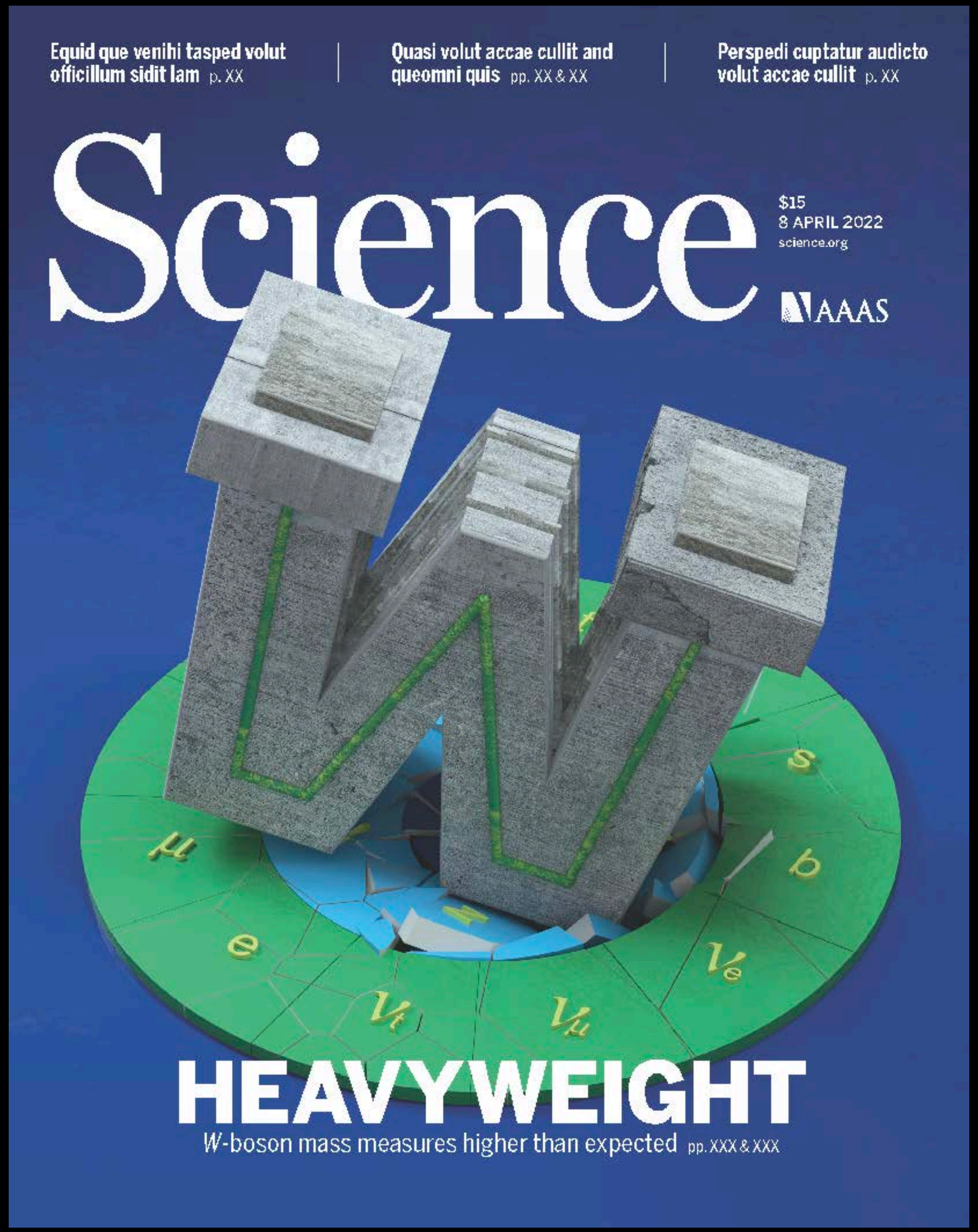
(a) (b)

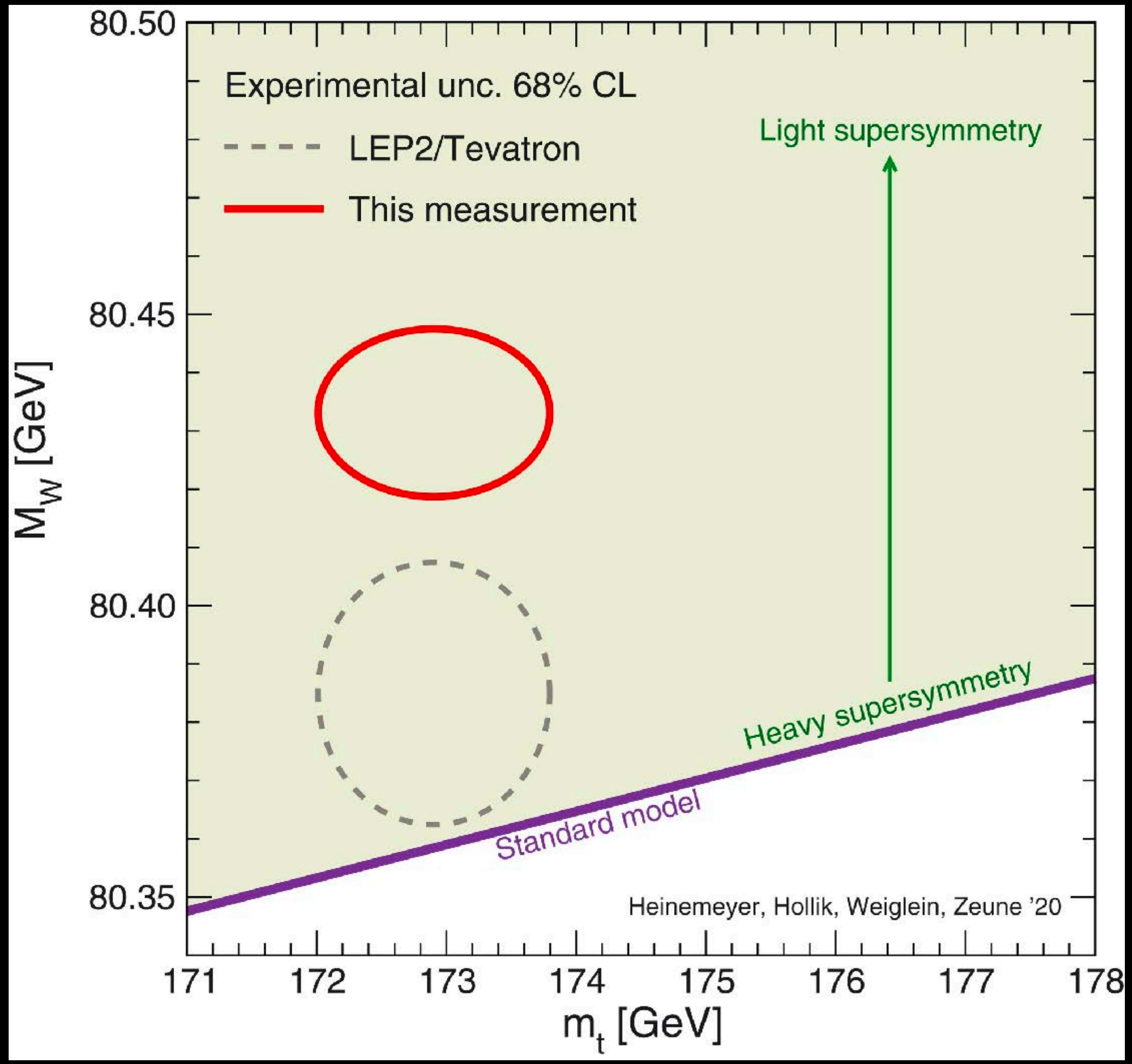
Higgs-charm coupling challenge: Improve identification algorithms by innovative usages of deep learning techniques. [See detail about the analysis here]



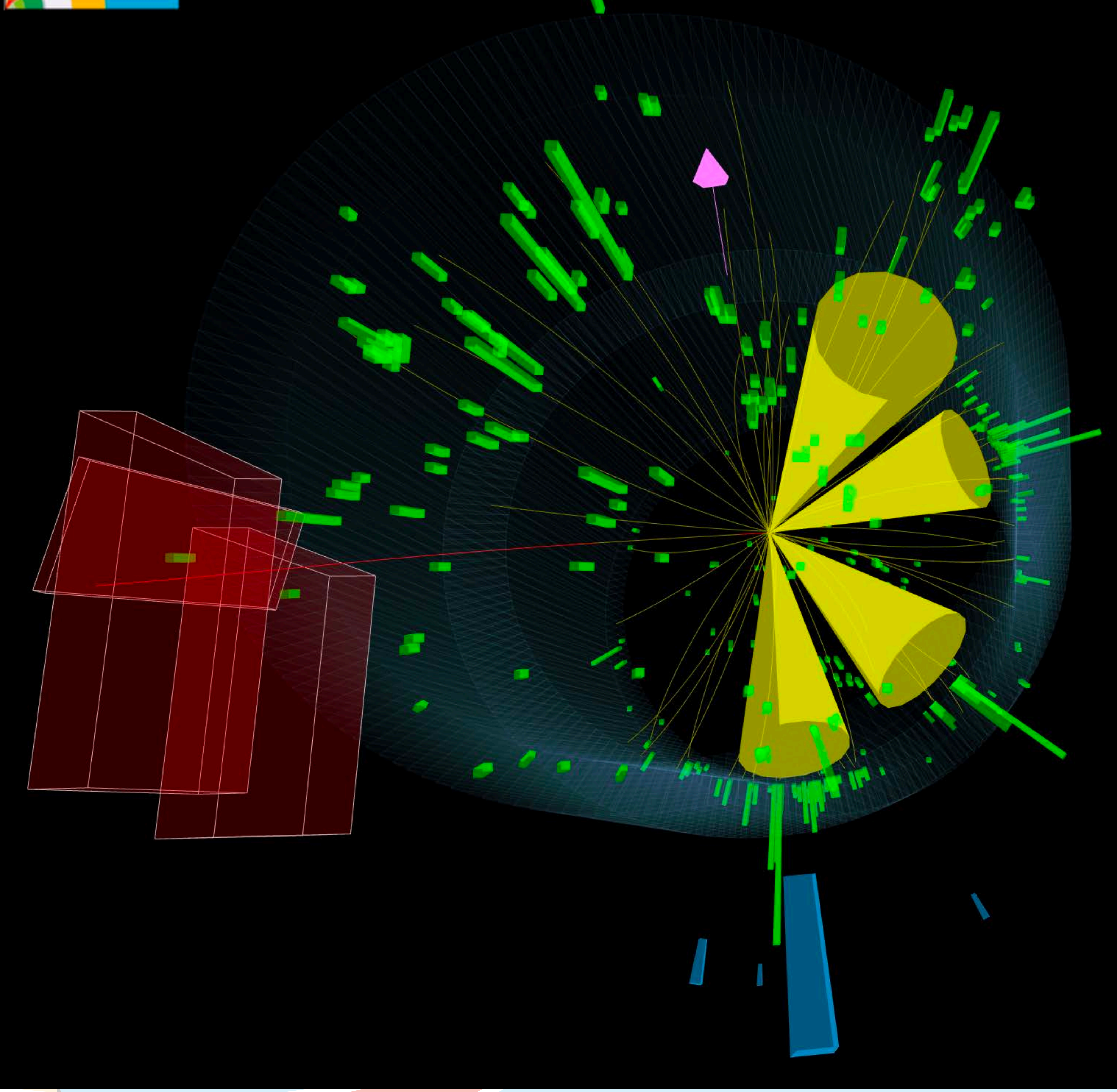
Top quark ... a tool for discoveries

- Discover in 1995 by CDF and D0 at Tevatron
- To predict the top quark mass, need to know accurately the W boson and Higgs boson masses
- Consequently, use top and Higgs masses to produce W boson mass ... reported on 7 April 2022 by CDF that W boson mass extracted from data taken at the Tevatron ***(2002-2011)***





CMS Experiment at the LHC, CERN
Data recorded: 2016-Aug-17 08:01:23.065024 GMT
Run / Event / LS: 278969 / 229126383 / 184

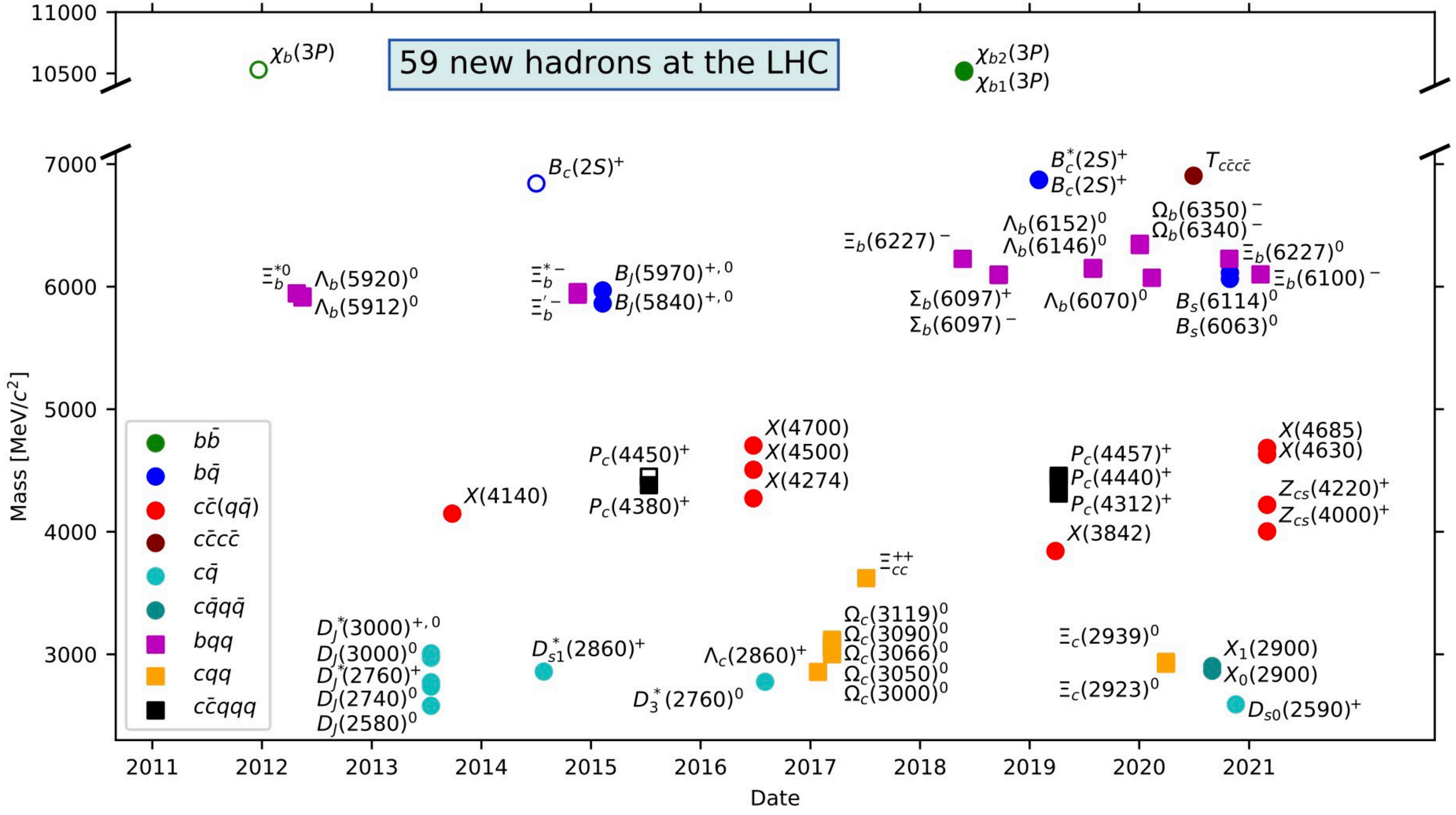


10 years (2011-2021) of LHC, 59 new hadrons

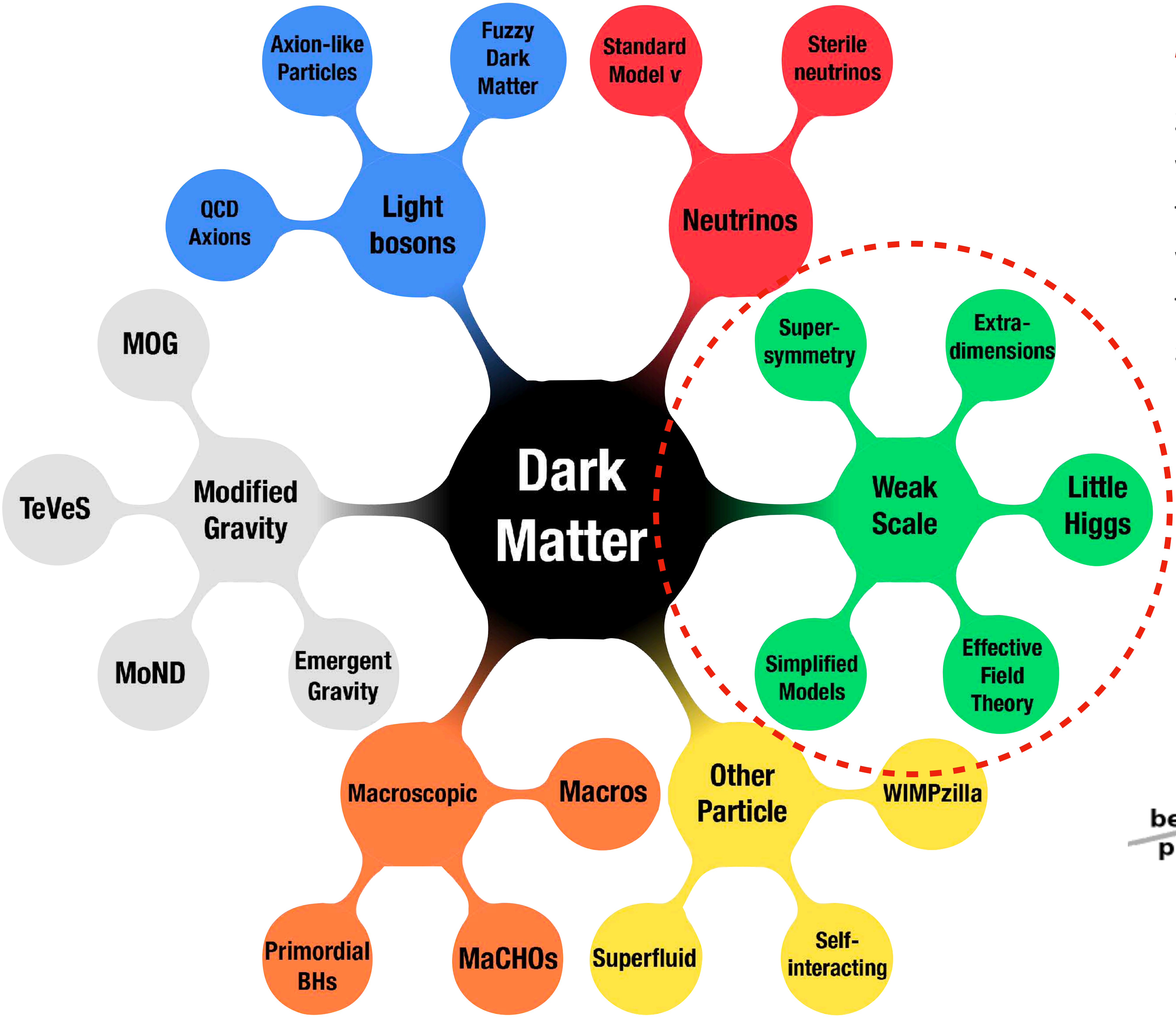
Quantum chromodynamics (or QCD) is still on very solid footing

- QCD is the theory to describe the strong interaction that holds quarks together inside hadrons.
- Experiments continue to discover hadrons including combination of
  - **mesons**: quarks and antiquarks,
  - **baryons**: three quarks,
  - **antibaryons**: three antiquarks,
  - **tetraquarks**: two quarks and two antiquarks,
  - **pentaquarks**: four quarks and one antiquark.
- Reminder: we cannot (yet) prove theoretically that quarks can't stay alone. In addition, we can't also calculate of which combinations of quarks would be/ would not be viable in nature.

LHCB-FIGURE-2021-001



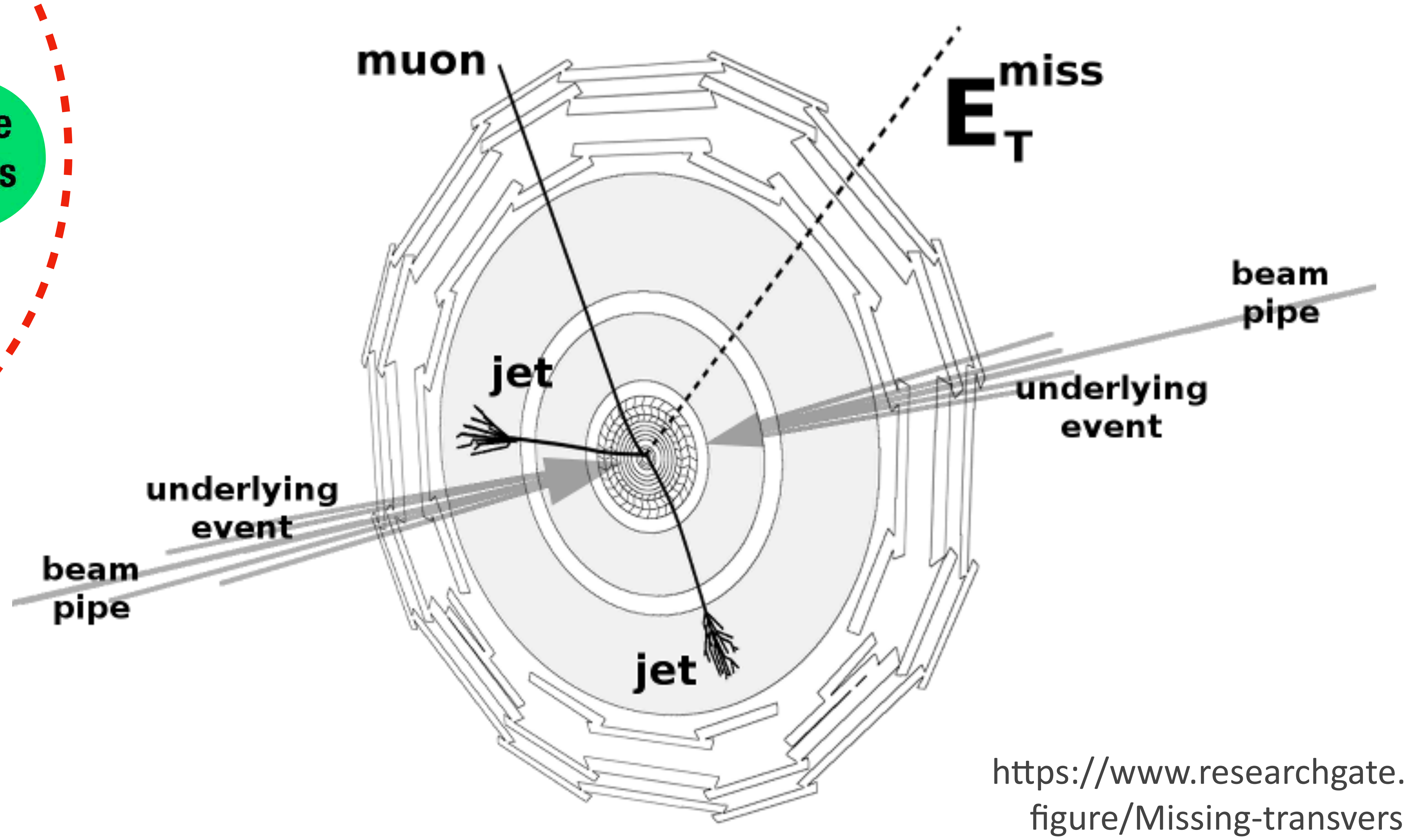
Exotic searches: Dark Matter searches at collider



https://home.cern/news/series/lhc-physics-ten/breaking-new-ground-search-dark-matter

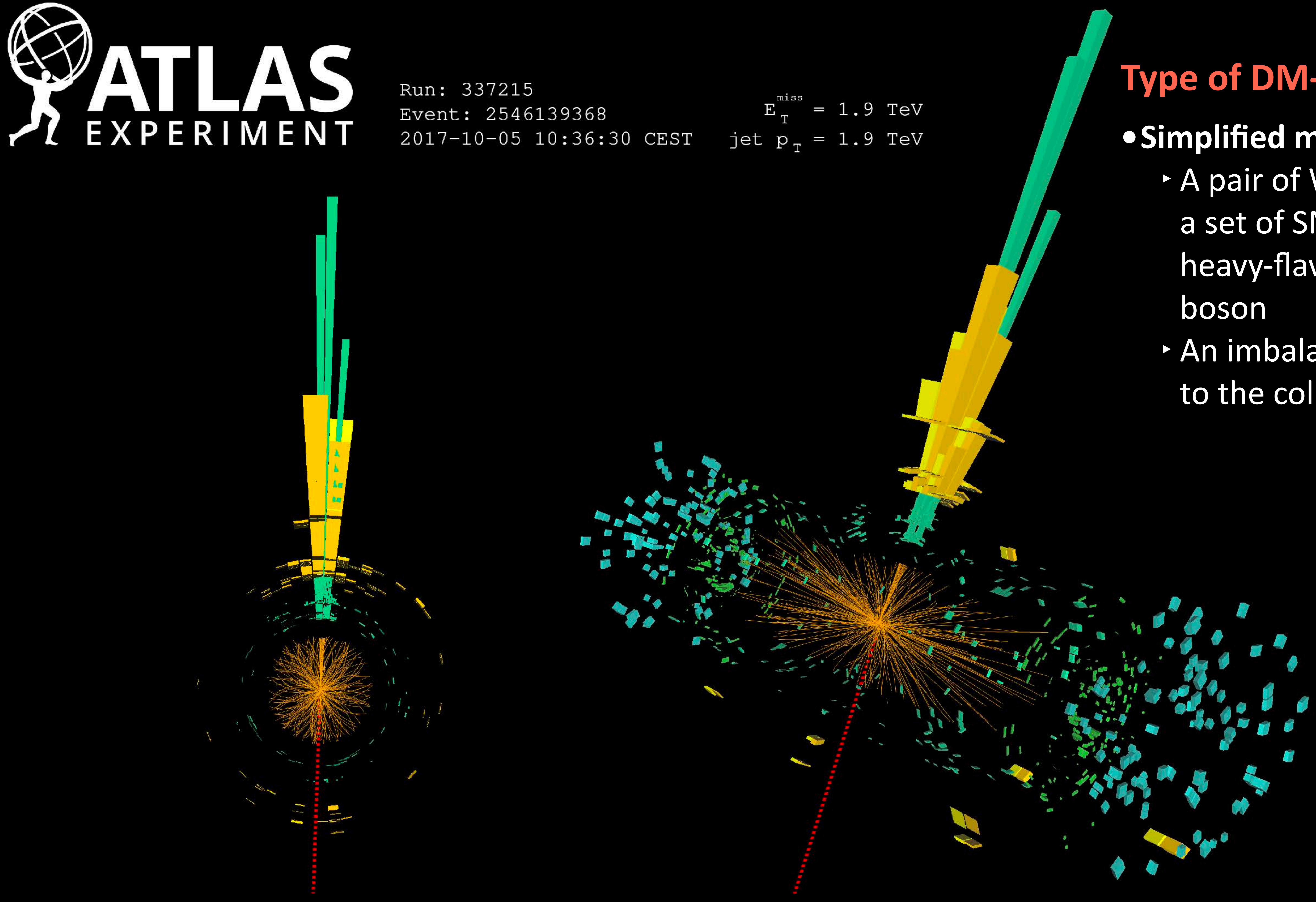
How do we search for dark matter at the collider?

Since the dark matter does not interact to the material in the way we know (e.g. without electromagnetic interaction), so we assume that if it is produced at the LHC, it will leave from our detector without making a signal (energy loss) to the sensitive regions of the detector. Missing (transverse) momentum is the basis of search at the LHC.



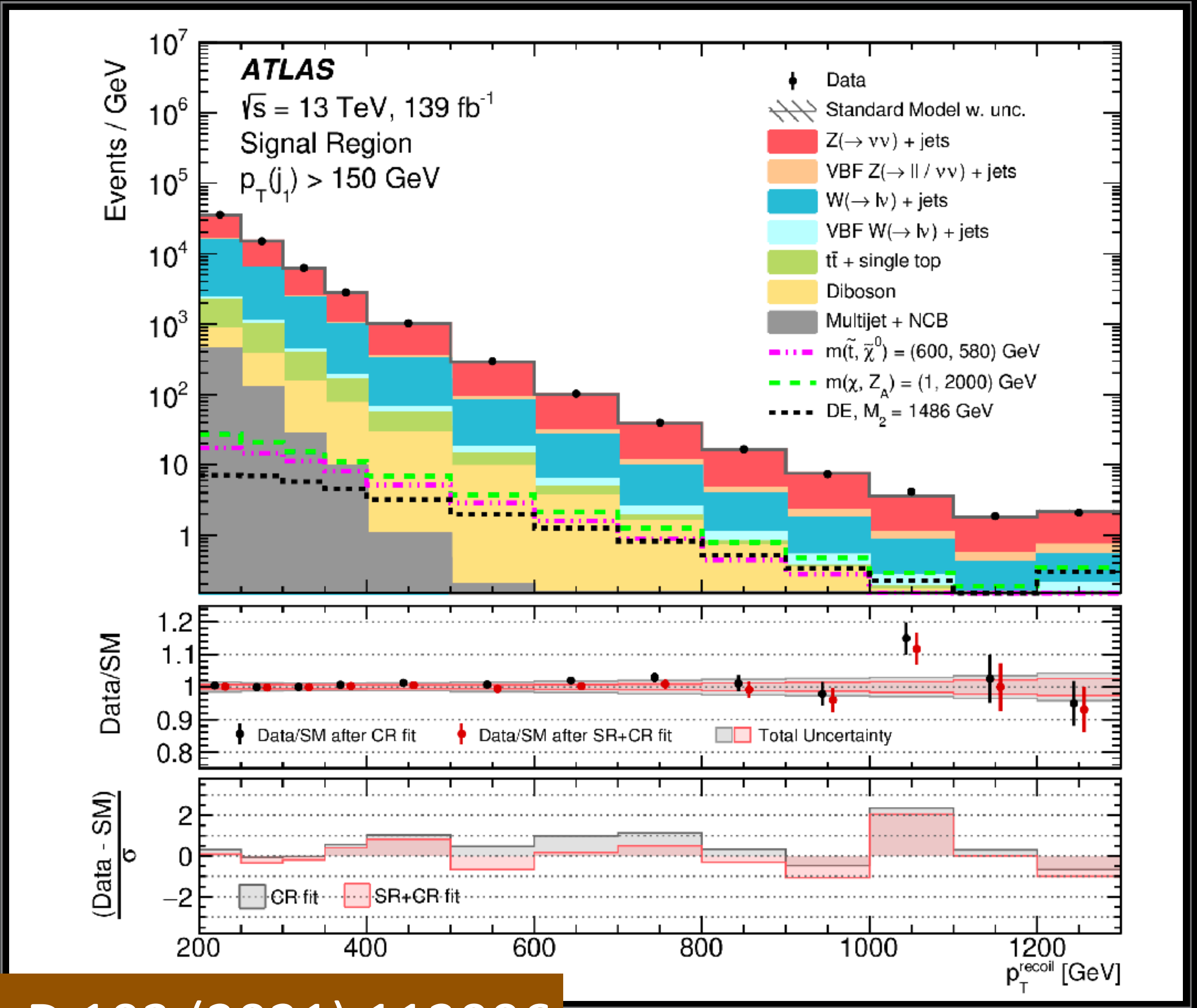
https://www.researchgate.net/figure/Missing-transverse-momentum_fig2_331397740

Exotic searches: ~~Darth Vader~~ Dark Matter



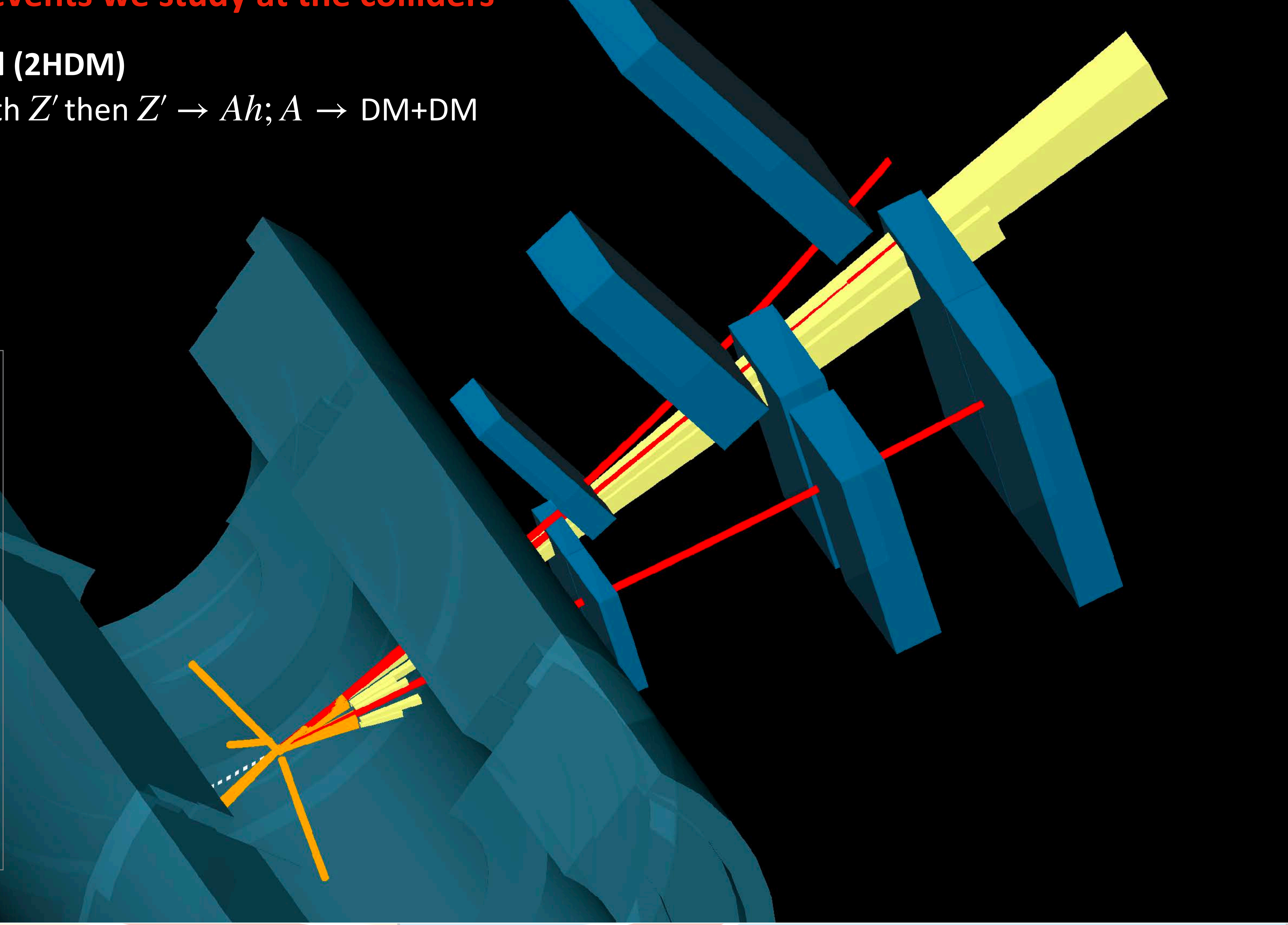
Type of DM-candidate events we study at the colliders

- **Simplified models, one s-channel mediator (Mono-X)**
  - A pair of WIMPs that recoil against X (a visible SM particle, or a set of SM particles). Currently, X includes hadronic jet, heavy-flavor quarks, a photon, or a W or Z boson, even Higgs boson
  - An imbalance in the total momentum in the plane transverse to the colliding beams as reconstructed in the detector



Phys. Rev. D 103 (2021) 112006

Exotic searches: ~~Darth Vader~~ Dark Matter

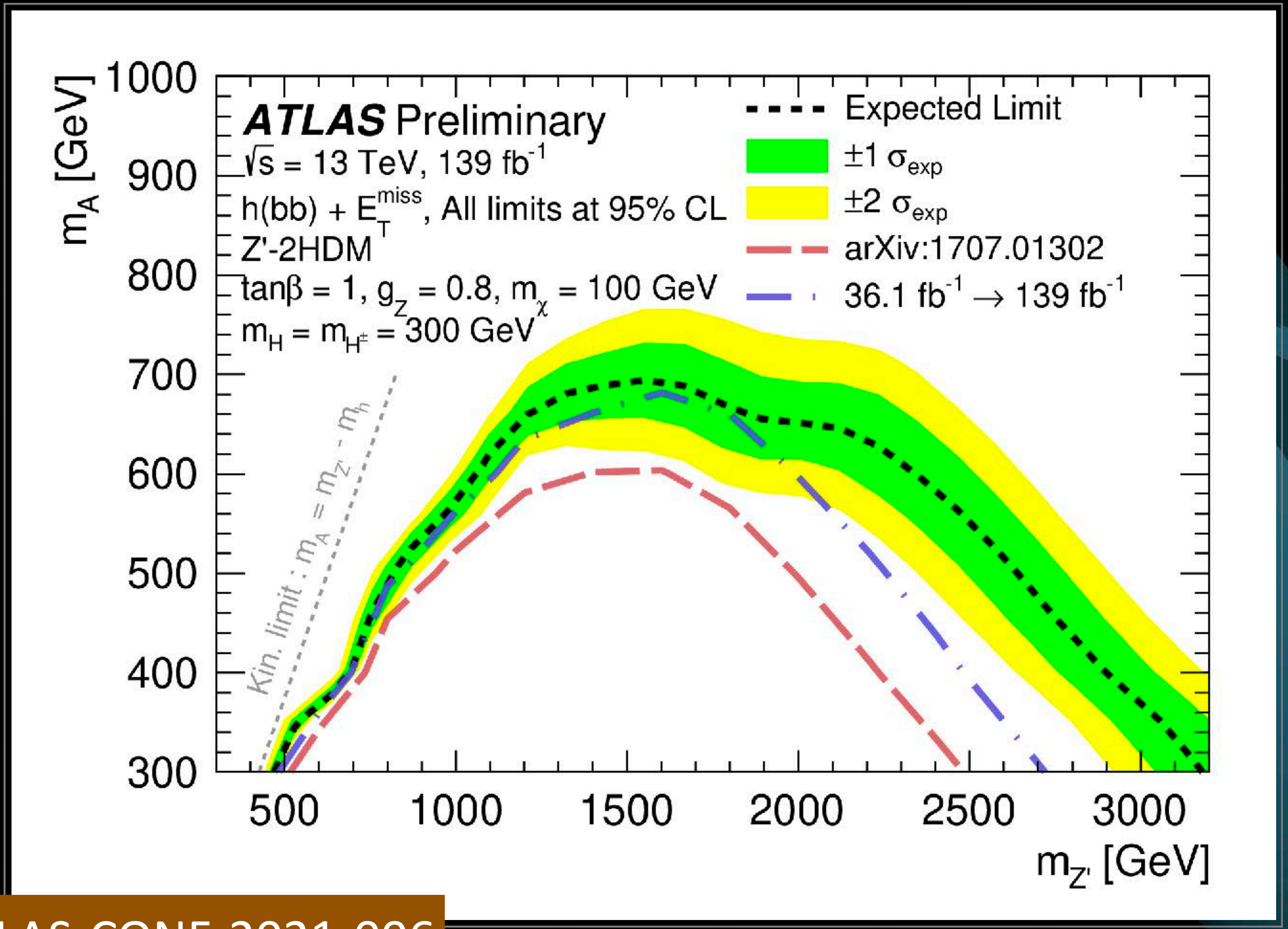


ATLAS EXPERIMENT

Run: 349309
Event: 769175011
2018-05-01 13:57:22 CEST

Type of DM-candidate events we study at the colliders

- **two-Higgs-doublet model (2HDM)**
  - Example: extension with Z' then $Z' \to Ah; A \to$ DM+DM



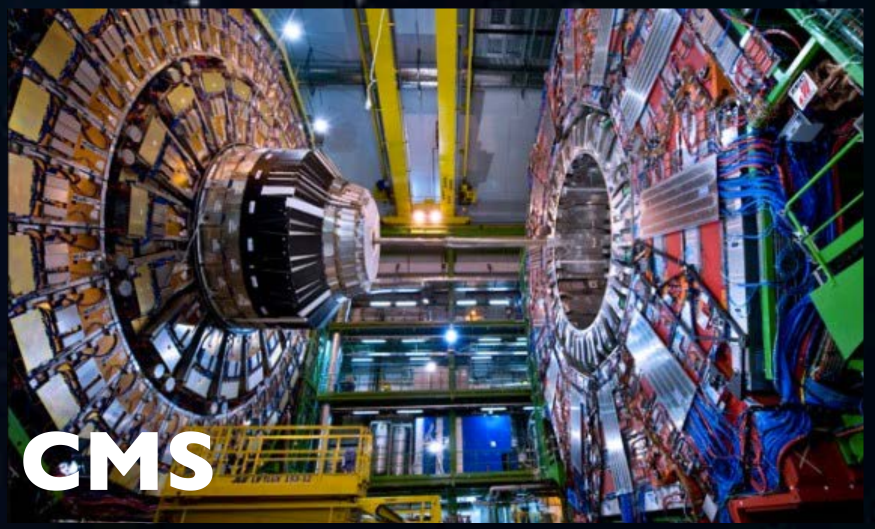
ATLAS-CONF-2021-006

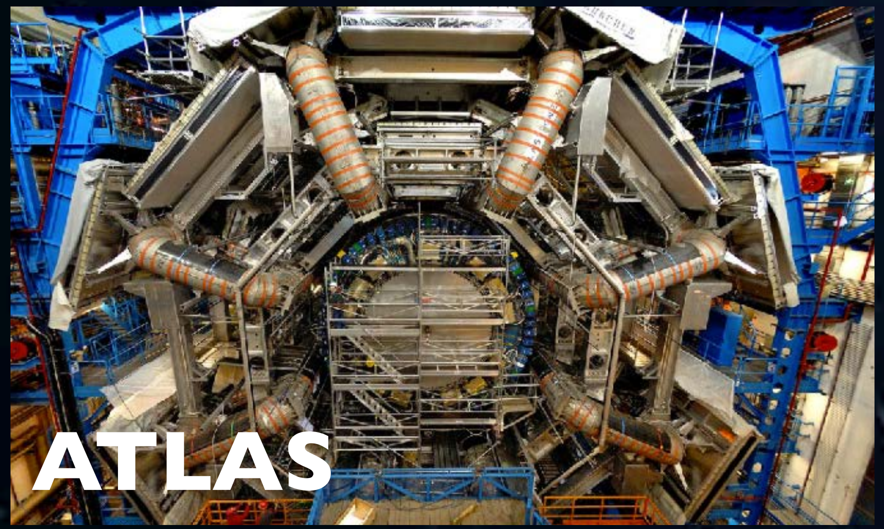
Dark matter searches

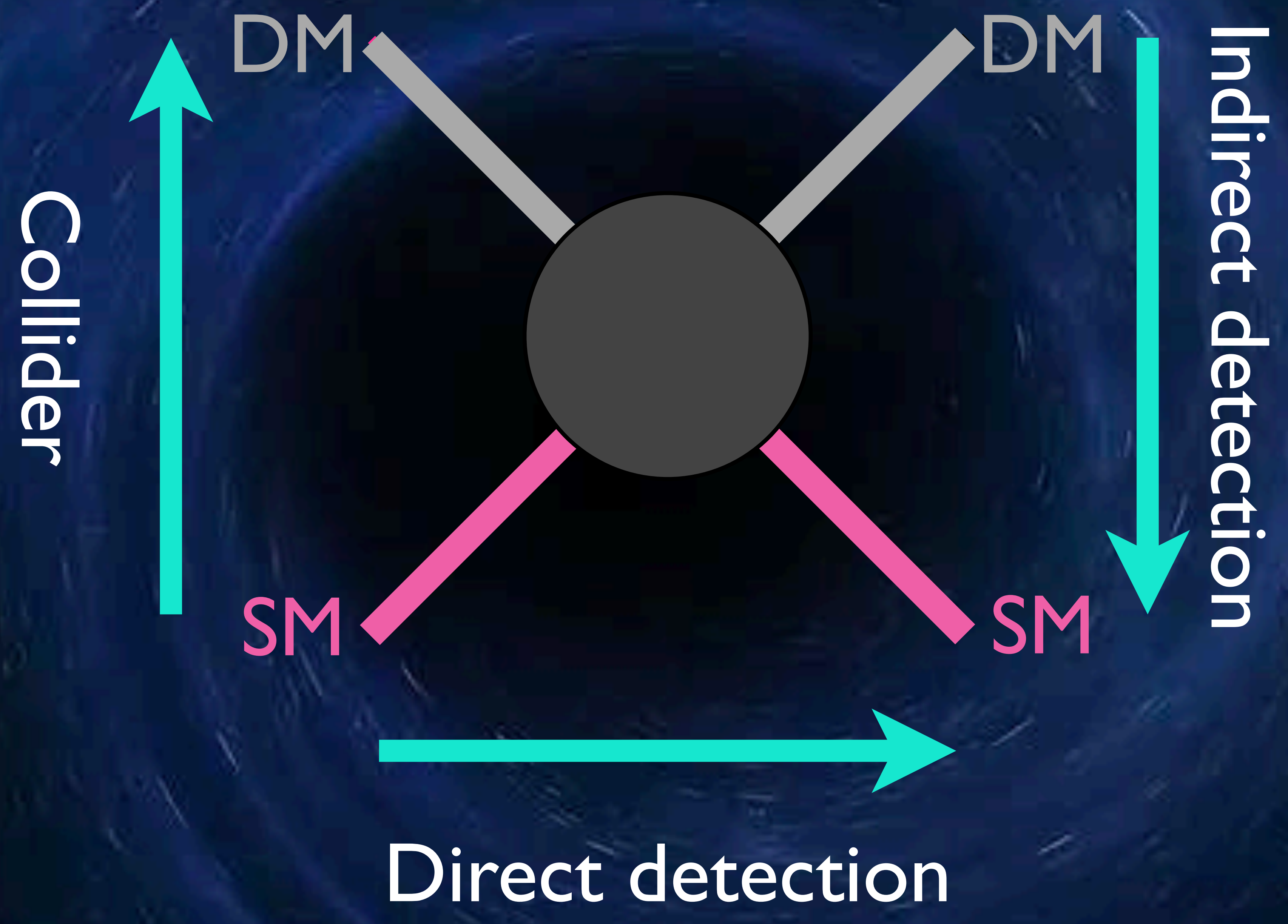
- Identify DM is one of the most important in physics.
- DM is likely to be (direct-)undetected particles.

Laboratory production of DM particles


LHC

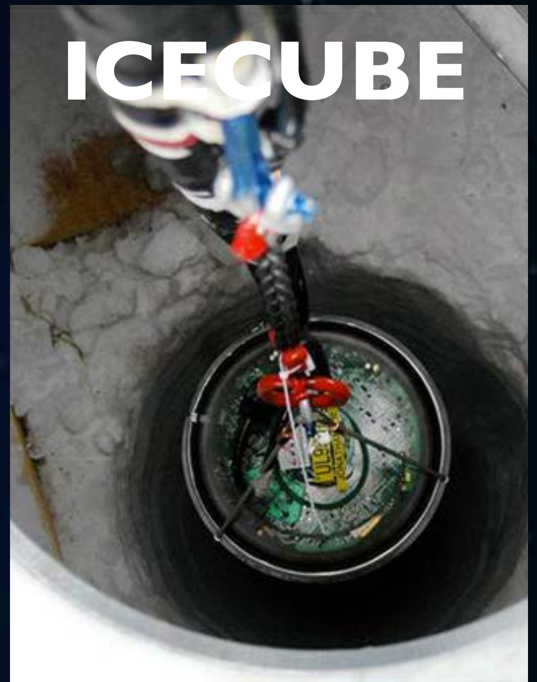

CMS

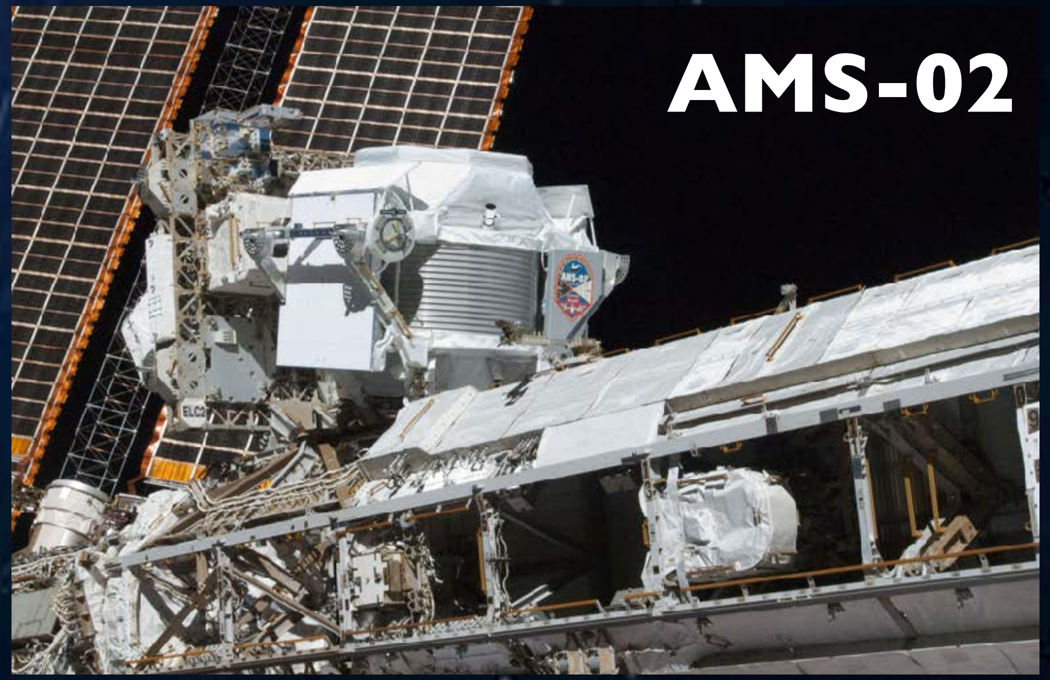

ATLAS


DM
DM
SM
SM
Collider
Indirect detection
Direct detection

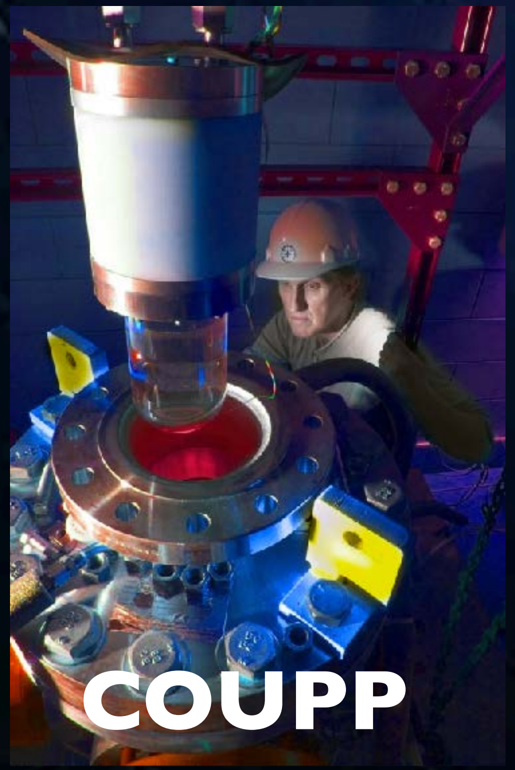
Observe DM annihilation products

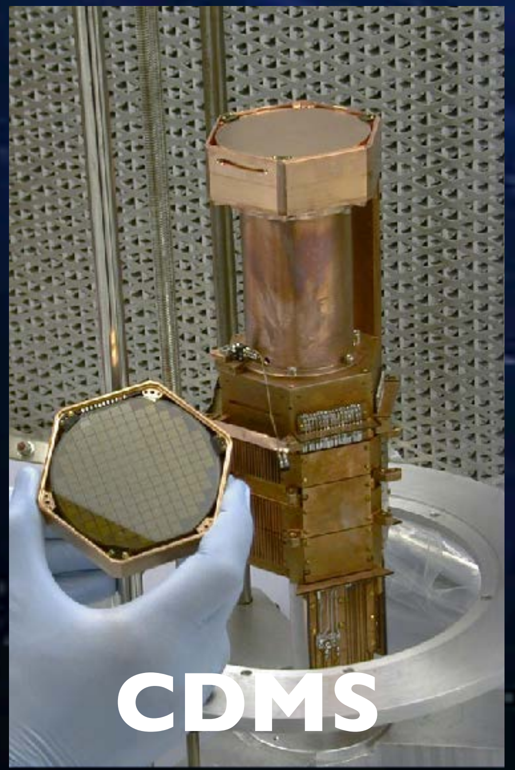

FERMILAT


ICECUBE

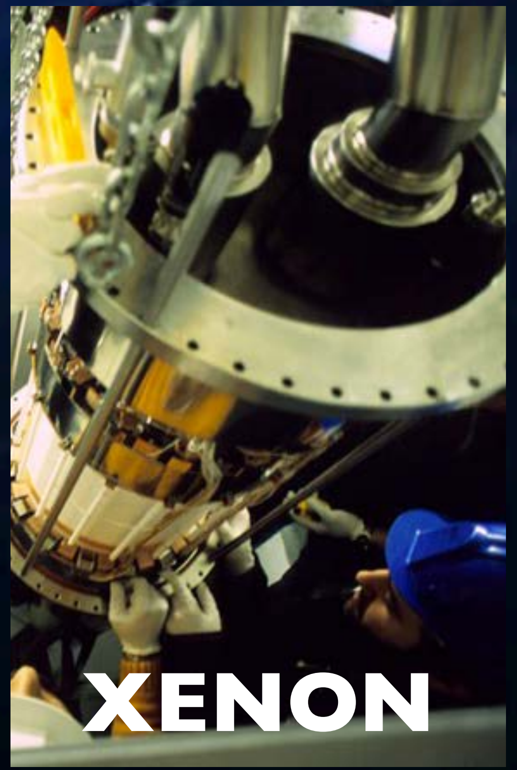

AMS-02

Dark Matter-nucleus scattering

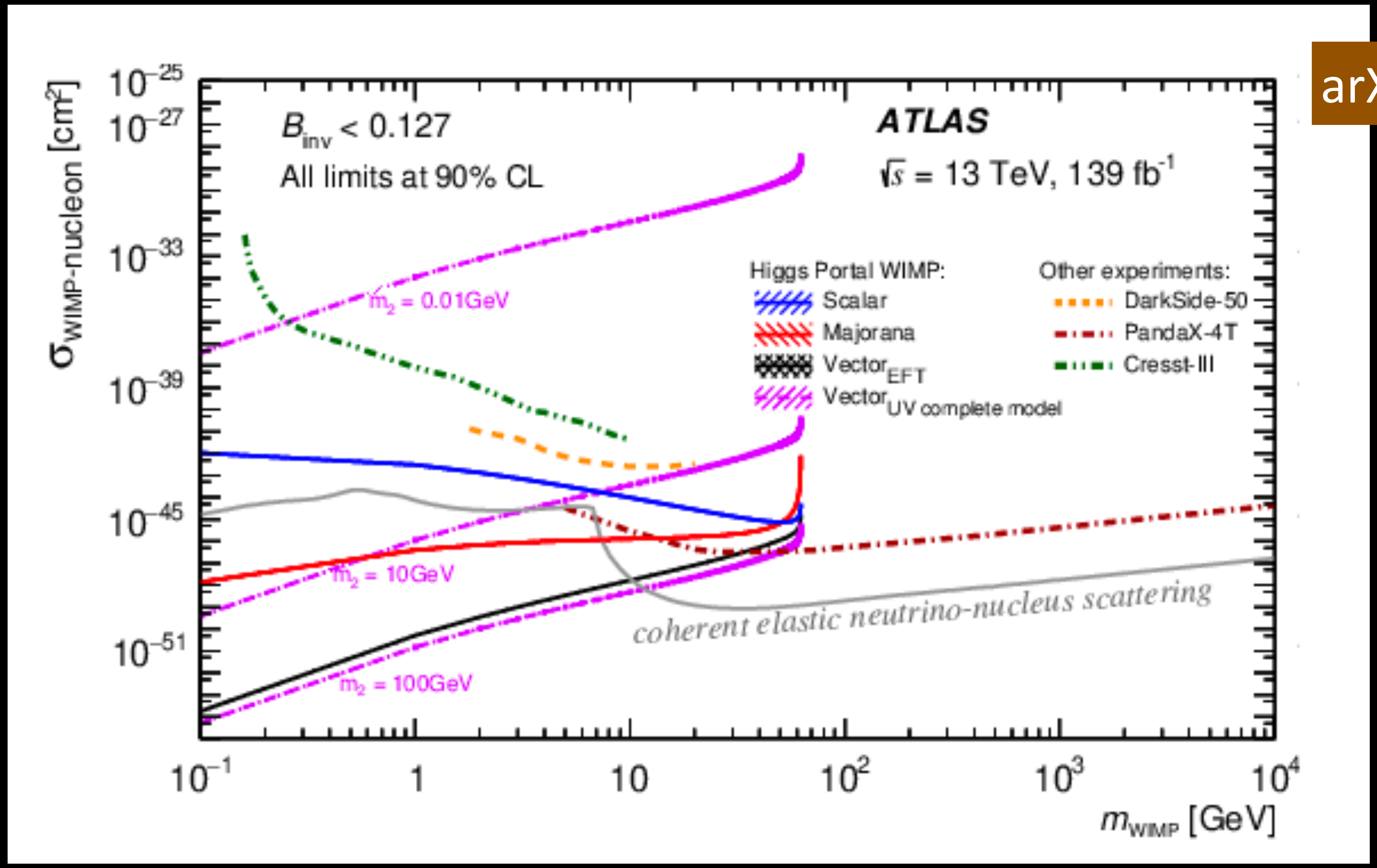

COUPP


CDMS


LUX


XENON

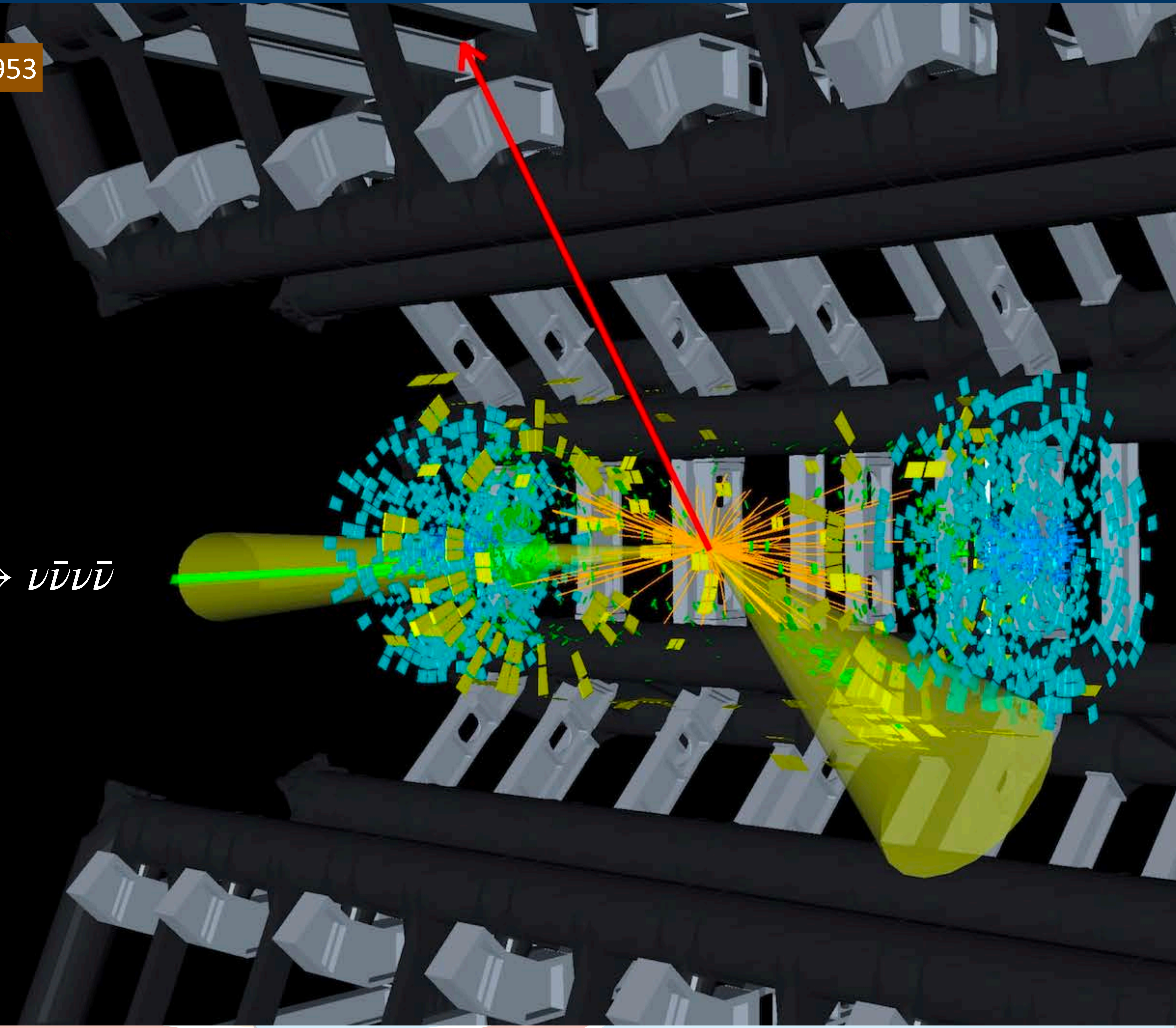
Invisible Higgs



arXiv:2202.07953

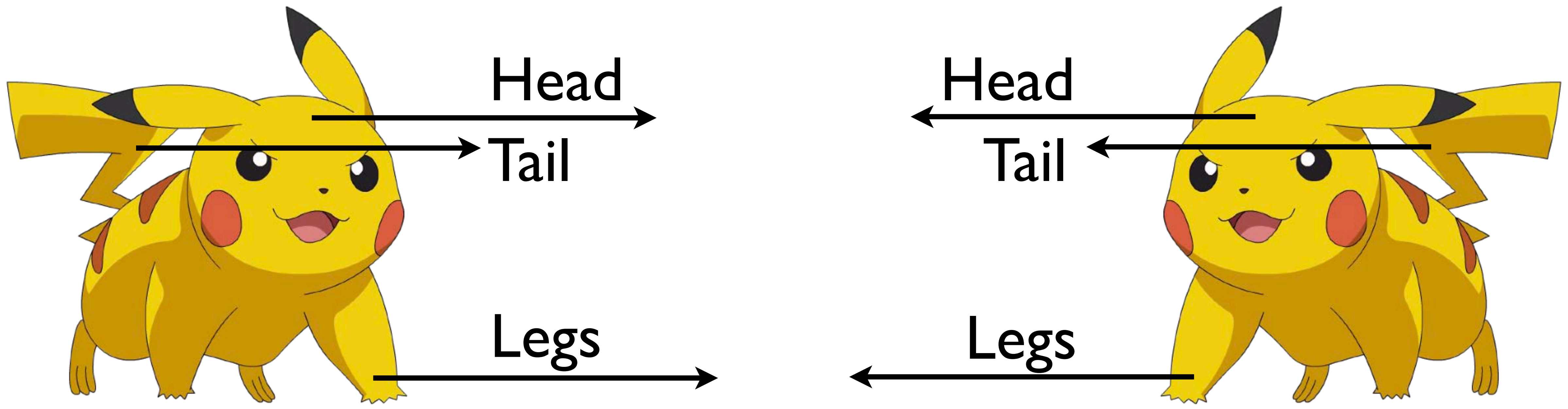
- SM Higgs decay invisible, $H \rightarrow ZZ \rightarrow \nu\bar{\nu}\nu\bar{\nu}$
- DM model $H \rightarrow \chi\chi$

ATLAS EXPERIMENT

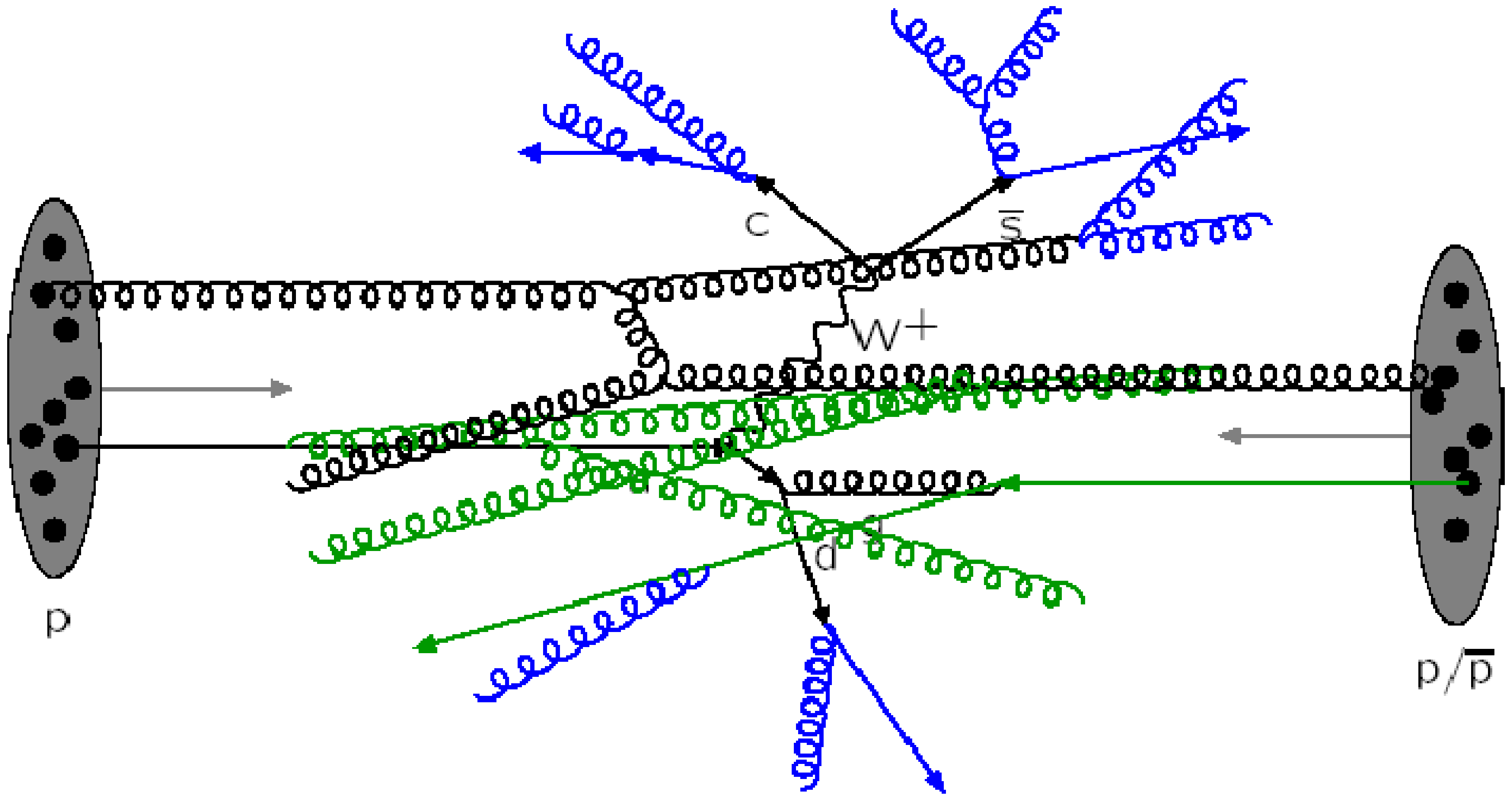


Proton collision

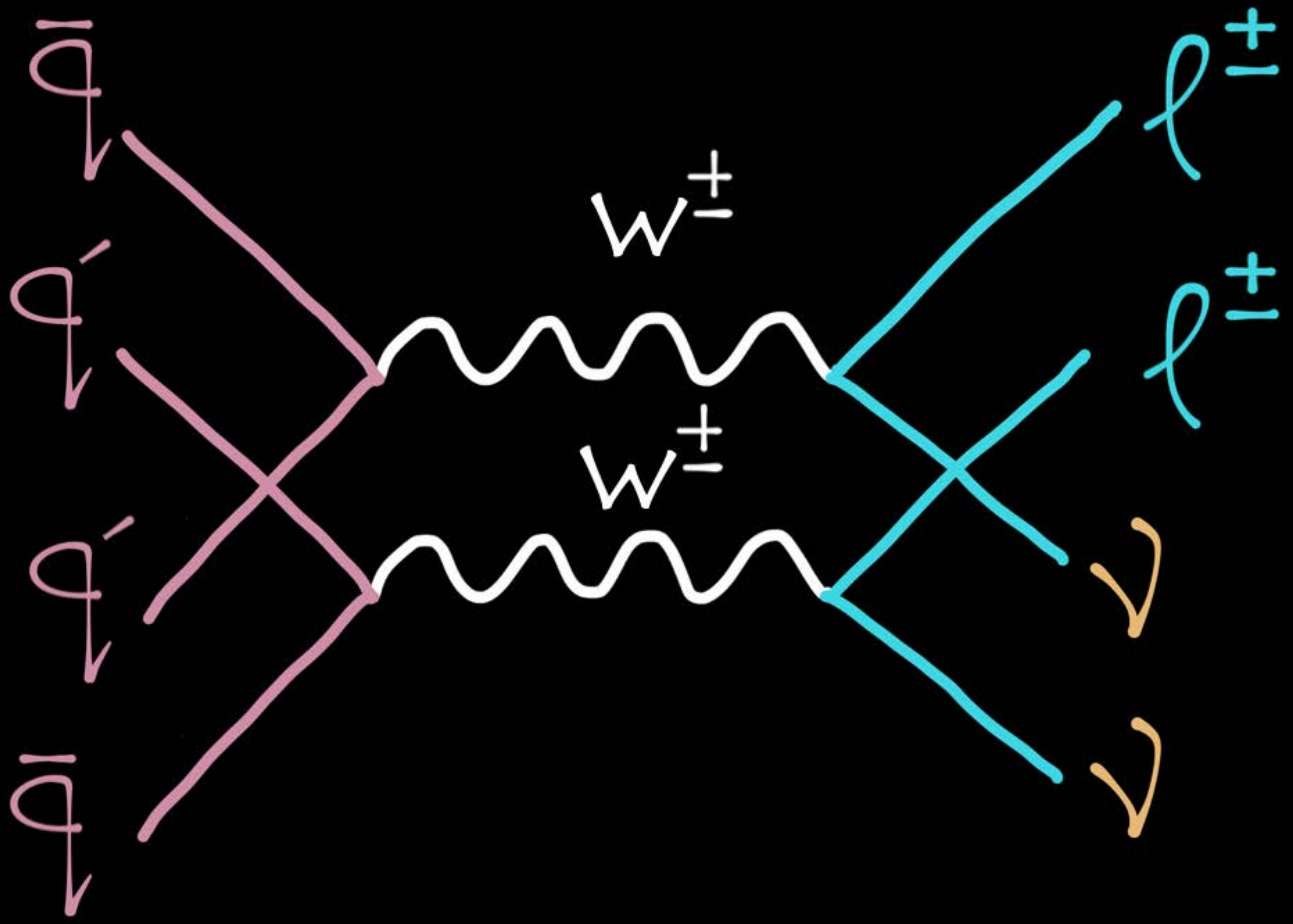
When “You” watch Pikachu fighting, you watch one-by-one interaction, i.e. Head-vs-Head, Tail-vs-Head, Head-vs-Leg, and then you are looking for the final result. This is the same case as proton interaction.

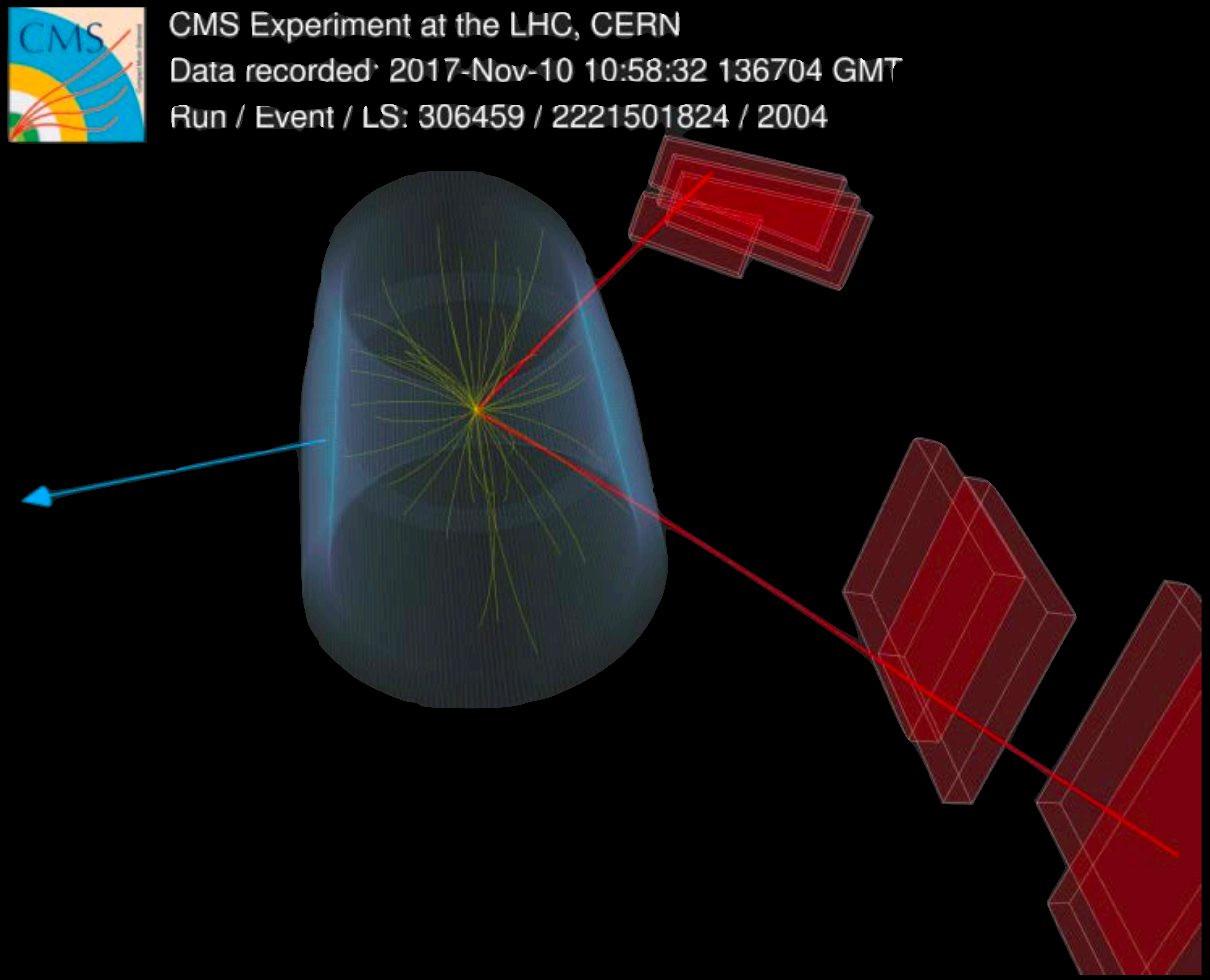


Really?

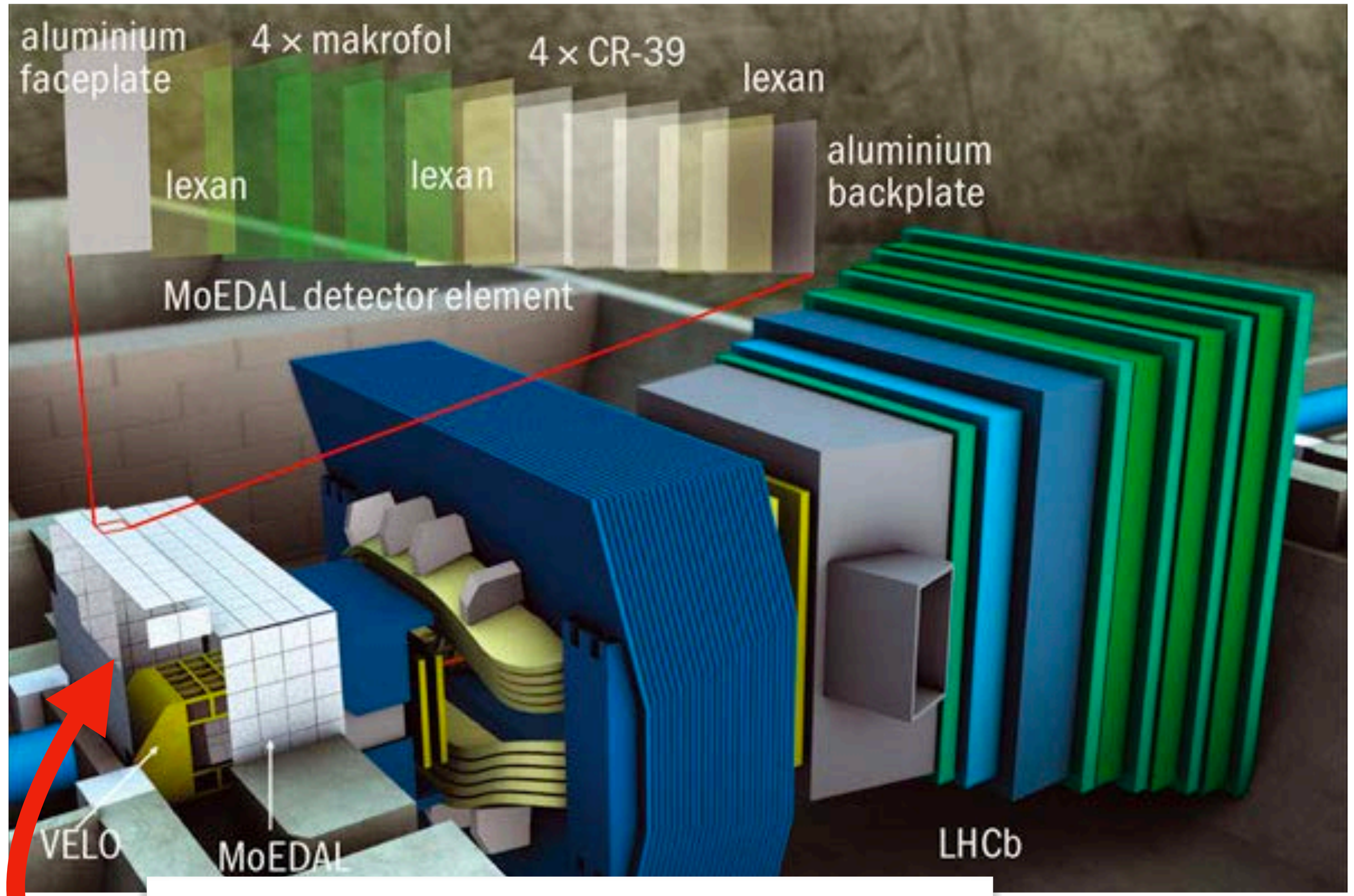


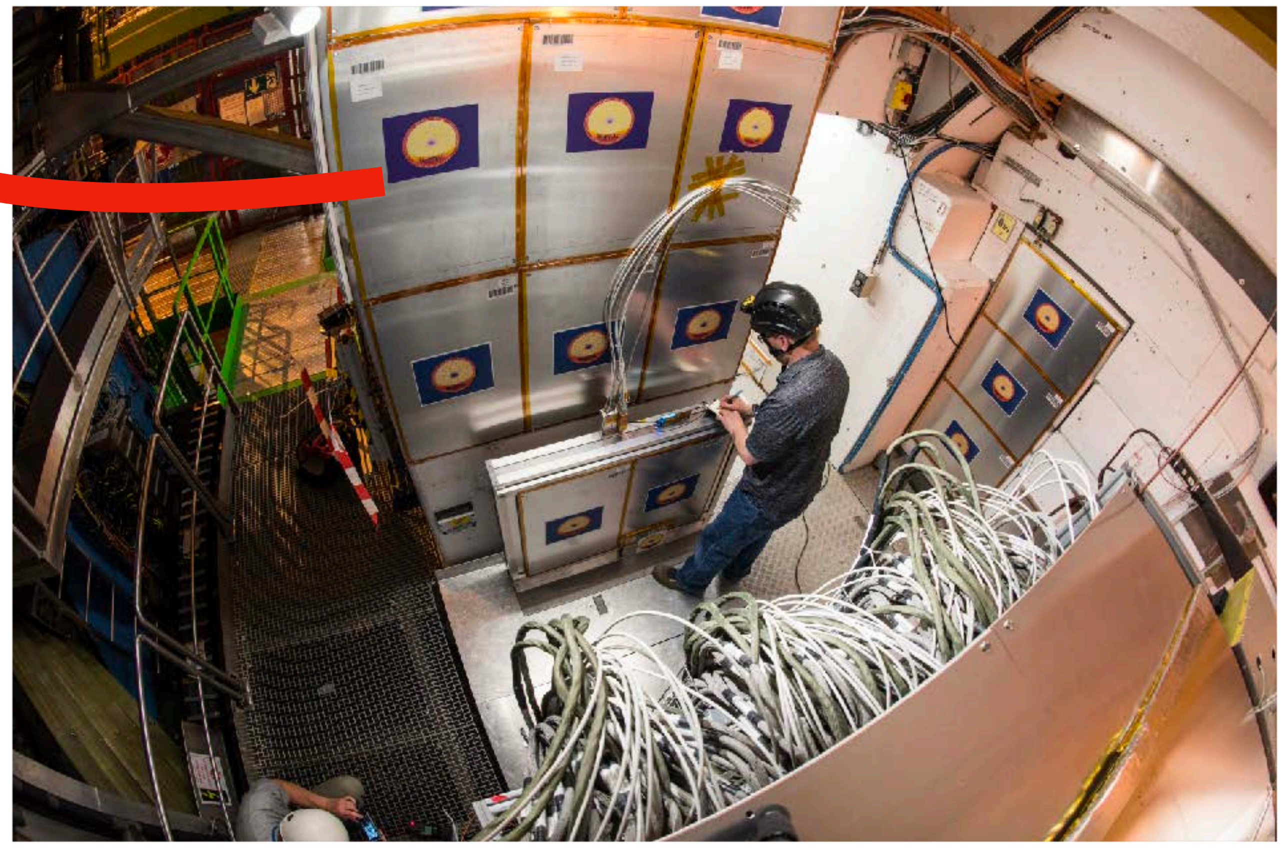
Double parton scattering





Small experiments but big Physics potentials at the LHC

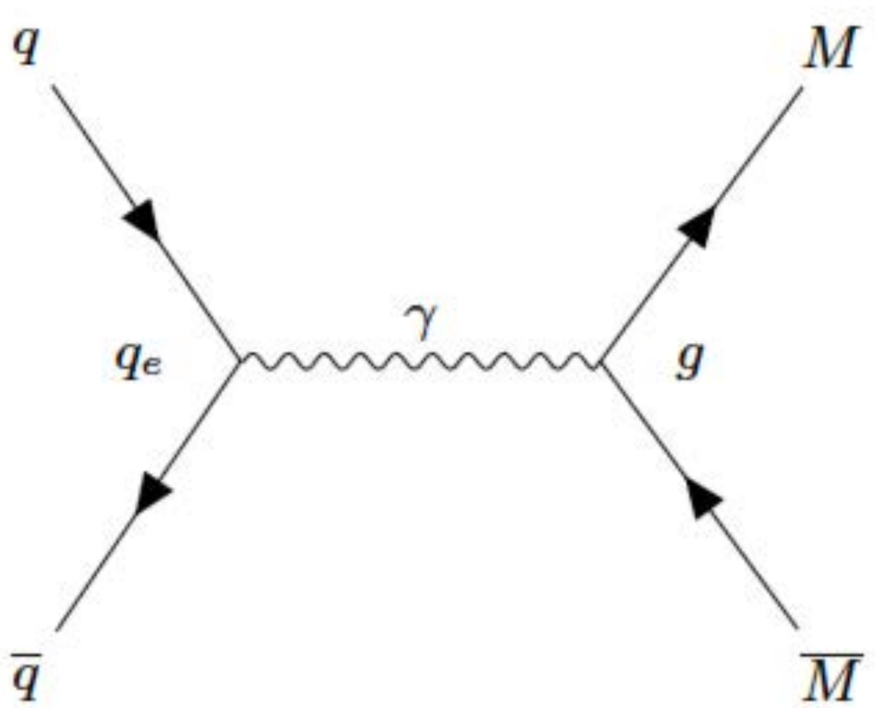


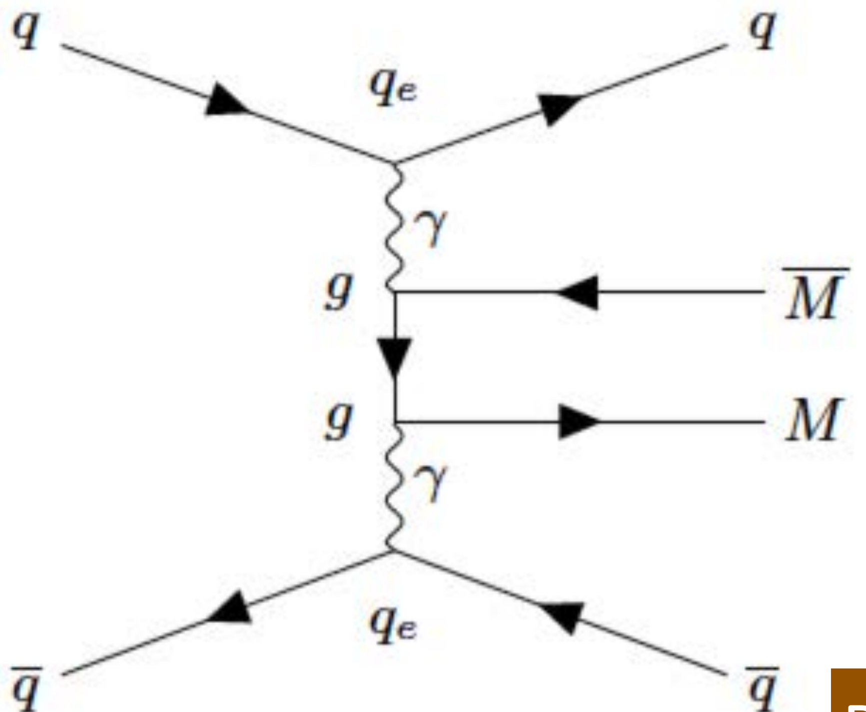


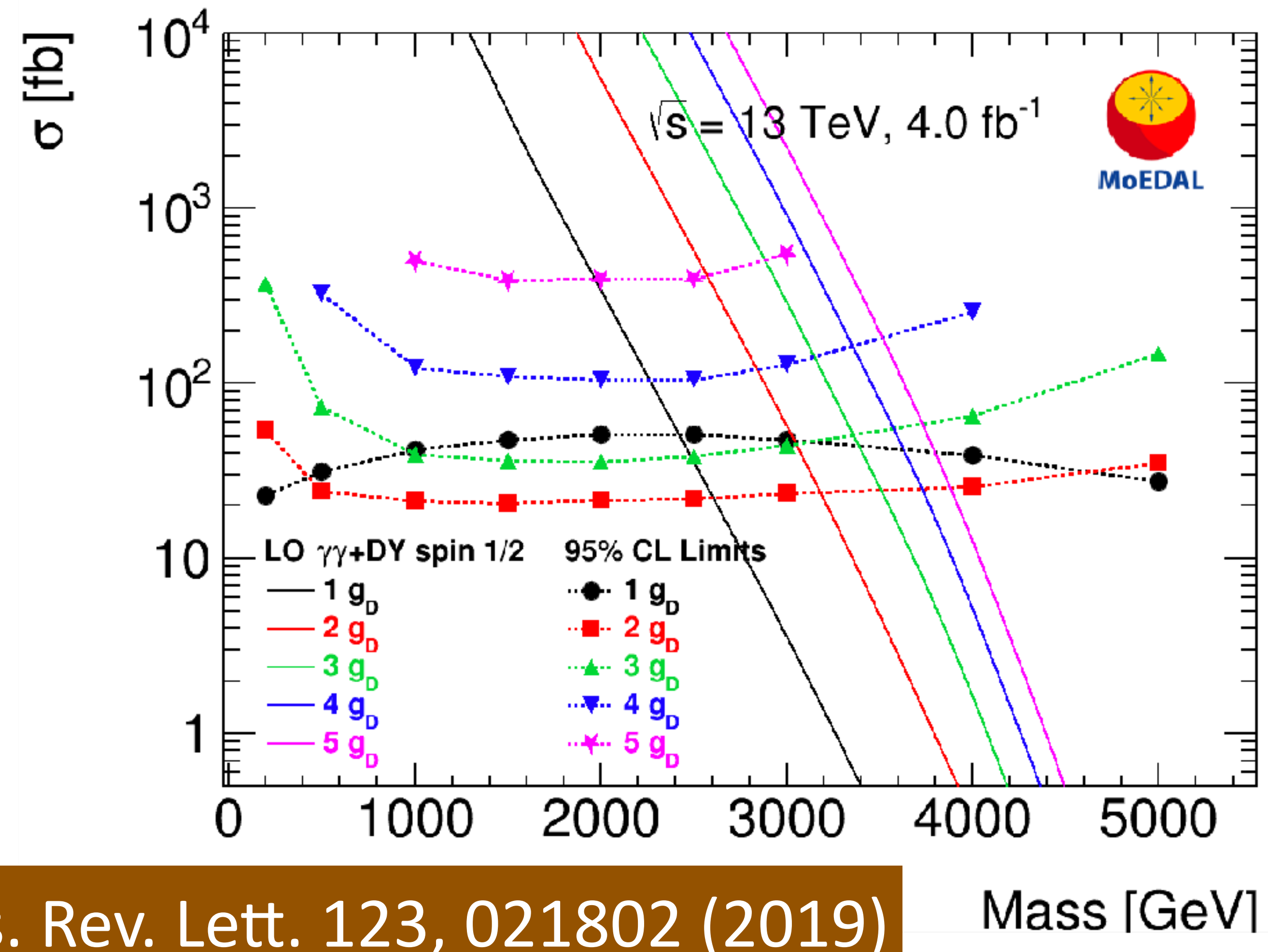
MoEDAL (the Monopole and Exotics Detector At the LHC)

Physicists uses the MoEDAL detector to search for a stable particle such as a magnetic monopole or a massive stable supersymmetric particle crossing through the plastic. MoEDAL detector is placed to the walls and ceiling of the cavern that houses the Vertex Locator (VELO) detector of the LHCb experiment. It consists of

- **plastic Nuclear Track Detectors (NTDs)**: plastics to capture any signals from magnetic monopoles,
- **Magnetic Monopole Trapper (MMT)**: roughly a ton of aluminium detectors that act as a trap for magnetic charge (trapping detectors),
- **Timepix Radiation Monitoring System**: an array of silicon pixel detectors used to monitor the experiment's environment in real time.





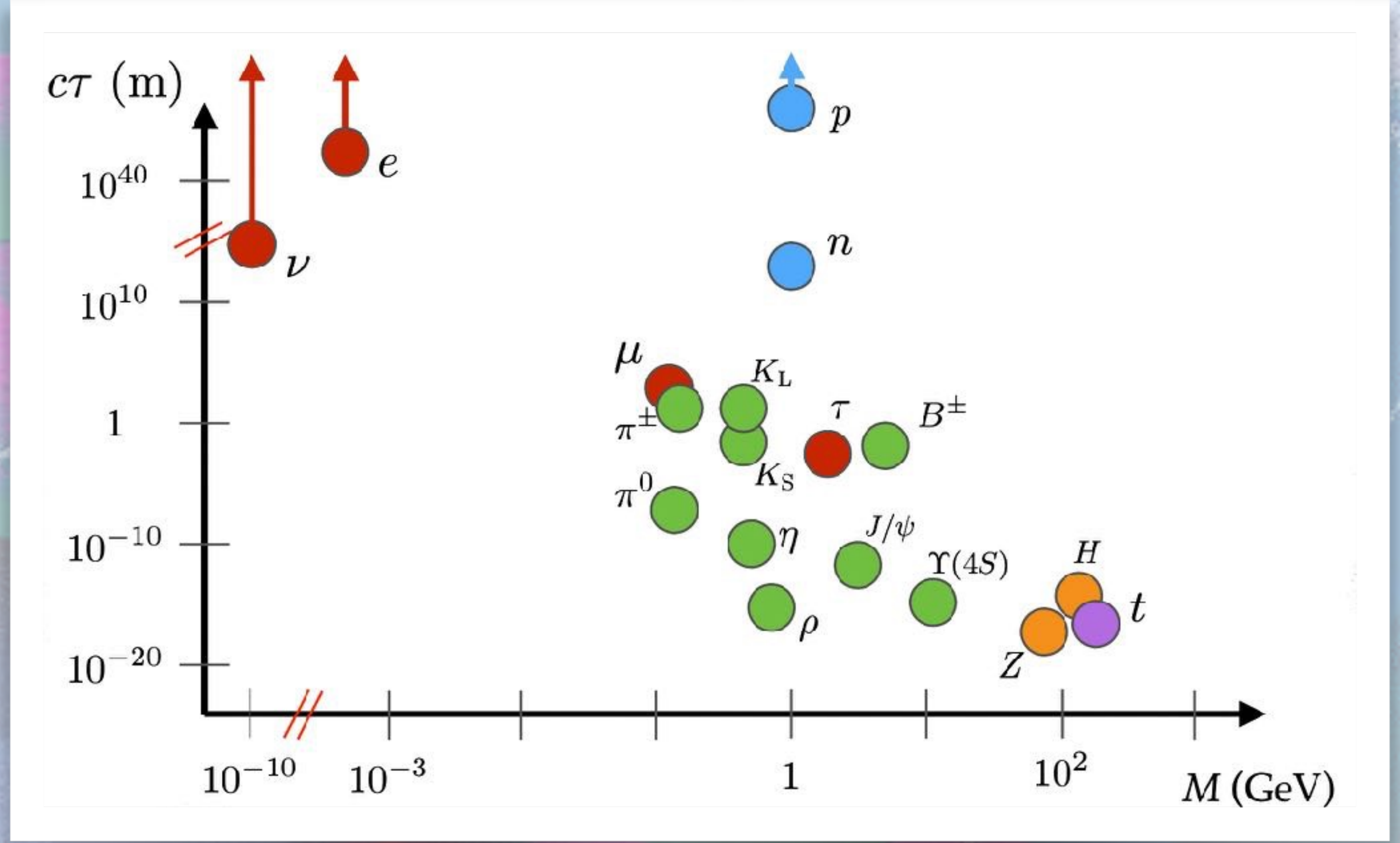


Phys. Rev. Lett. 123, 021802 (2019)

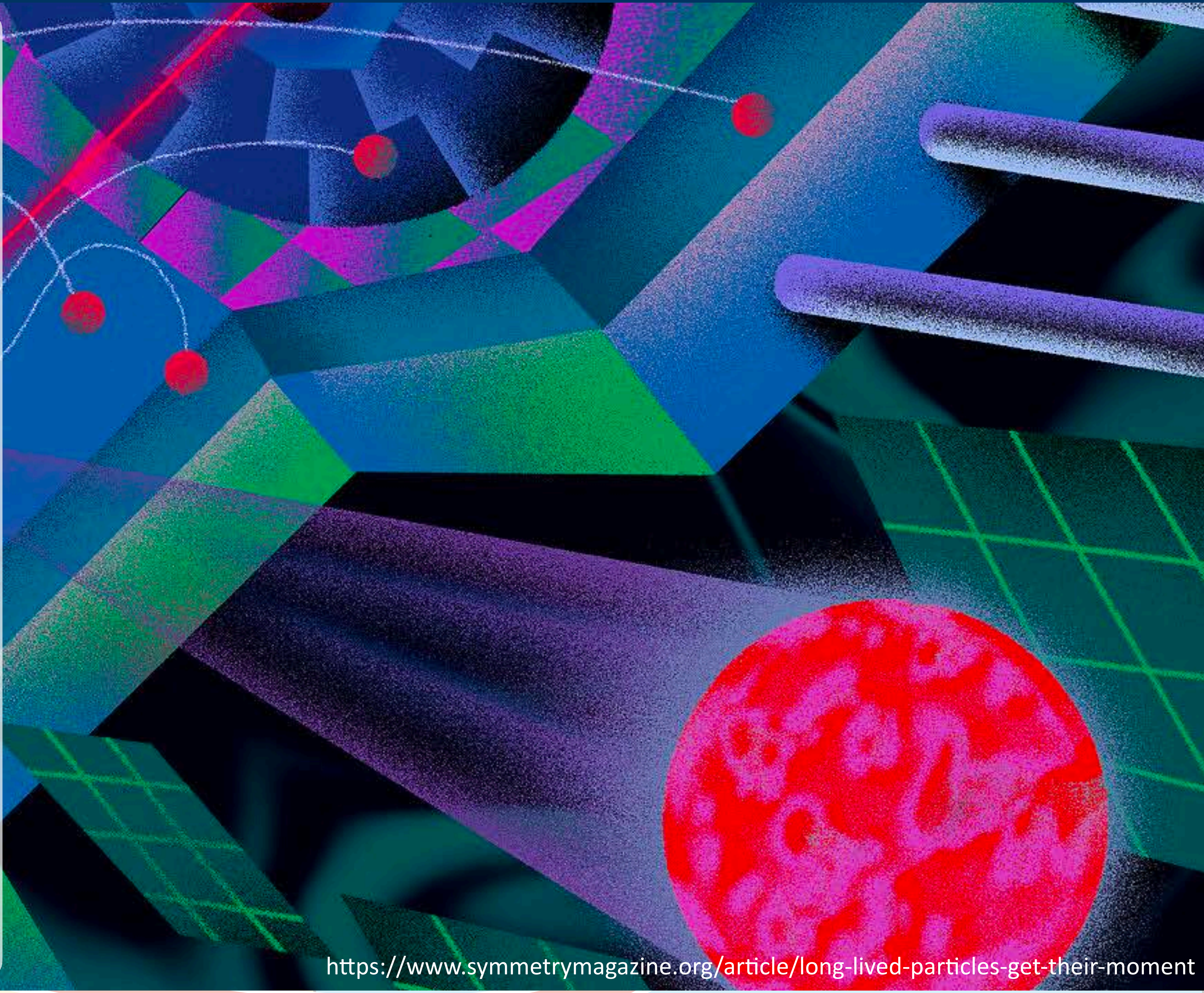
Exotic searches: Long-lived particles

When produced particles will not decay immediately …

In high energy particle physics experiments, physicists often assumes that new *massive* particles produced in particle collisions would decay immediately, closed to their points of origin, e.g. Higgs boson. However, we also know that there are particles which have long lifetimes, e.g. muons which can travel several kilometers (with the help of special relativity) before transforming into electrons and neutrinos.



What if new particles we are hunting for has long lifetimes and traveled centimeters—even kilometers—before transforming into something physicists could detect?



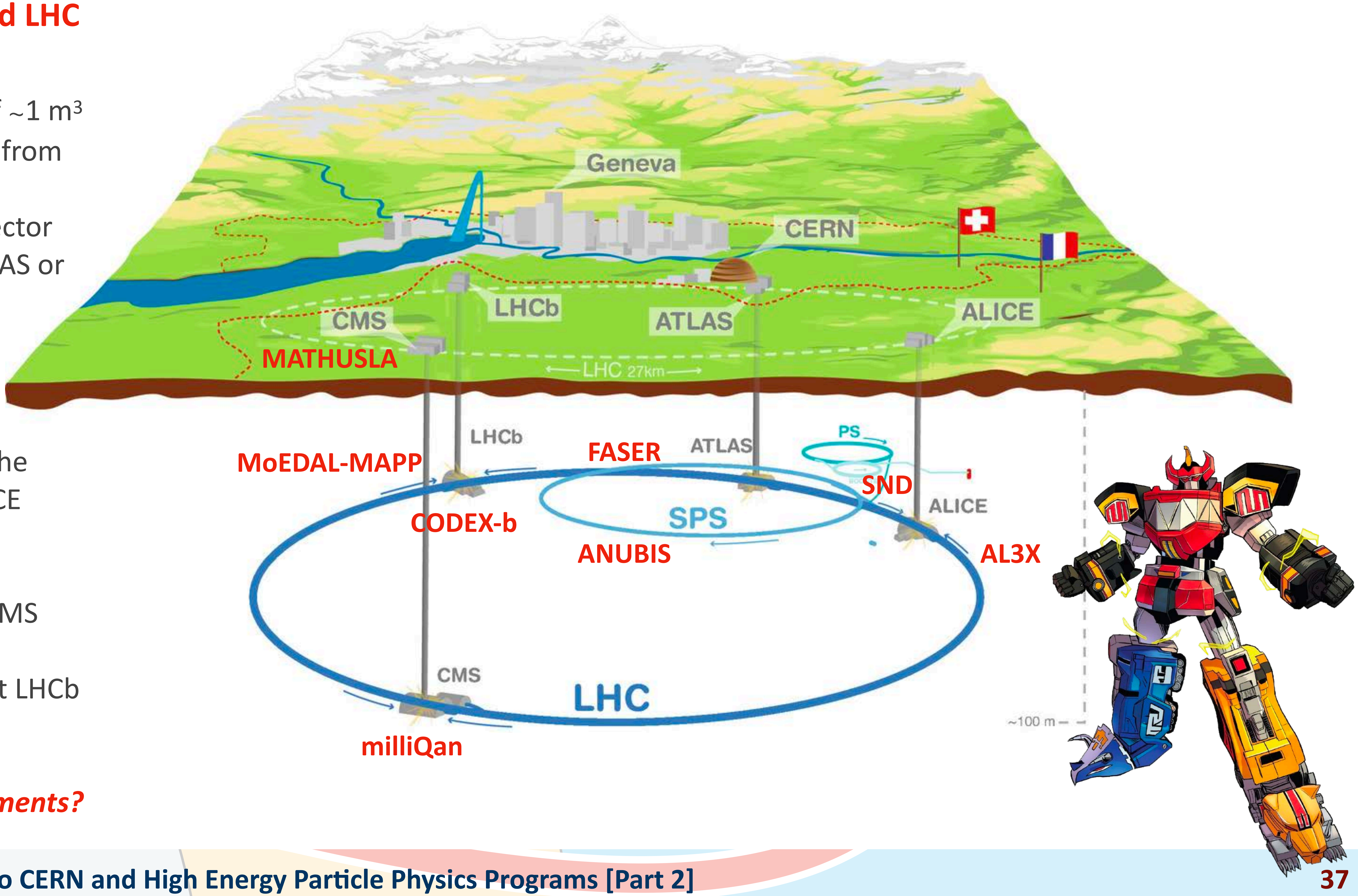
https://www.symmetrymagazine.org/article/long-lived-particles-get-their-moment

~~Power~~ Detector Rangers: To search for Long-lived particles

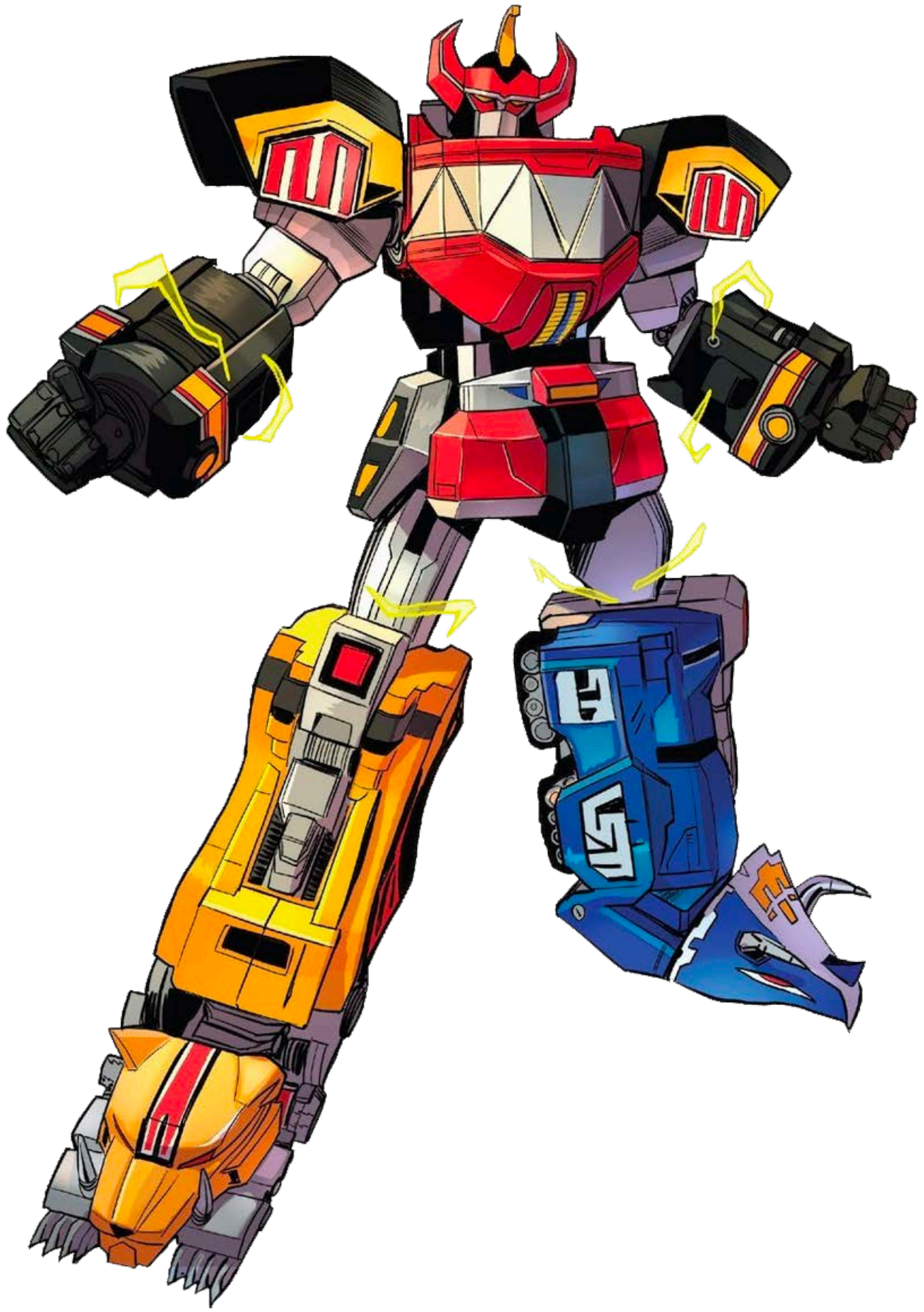
Several small experiments around LHC to search for LLPs

- **FASER** (Approved): with a volume of ~1 m^3 will be installed 480 m downstream from the ATLAS interaction point
- **MATHUSLA**: large scale surface detector instrumenting ~8×10^5 m^3 above ATLAS or CMS
- **CODEX-b**: ~10^3 m^3 detector to be installed in the LHCb cavern
- **AL3X** to use a cylindrical ~900 m^3 detector inside the L3 magnet and the time-projection chamber of the ALICE experiment
- **MilliQan** to search for millicharged particles in the drainage gallery of CMS
- **MoEDAL** to look for highly ionizing particles like magnetic monopoles at LHCb alongside **MAPP**

.... Why do need need several experiments?



~~Power~~ Detector Rangers: To search for Long-lived particles

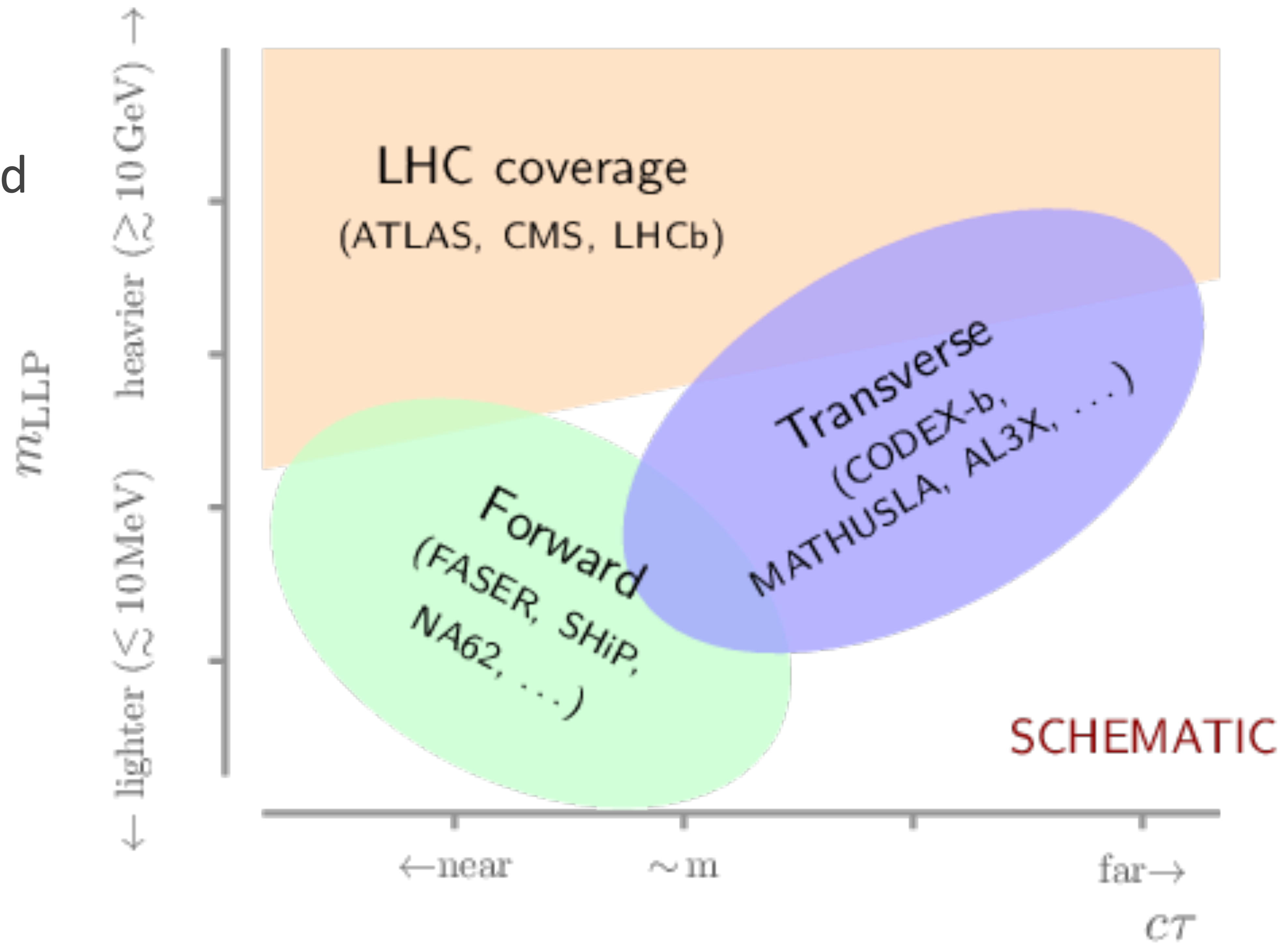


Why do we need detector rangers to search for LLP?

their masses ... don't know
their lifetimes ... don't know

Properties of LLPs may span many orders of magnitude. This makes us impossible from first principles to construct a single detector which would have the ultimate sensitivity to all possible LLP signatures. Multiple complementary experiments are necessary. ***However, we still need to connect to main-big detector. Why?***

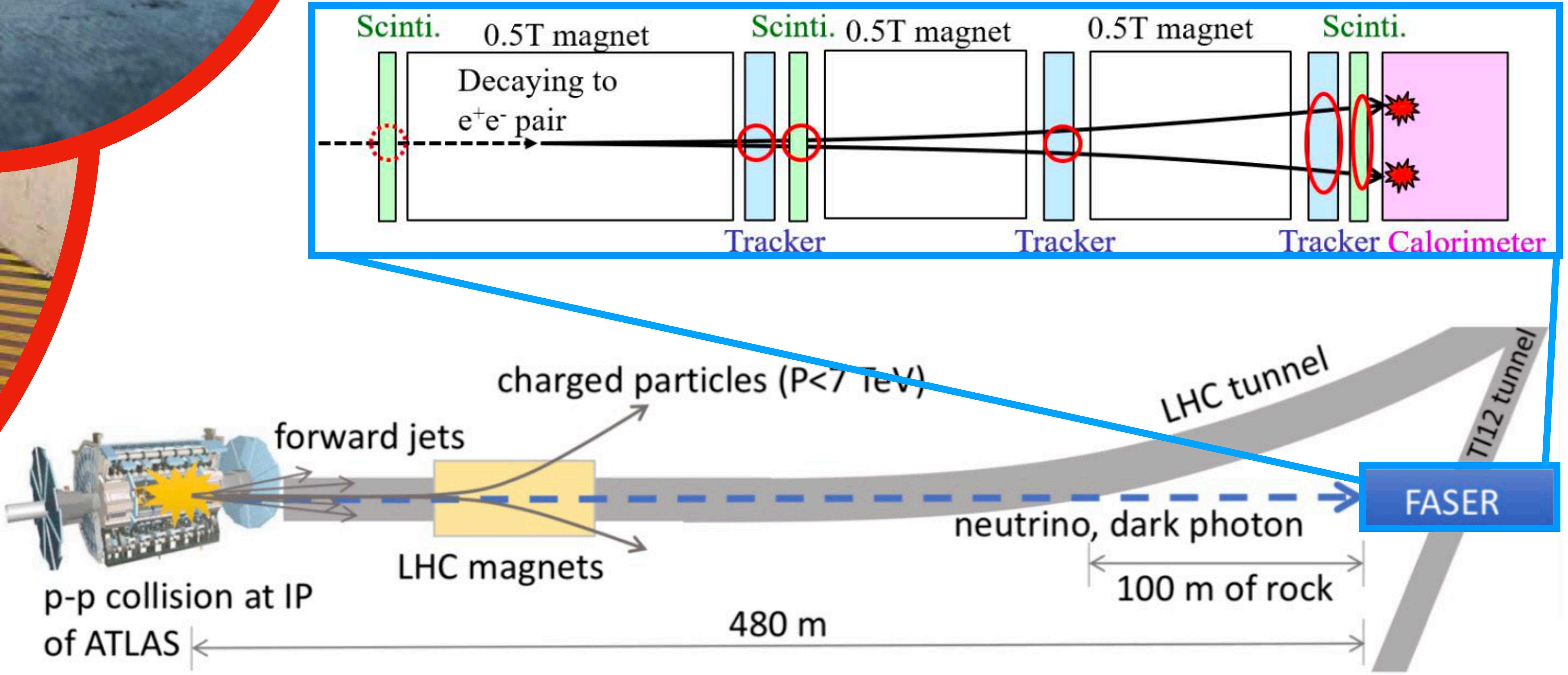
Because we assume that LLPs are produced at the four collision points of LHC. Information including timing can be obtained from big four experiment, to track events of interest.



ForwArd Search ExpeRiment (FASER)

Searches for new weakly-interacting light long-lived particles

- New particles produced in decays of light mesons
- Travel at ~zero angle
- Escaping detection in ATLAS (for FASER)/CMS
- $pp \rightarrow X + LLP$, then LLP travels for ~480m, $LLP \rightarrow e^+e^-, \mu^+\mu^-, \gamma\gamma, \ldots$
  - Several models including dark photon, axion-like particles (ALPs), heavy neutral leptons (HNLs), and dark Higgs bosons



The Scattering and Neutrino Detector at the LHC (SND@LHC)

The SND@LHC is located underground close to the ATLAS experiment, in an unused tunnel that links the LHC to the Super Proton Synchrotron. Positioned slightly off the LHC's beamline, it will be able to detect neutrinos produced in the LHC collisions at small angles with respect to the beamline.

SND@LHC consists of a neutrino target followed downstream by a device to measure the neutrino energy and to detect muons (the heavier cousins of electrons) that are produced when neutrinos interact with the target.

MoEDAL Apparatus for Penetrating Particles (MAPP)

Several small experiments around LHC to search for LLPs

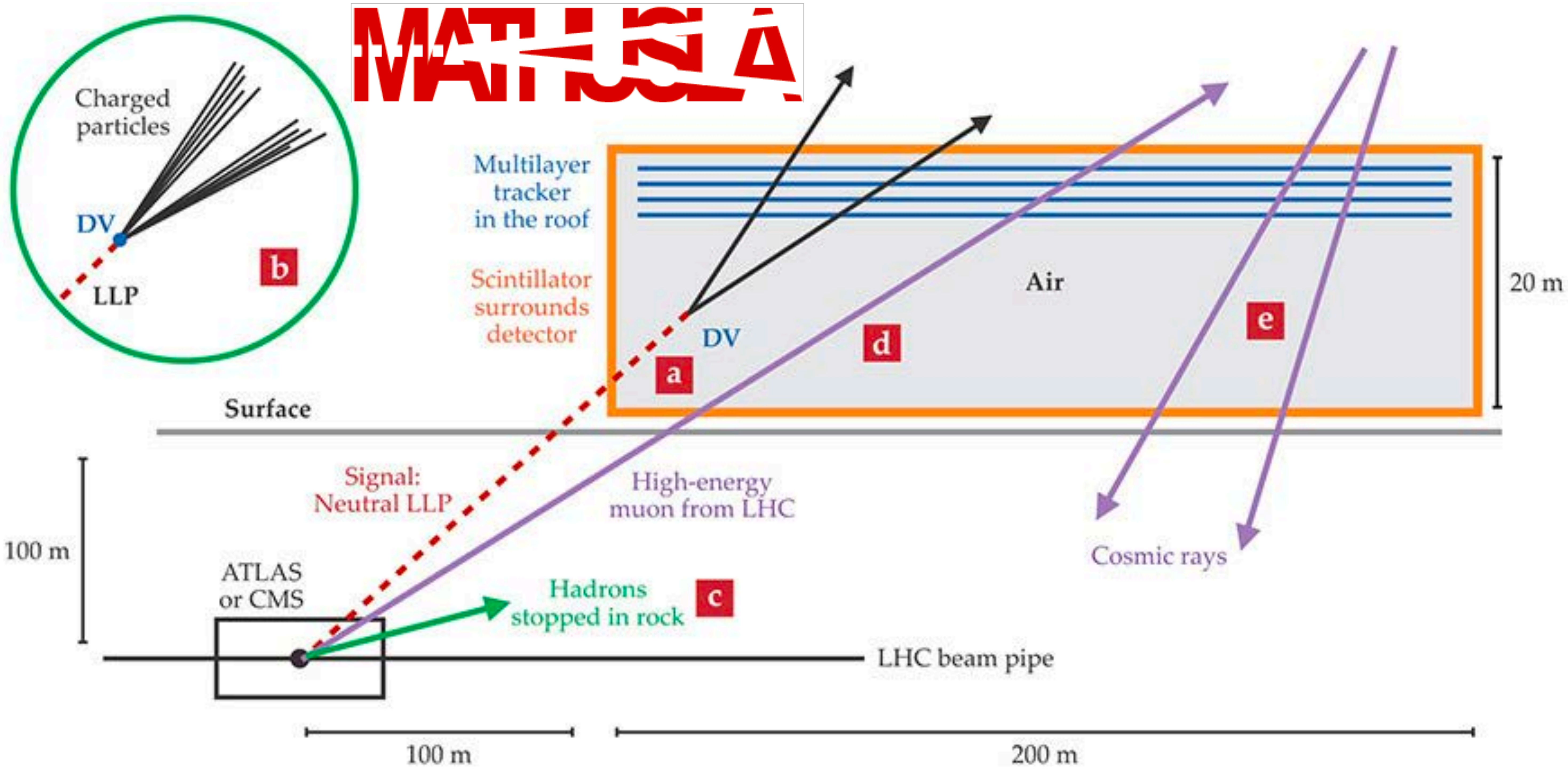
- For Phase-1 (LHC RUN-3): The baseline MoEDAL detector will be reinstalled and two MAPP sub detectors for two class of particles:
  - **MAPP-LLP**: nw pseudo-stable weakly interactive neutral particles with long lifetime
  - **MAPP-mQP**: mini-charged particle detector
- Positioned at an angle of 5-degree w.r.t. beam axis

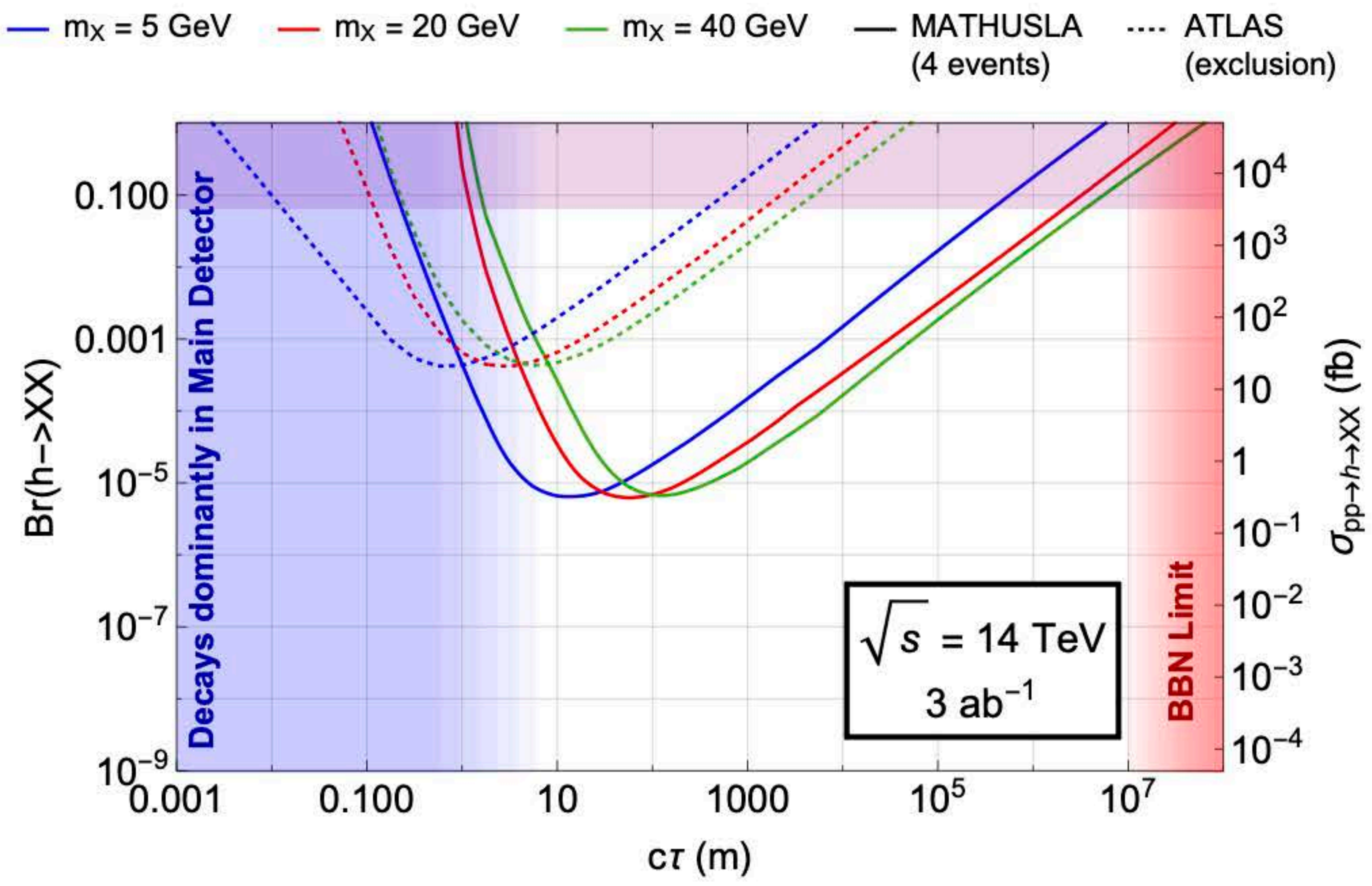
MAssive Timing Hodoscope for Ultra-Stable neutraL pArticles (MATHUSLA)

Ultra-long-lived particles (ULLP), with surface detector

Requirement: New detector that minimizes background as much as possible; Maintain reasonably large radial detector size and solid angle coverage relative to the main interaction point (IP); Cheap. The proposal is to go for surface detector:

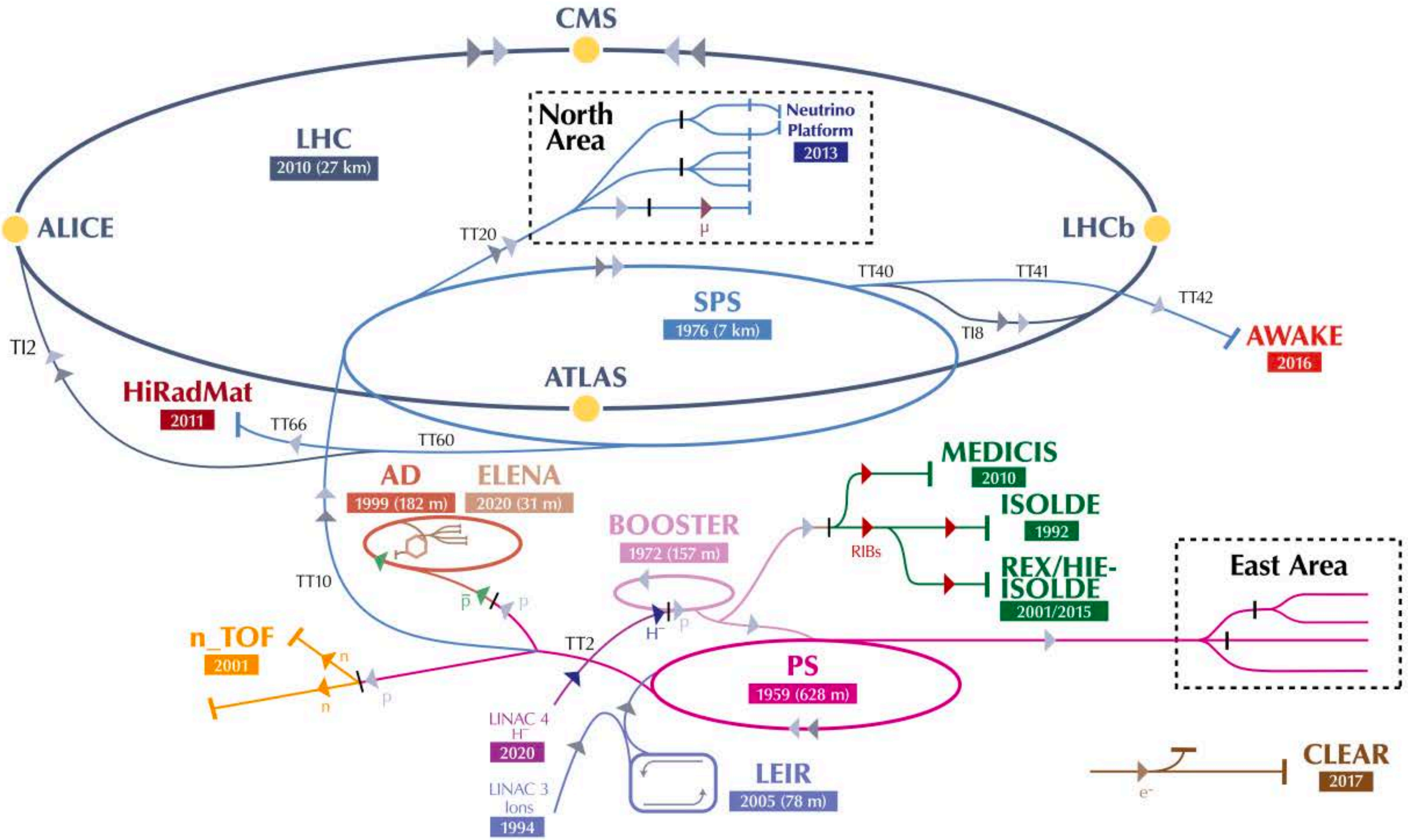
- No additional tunnel
- 100m of rock to protect radiation for LHC
- Background from cosmic muons which are rarely pointed towards IP. Mostly coming from the opposite direction (above instead of below)
- Decay volume filled with air with several detector layers for tracking





Physics Letter B 767 (2017) 29-36

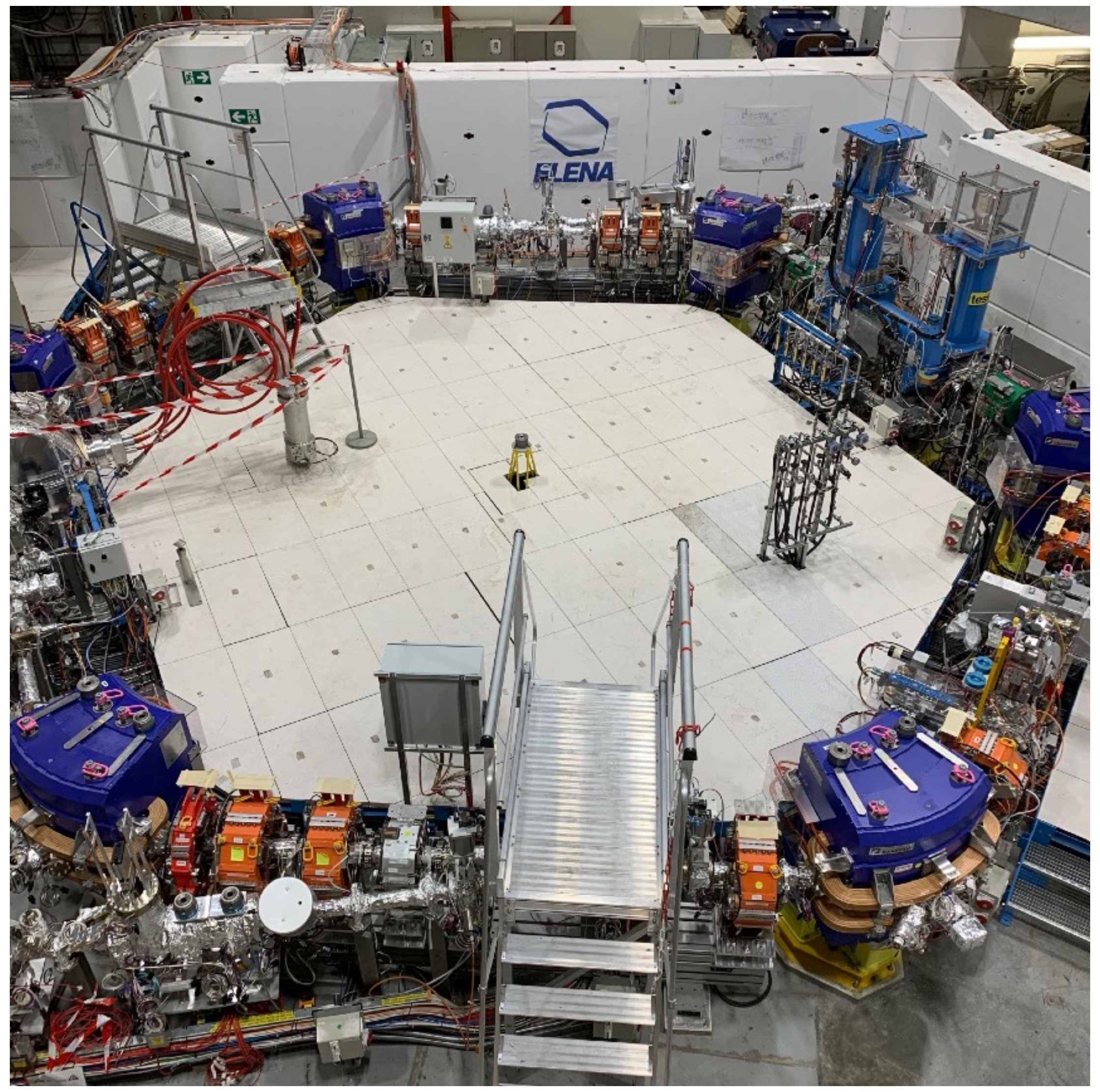
CERN accelerator complex: Not only LHC



Not only accelerate, but also decelerate

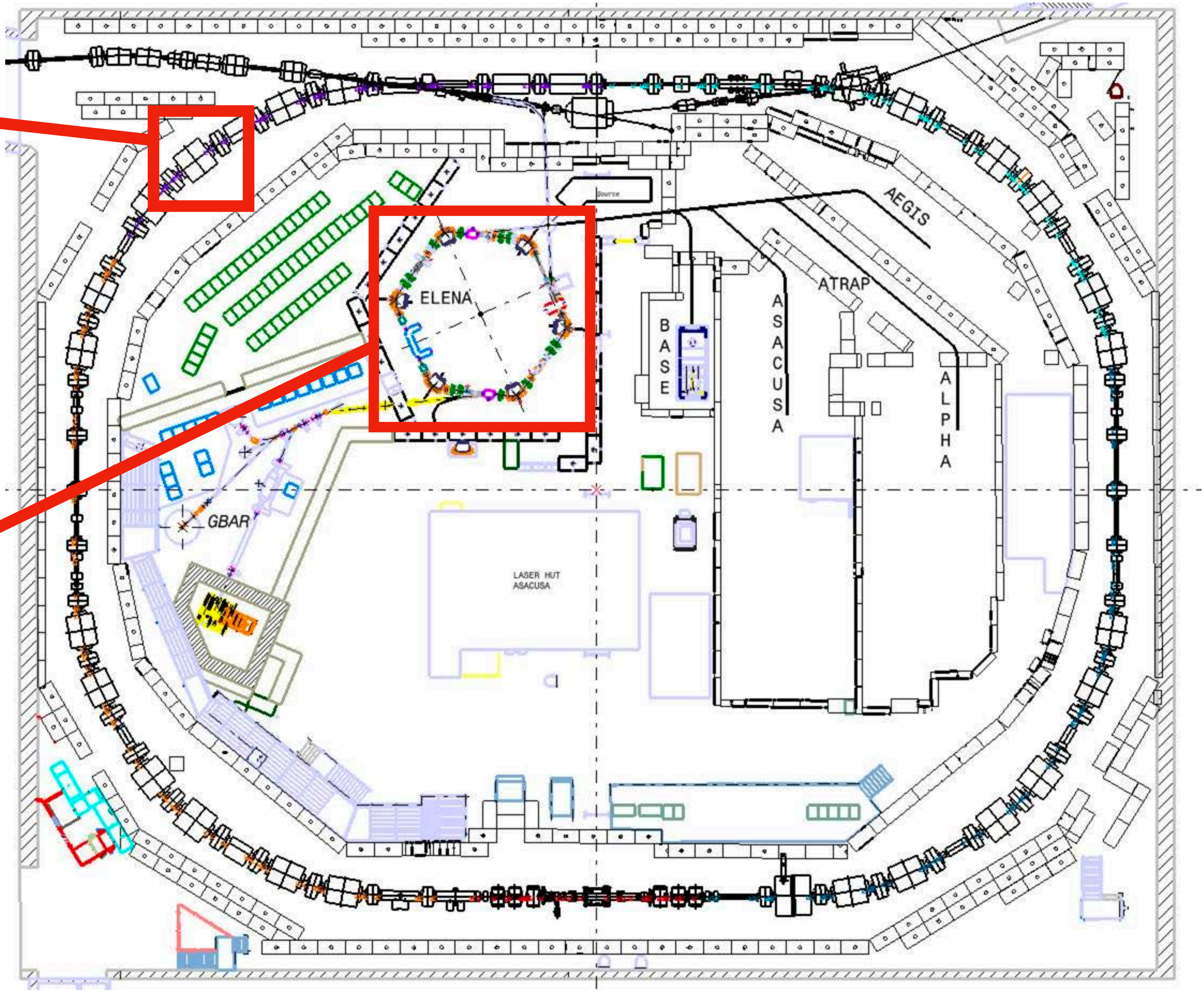
Antiproton Decelerator (AD)

A machine that produces low-energy antiprotons for studies of antimatter, and also creates antiatoms.



Extra Low ENergy Antiproton (ELENA)

A machine to slow more the antiprotons from AD. This is to improve the efficiency of the experiments



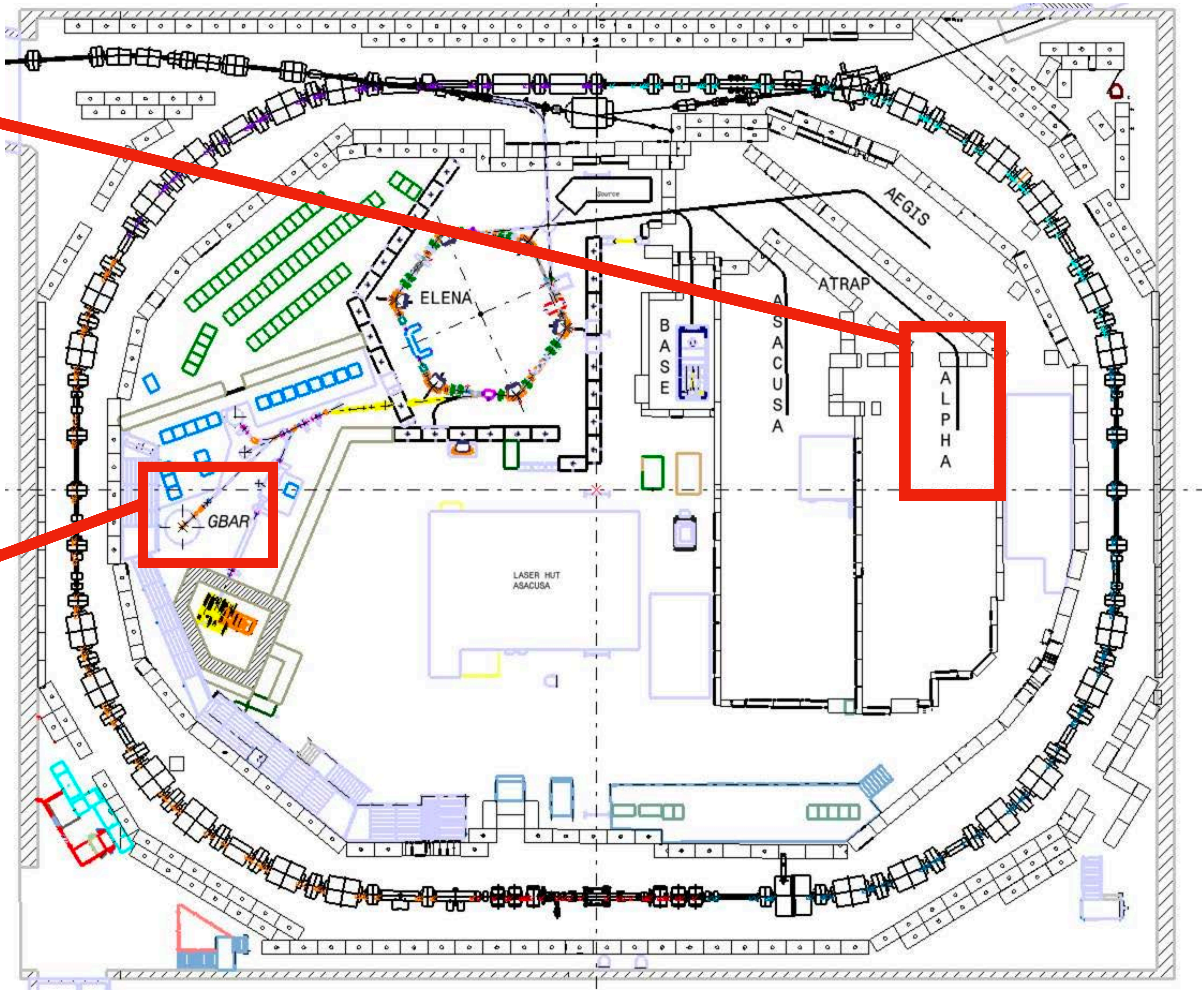
To study anti-matter

Antihydrogen Laser Physics Apparatus (ALPHA)

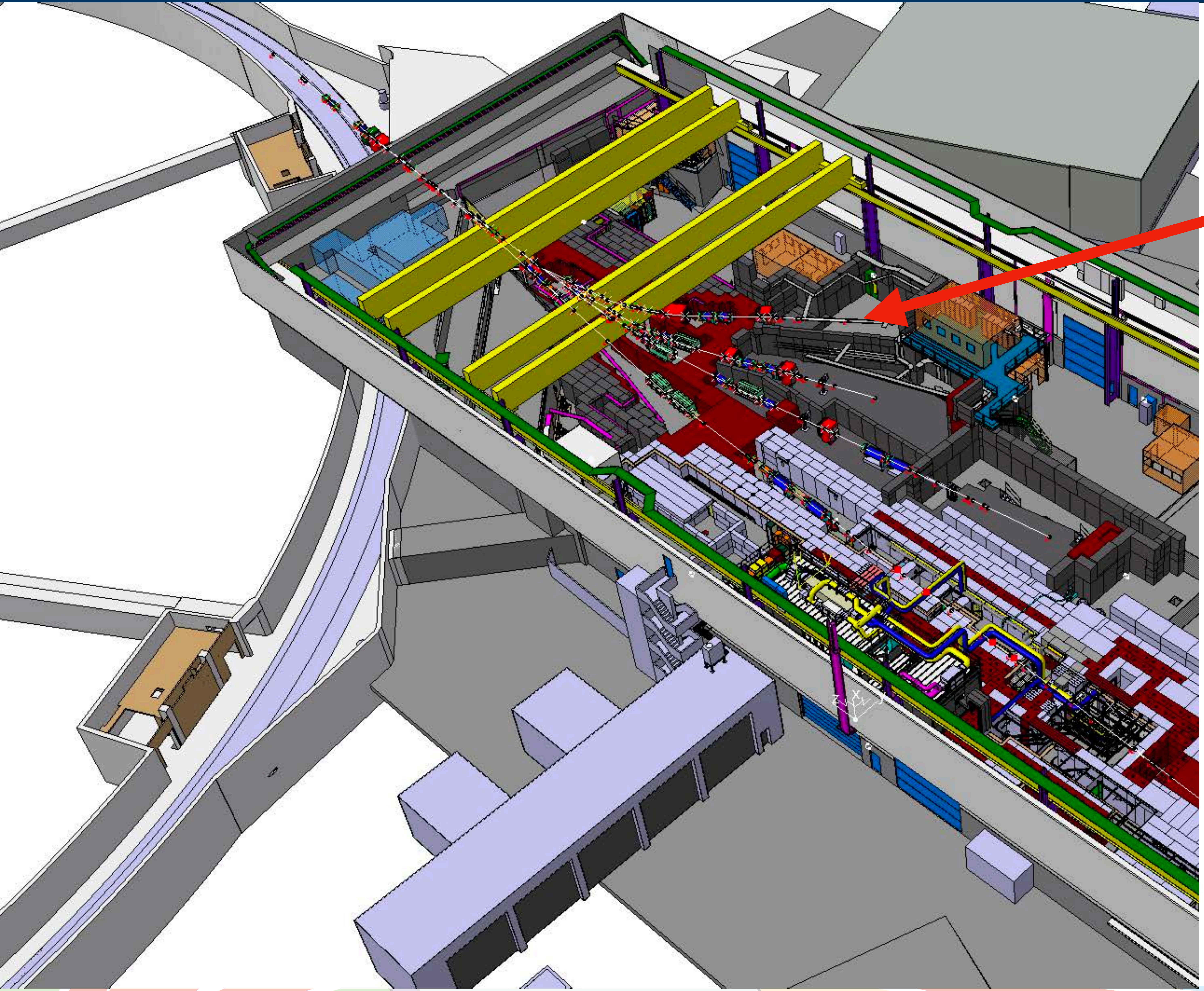
create, capture and then cool antihydrogen to use for experiment

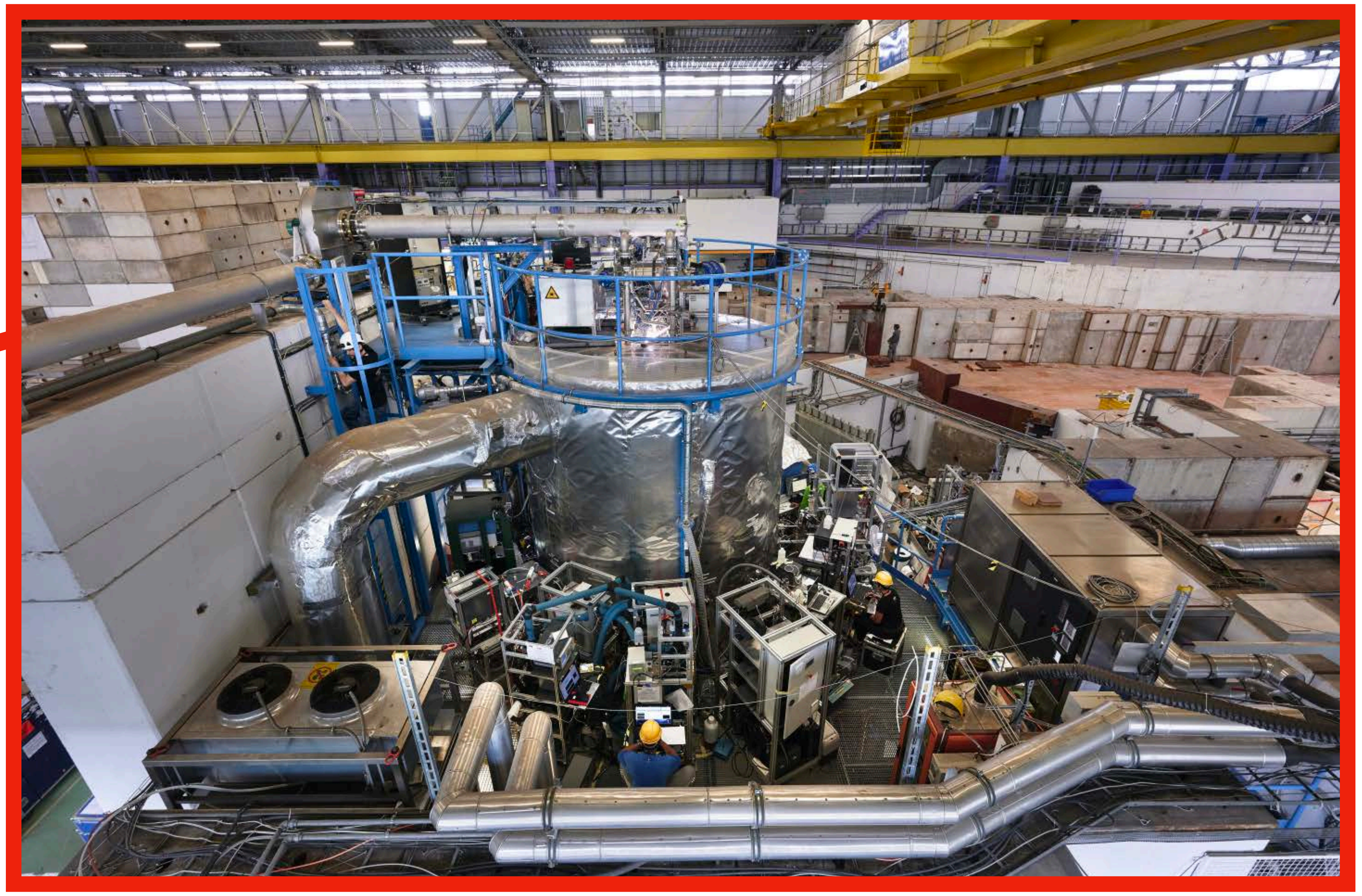
Gravitational Behaviour of Antimatter at Rest (GBAR)

Study different behavior of hydrogen/anti-hydrogen under gravity (free fall)



To study links between cosmic rays and cloud formation

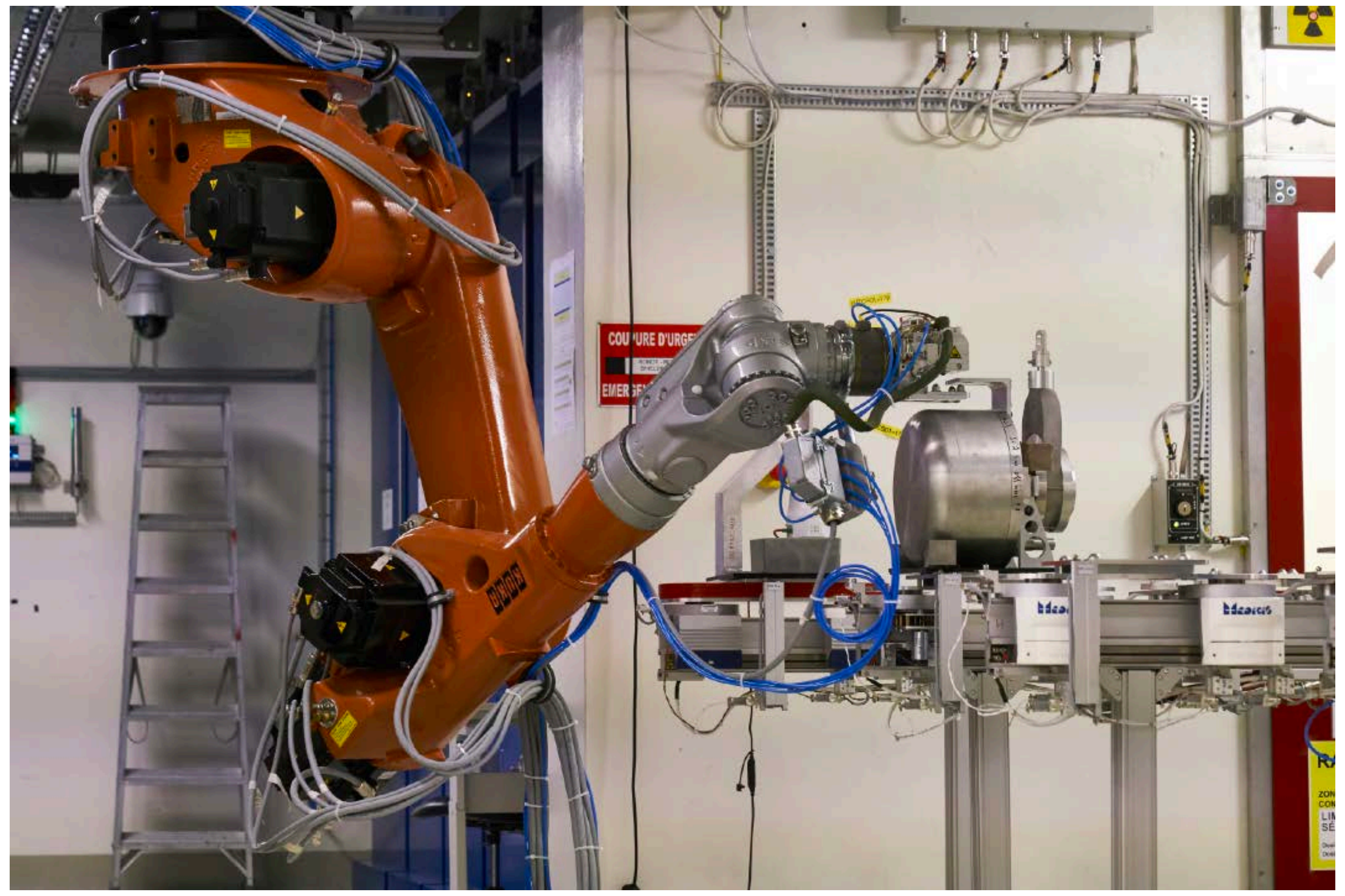




CLOUD

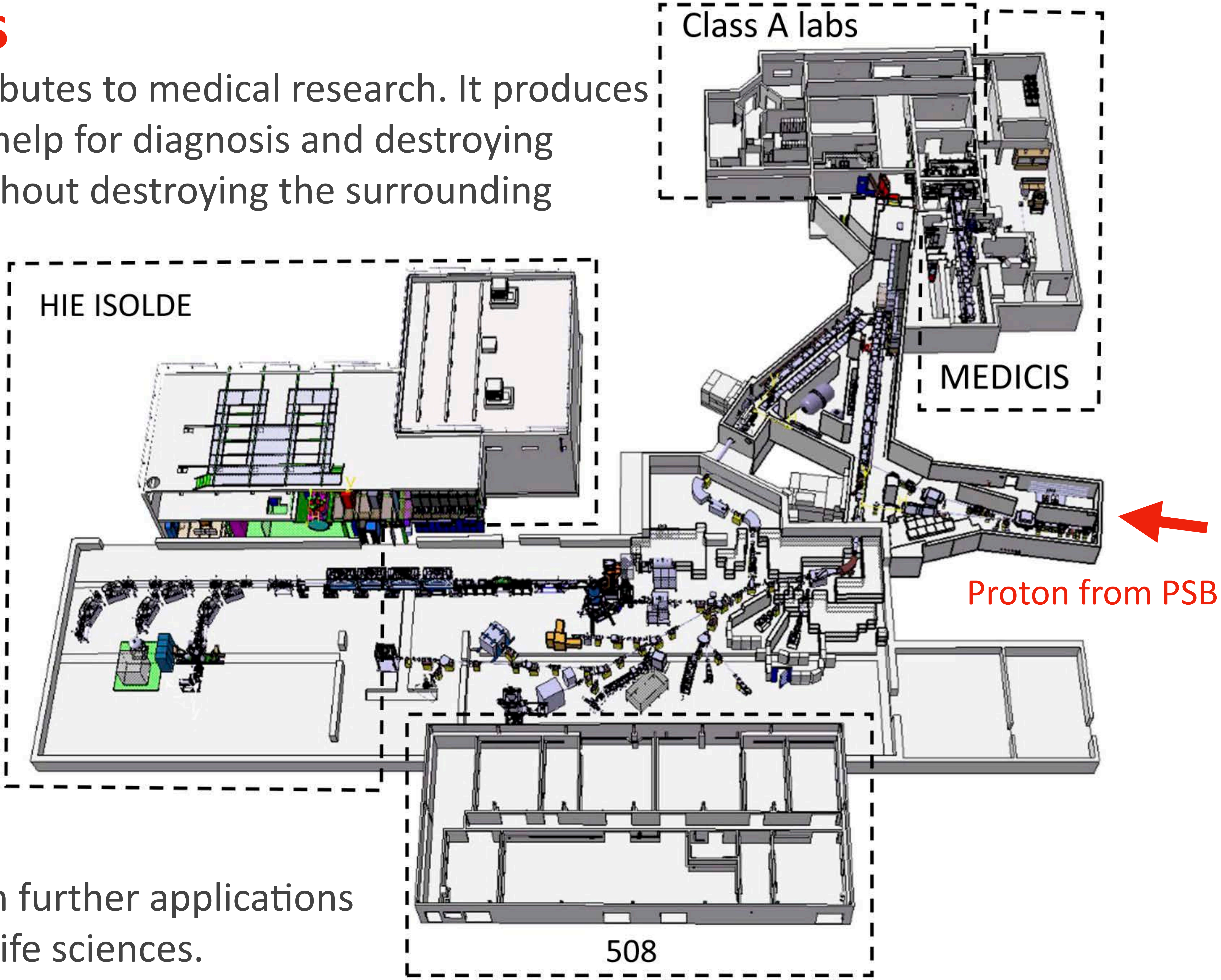
Could there be a link between galactic cosmic rays and cloud formation? An experiment at CERN is using the cleanest box in the world to find out.

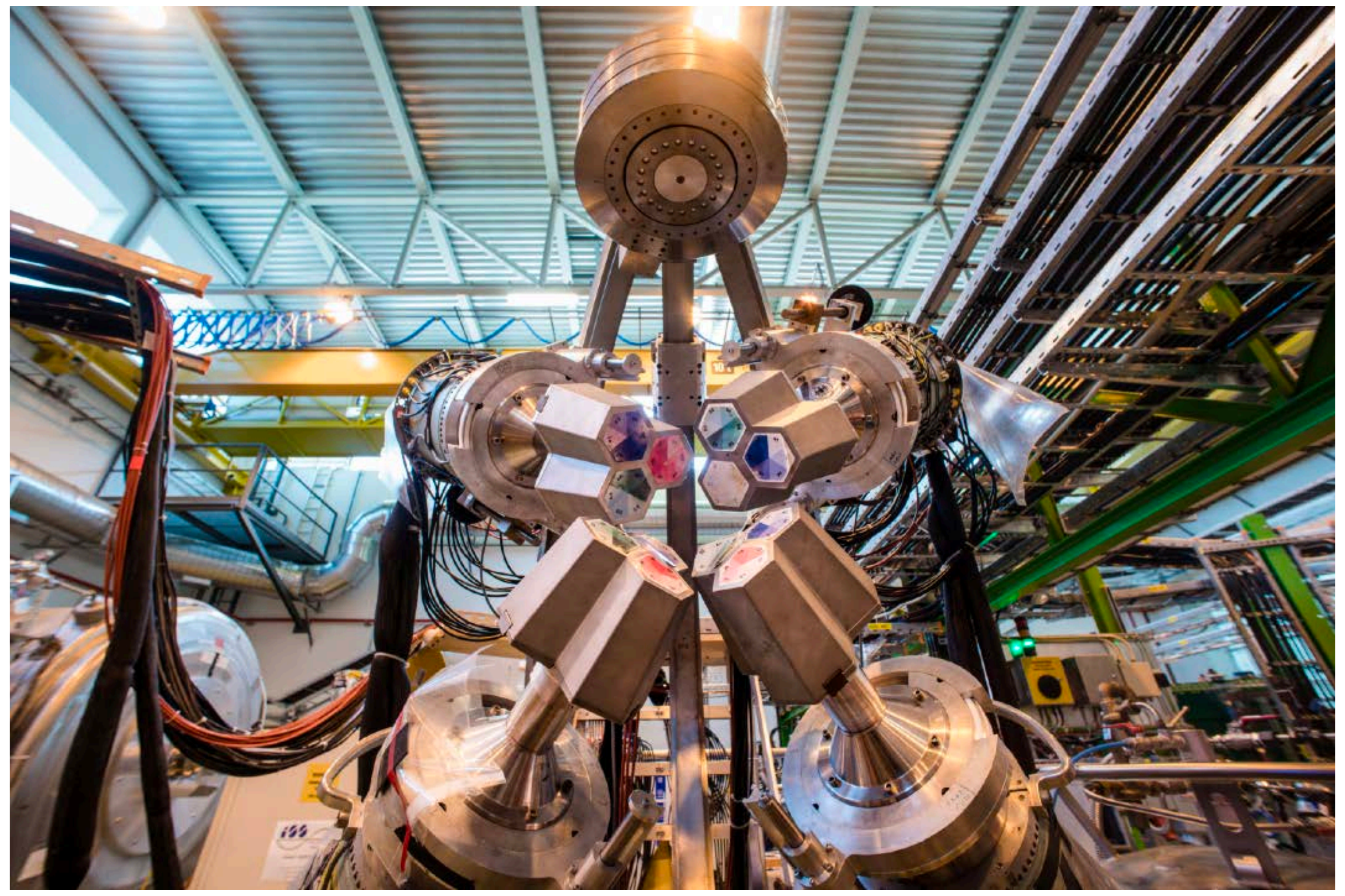
To study on radioisotopes and applications, e.g. medical applications



CERN MEDICIS

The facility contributes to medical research. It produces radioisotopes to help for diagnosis and destroying diseased cells without destroying the surrounding healthy tissue.





ISOLDE

ISOLDE studies the properties of atomic nuclei, with further applications in fundamental studies, astrophysics, material and life sciences.

External experiments at CERN: AMS

AMS

The Alpha Magnetic Spectrometer looks for dark matter, antimatter and missing matter from a module on the International Space Station.

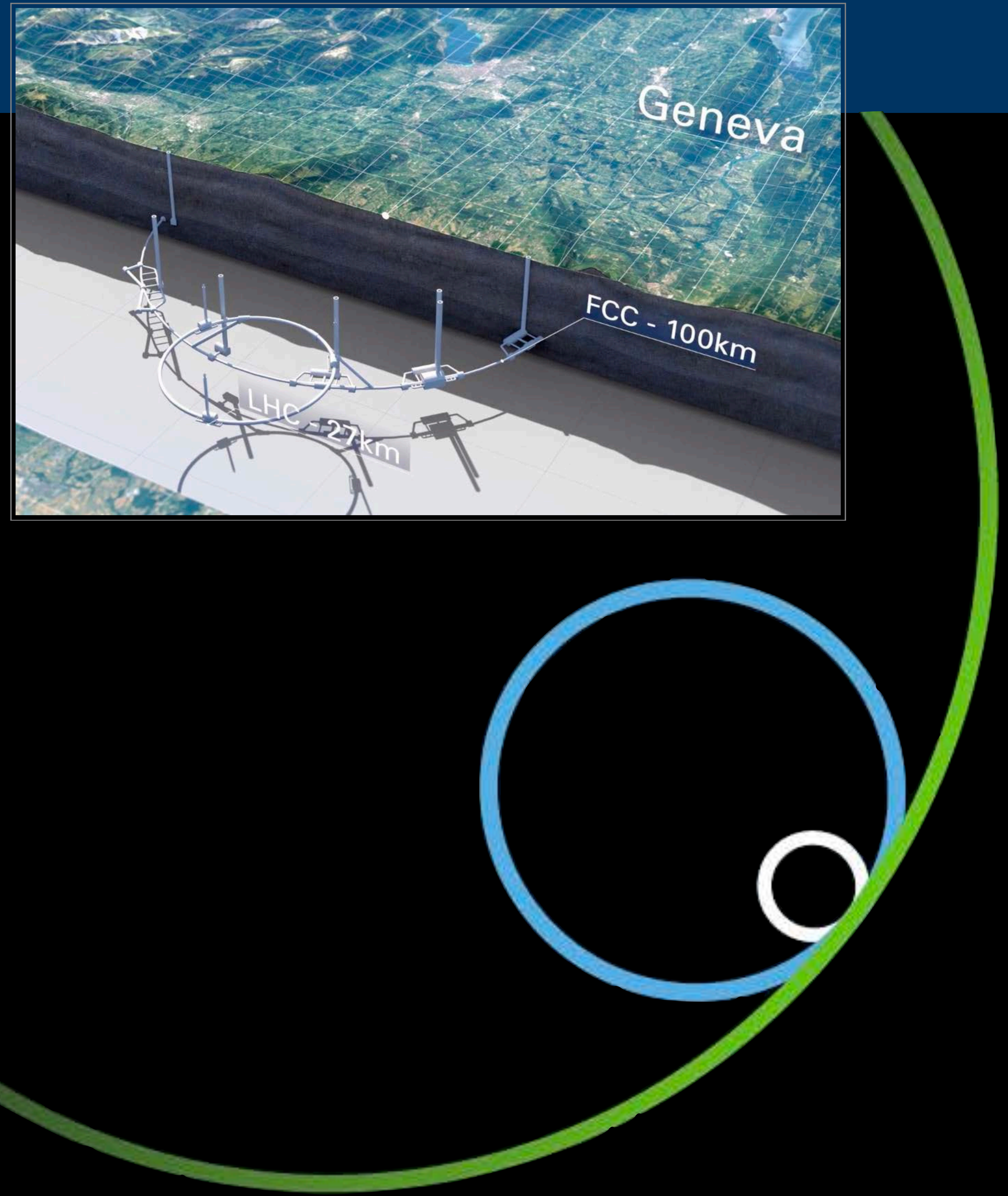
16 May 2011: Space shuttle Endeavour delivered the AMS detector to ISS.
19 May 2011 - Now: Data from AMS is sending back to Earth – to NASA in Houston and then from NASA to CERN for analysis.

Beyond LHC

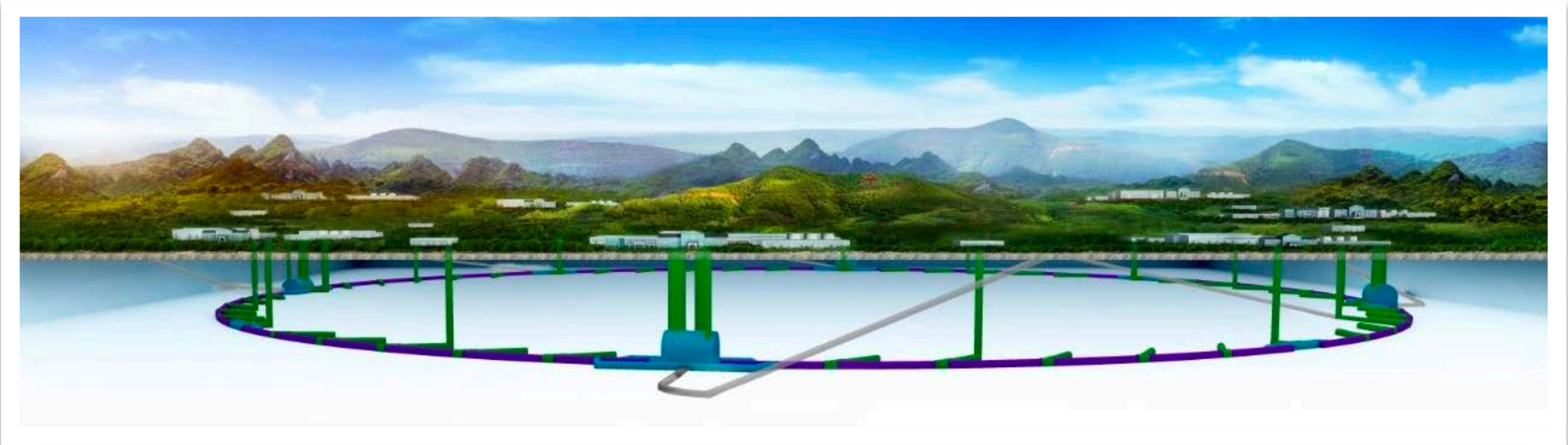
- **Future Circular Collider (FCC)**
  Circumference: 90 -100 km
  Energy: 100 TeV (pp) 90-350 GeV (e^+e^-)

- **Large Hadron Collider (LHC)**
  Large Electron-Positron Collider (LEP)
  Circumference: 27 km
  Energy: 14 TeV (pp) 209 GeV (e^+e^-)

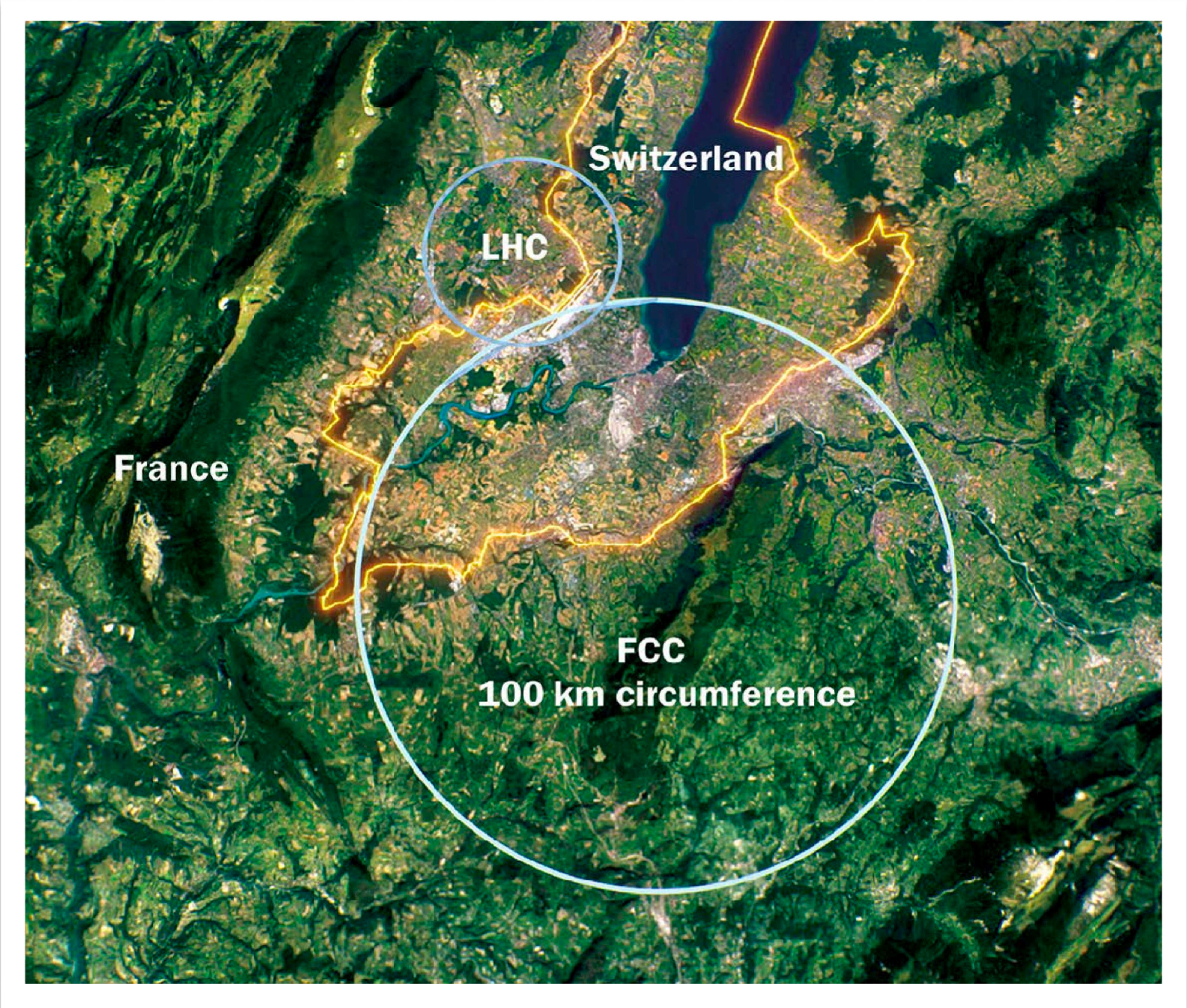
- **Tevatron**
  Circumference: 6.2 km
  Energy: 2 TeV ($p\bar{p}$)



Beyond LHC: Precision Measurement

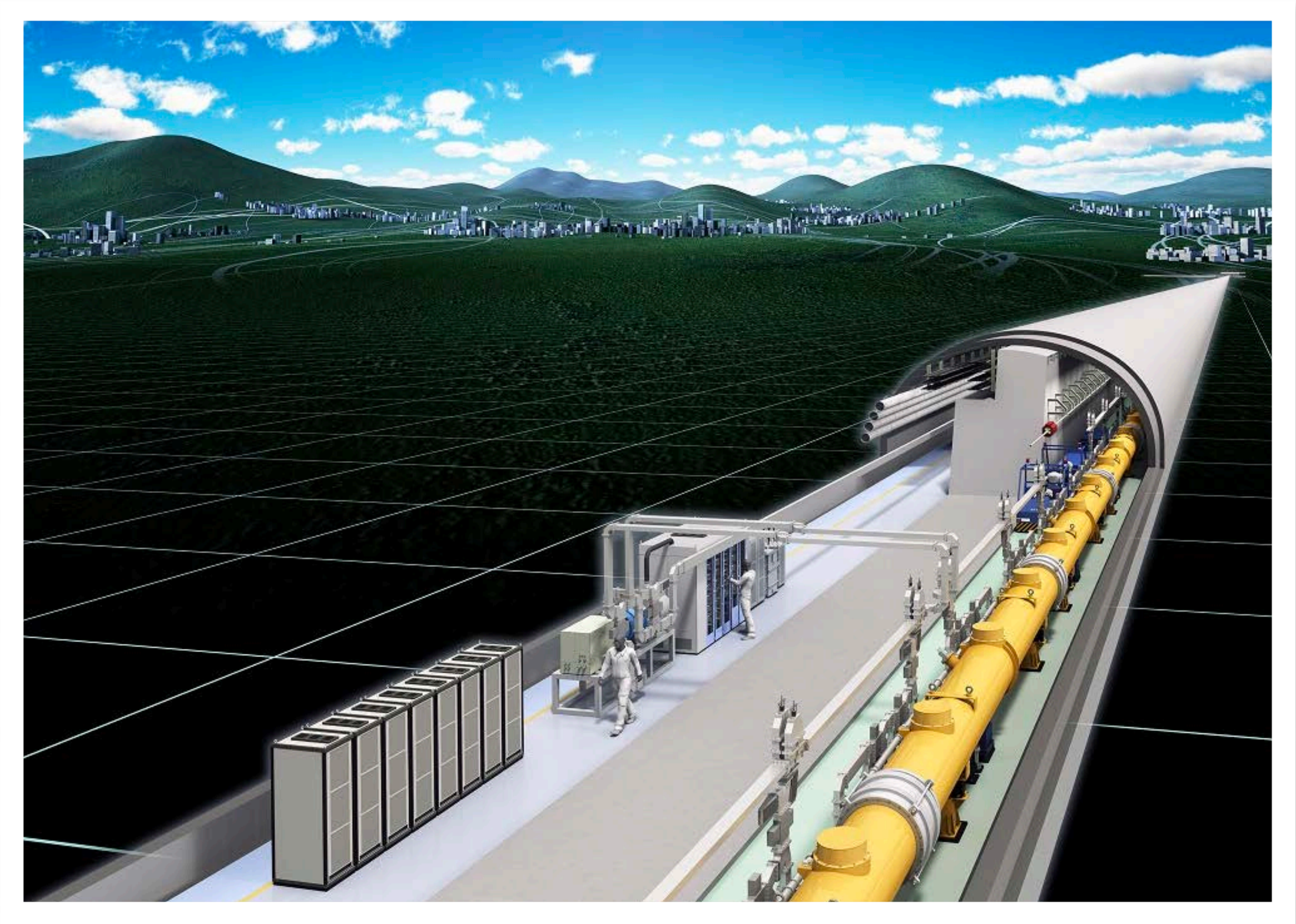


CEPC (Circular Electron Positron Collider), China

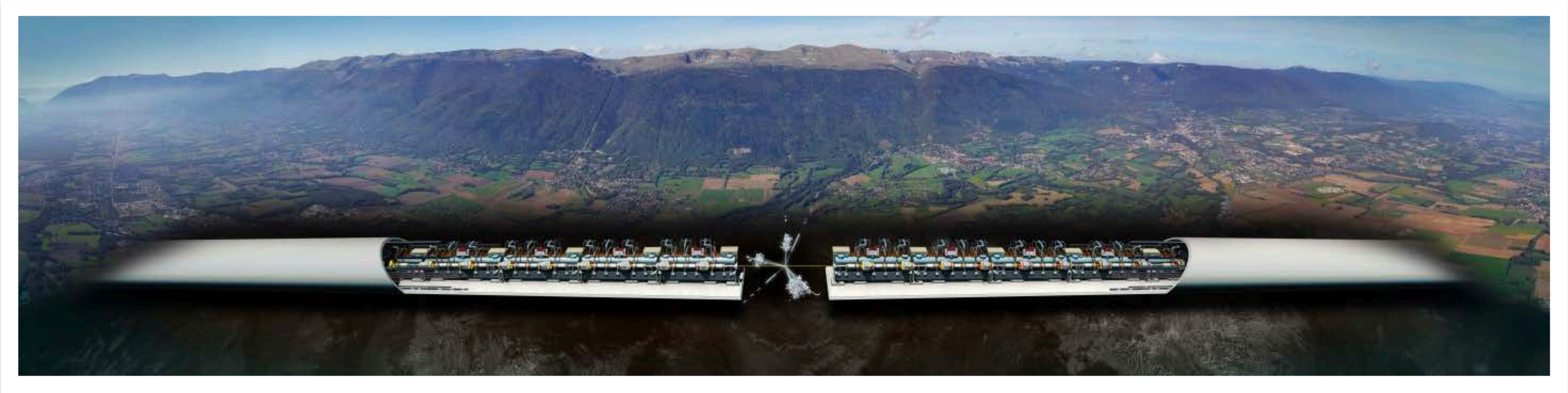


Future Circular Collider (FCC) - ee, Switzerland-France

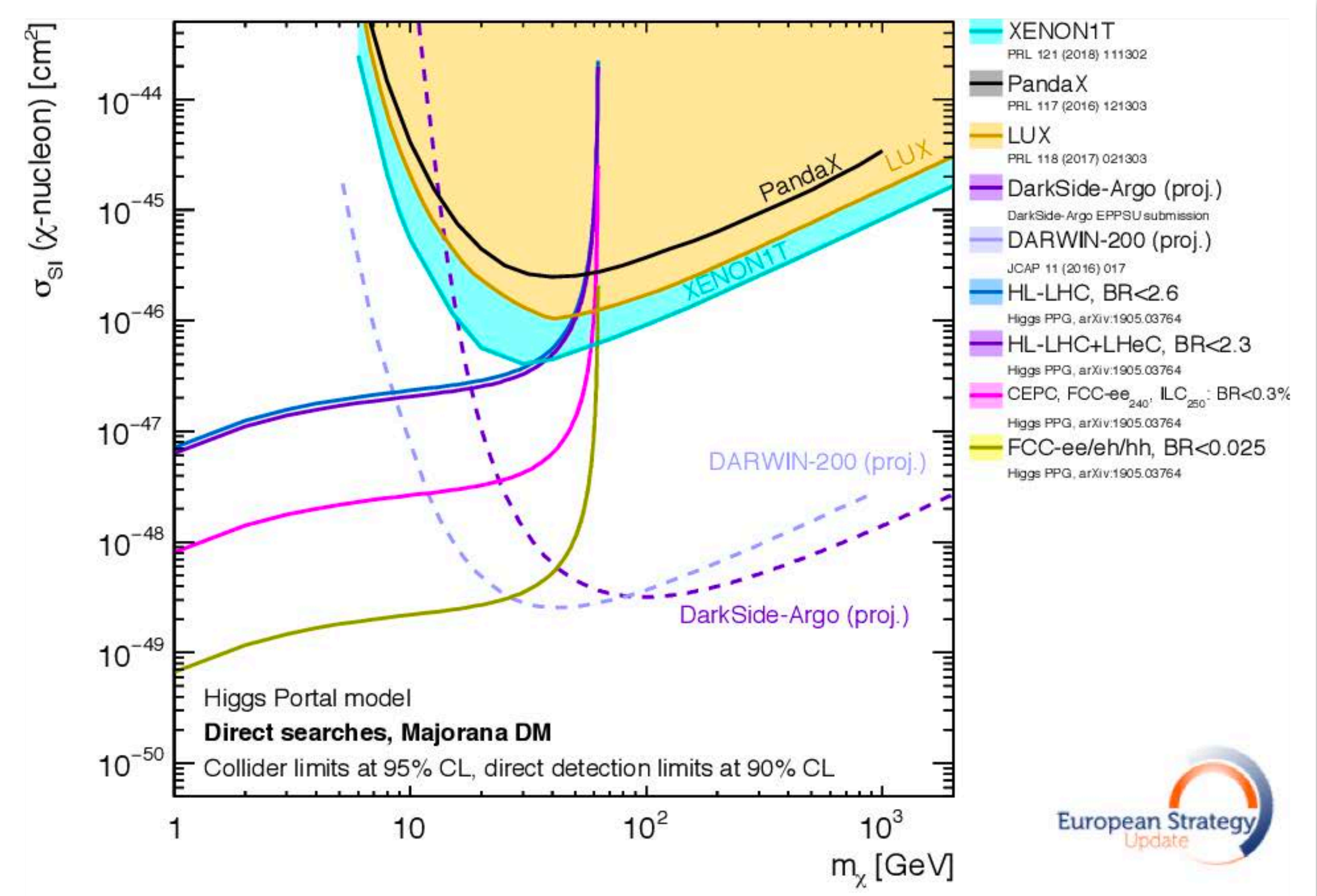
International Linear Collider (ILC)

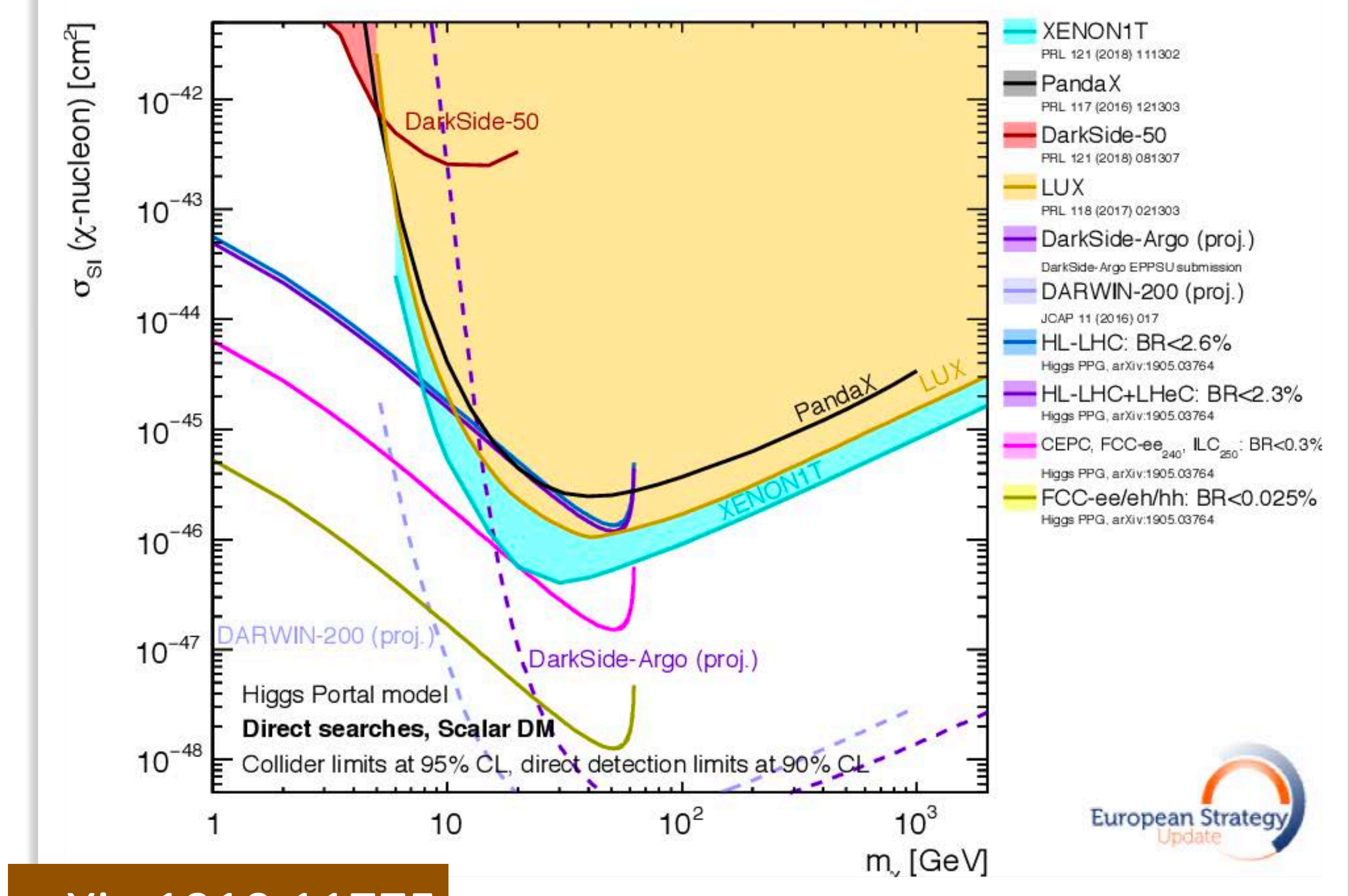


Compact Linear Collider (CLIC)

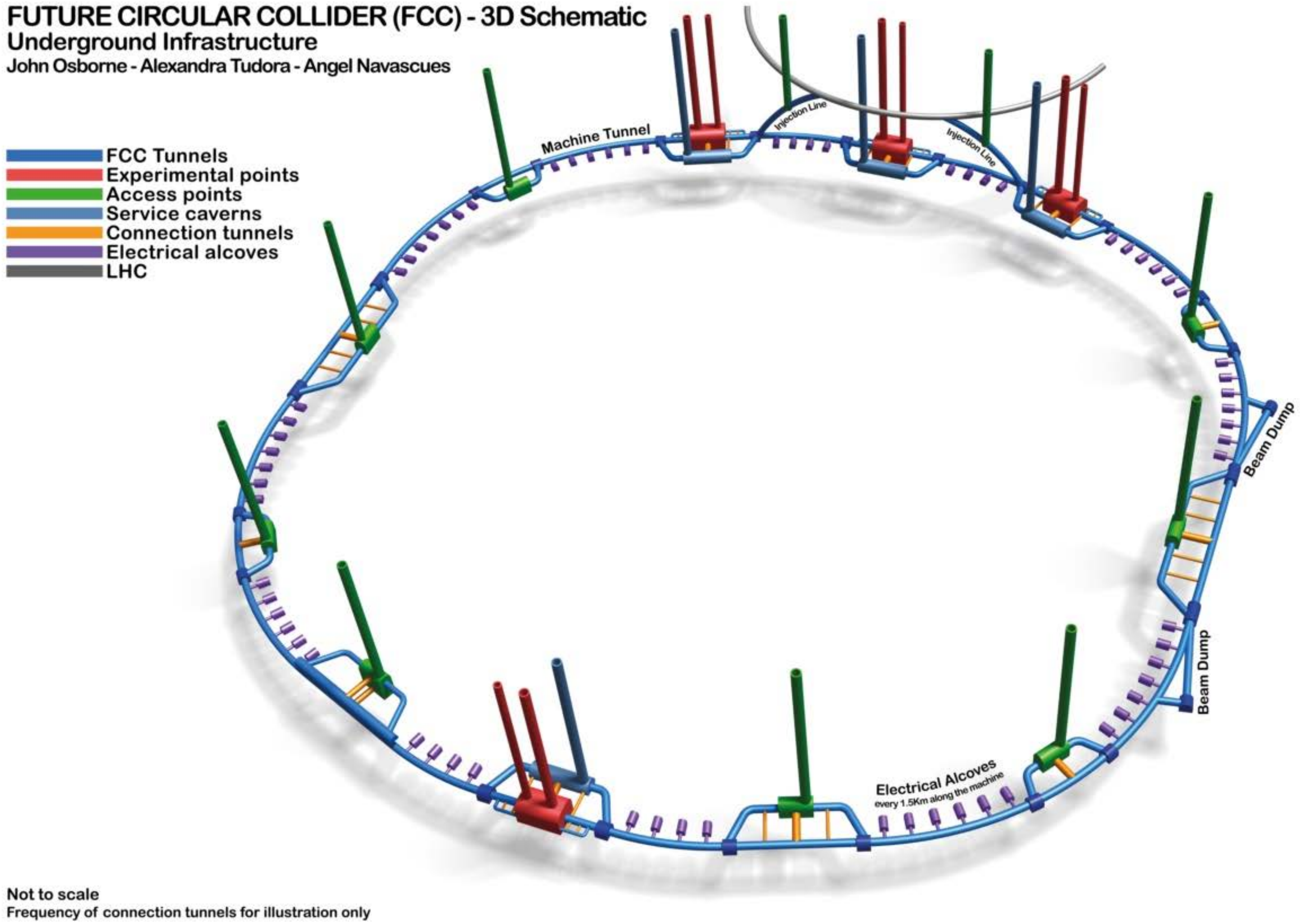


Beyond LHC: 100 TeV pp Collider





arXiv:1910.11775



https://cds.cern.ch/record/2653532

Beyond LHC: Muon Collider

Why muon collider?

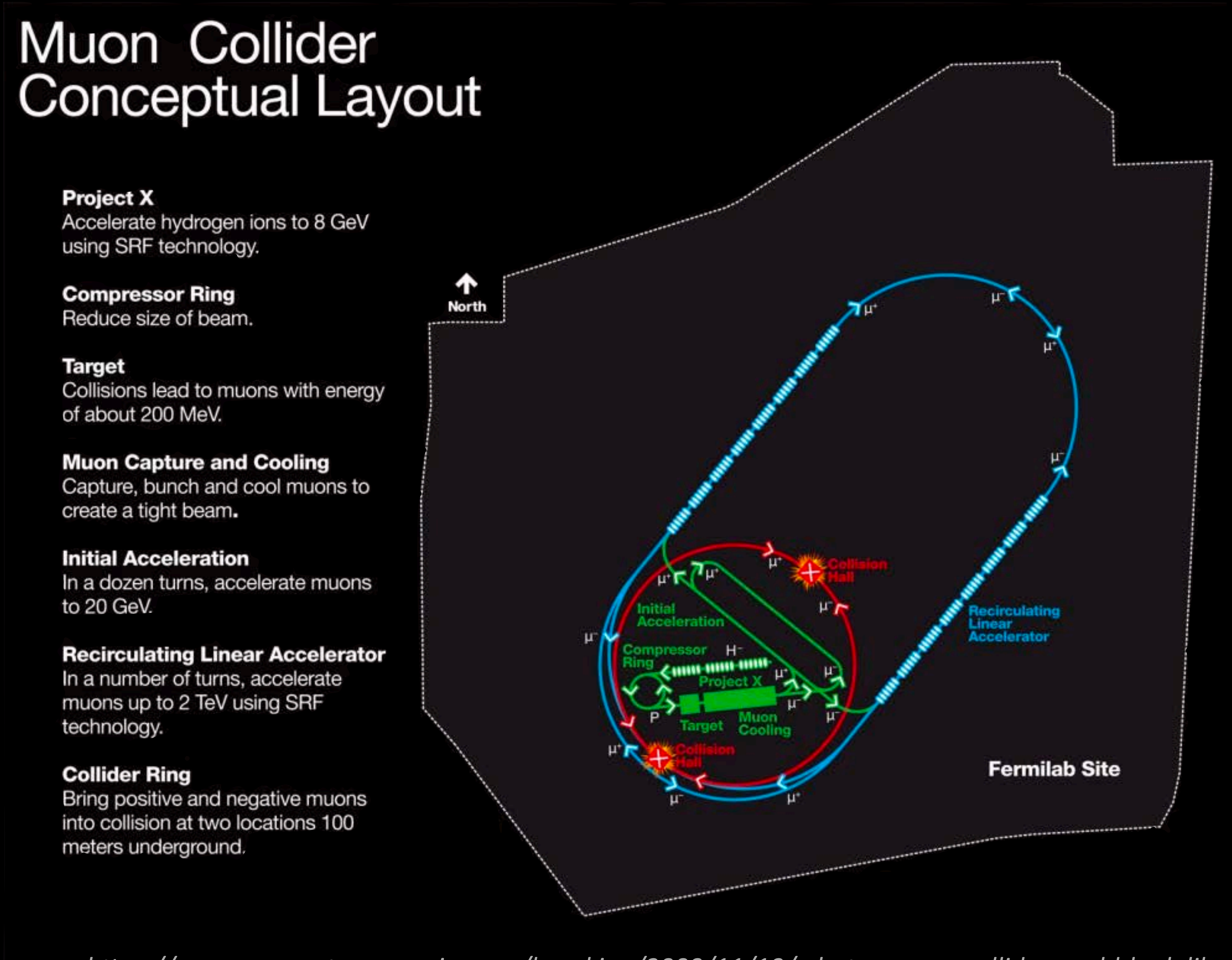
As electron, muon is elementary particle (AFAWK) with higher mass (x206 electron mass). The mass of muon is the key of high energy collision.

Consider the power emitted from charged particles which are accelerated in a curved path (known as synchrotron radiation), it is proportional to $\frac{1}{m^4}$. The amount of synchrotron radiation from a muon will be reduced by a factor of about 1 billion of an electron.

$$P = \frac{q^2}{6\pi\epsilon_0 m^4 c^5 r^2 \sin^2(\alpha)}(E^2 - m^2c^4)^2$$

Something to solve?

We need to handle the muon's lifetime. At rest, it will decay in 2 μs. If we can accelerate a muon close to the speed of light before decaying, its lifetime will stretch longer. This is the result of the special relativity.



Muon Collider Conceptual Layout

Project X
Accelerate hydrogen ions to 8 GeV using SRF technology.

Compressor Ring
Reduce size of beam.

Target
Collisions lead to muons with energy of about 200 MeV.

Muon Capture and Cooling
Capture, bunch and cool muons to create a tight beam.

Initial Acceleration
In a dozen turns, accelerate muons to 20 GeV.

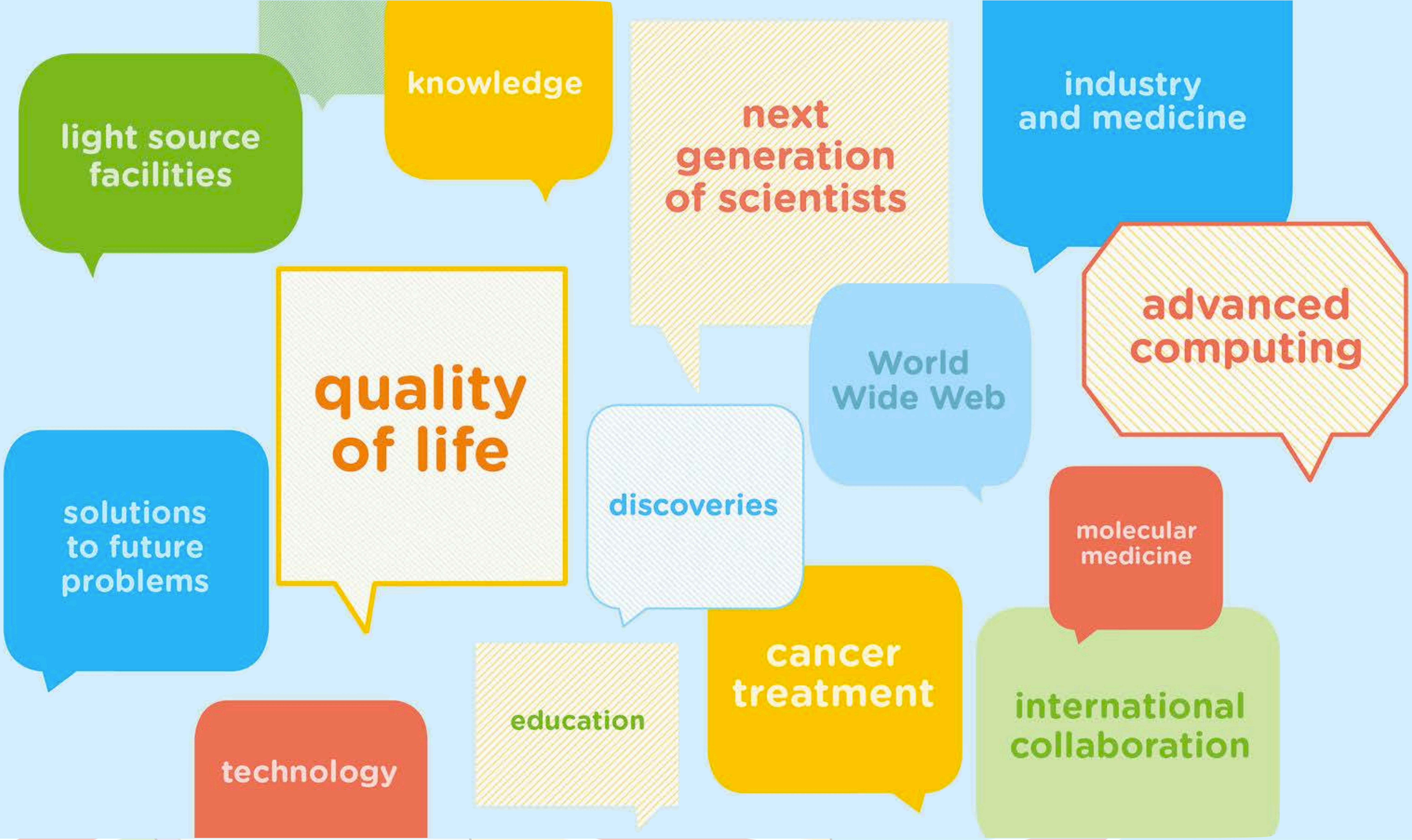
Recirculating Linear Accelerator
In a number of turns, accelerate muons up to 2 TeV using SRF technology.

Collider Ring
Bring positive and negative muons into collision at two locations 100 meters underground.

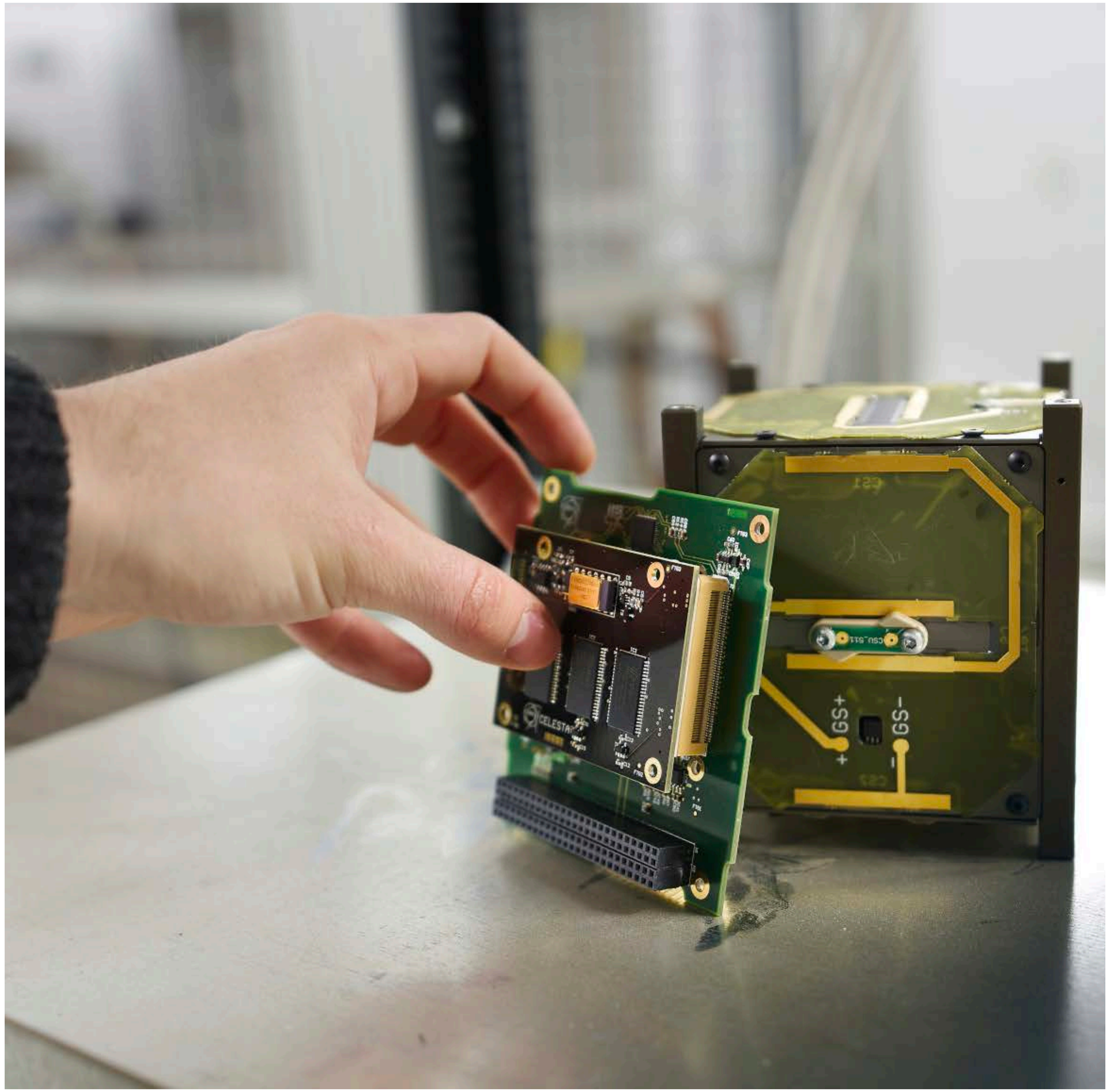
https://www.symmetrymagazine.org/breaking/2009/11/19/what-a-muon-collider-could-look-like

Why particle physics matters

http://www.symmetrymagazine.org/article/october-2013/why-particle-physics-matters

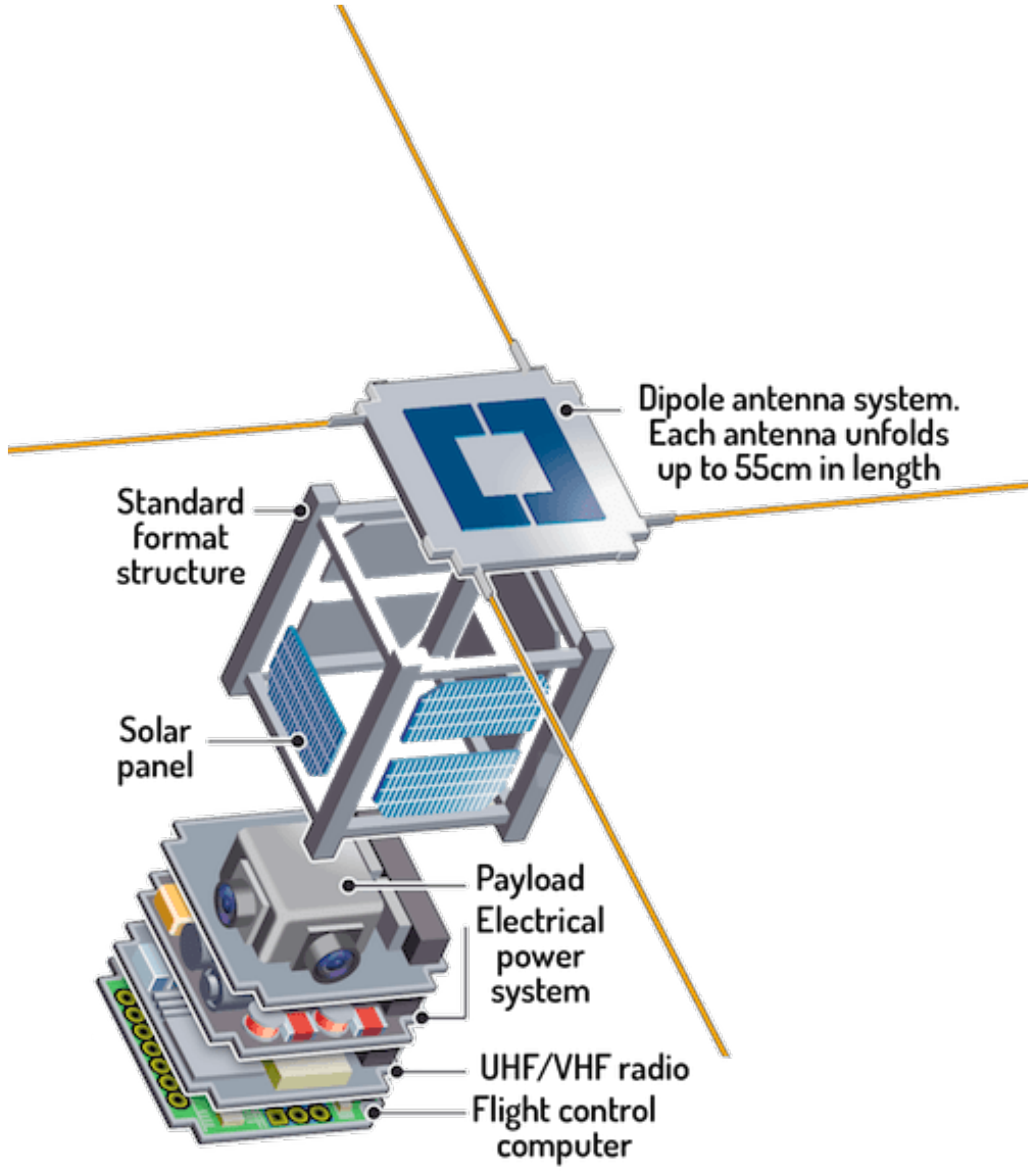


CERN latchup and radmon experiment student satellite

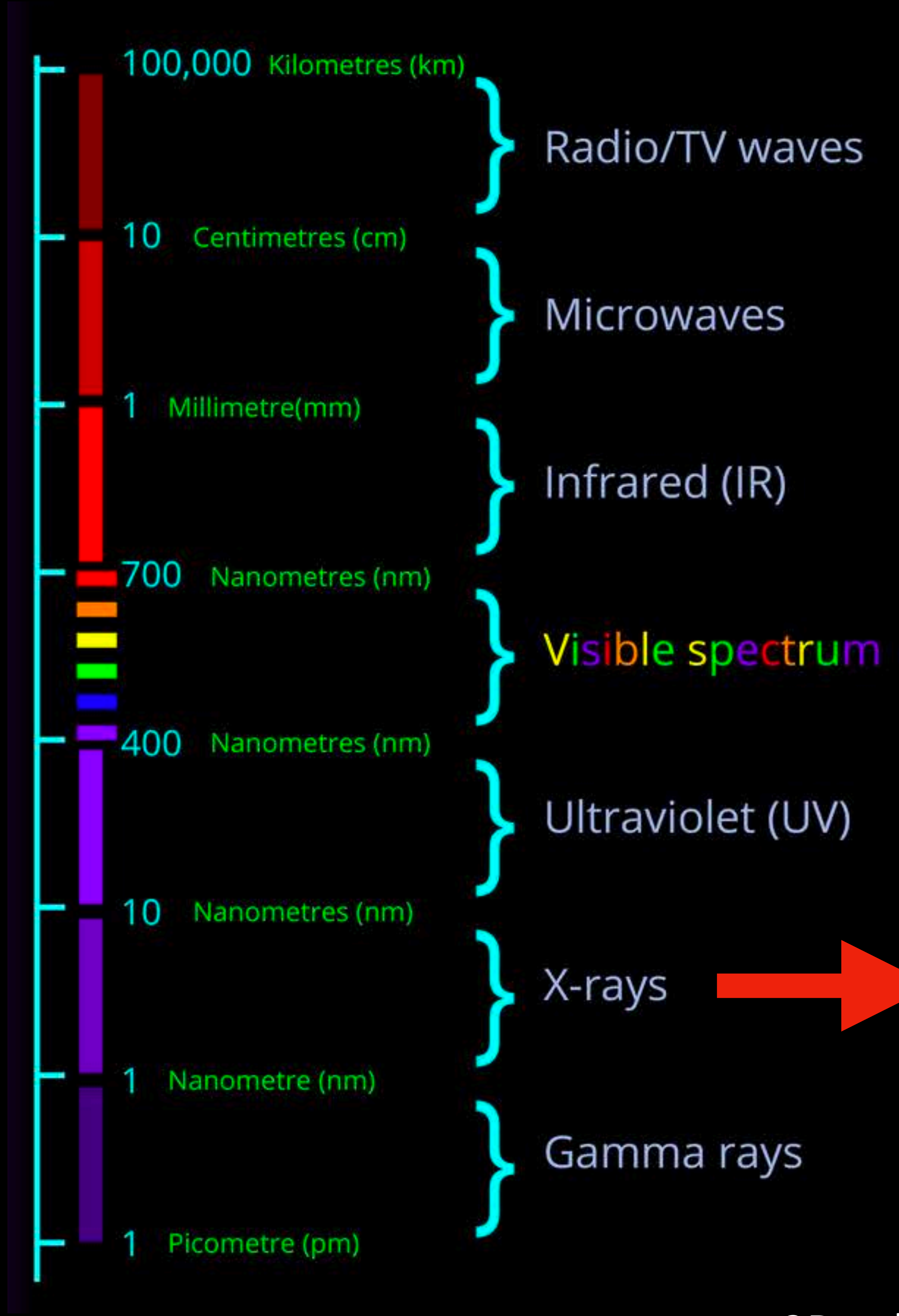


Ref: here

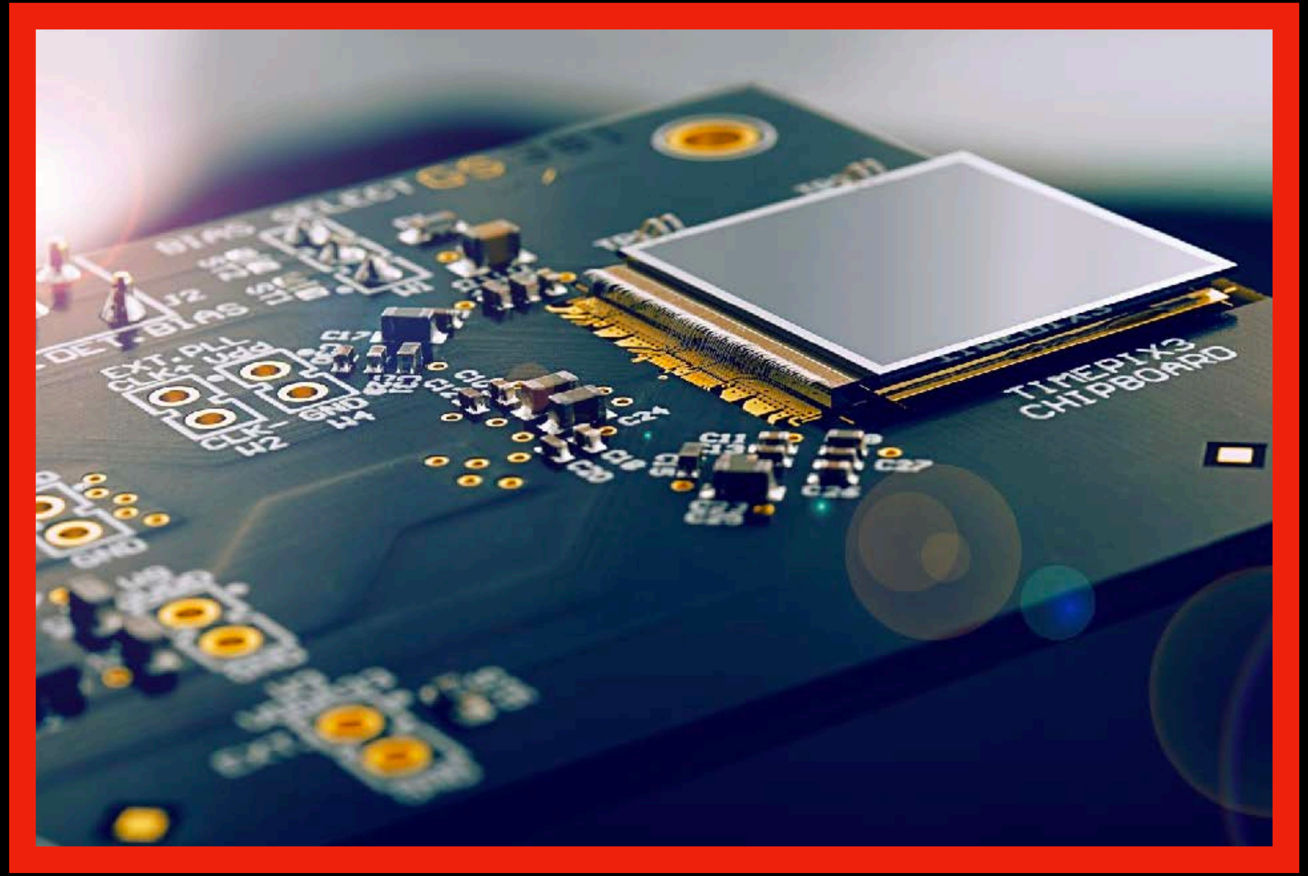
CELESTA (CERN latchup and radmon experiment student satellite) is a 1U CubeSat with weight of one kilogram and measuring 10 cm on each of its sides. It is designed to study the effects of cosmic radiation on electronics. The satellite carries a Space RadMon, a miniature version of a well-proven radiation monitoring device deployed in CERN's Large Hadron Collider (LHC).



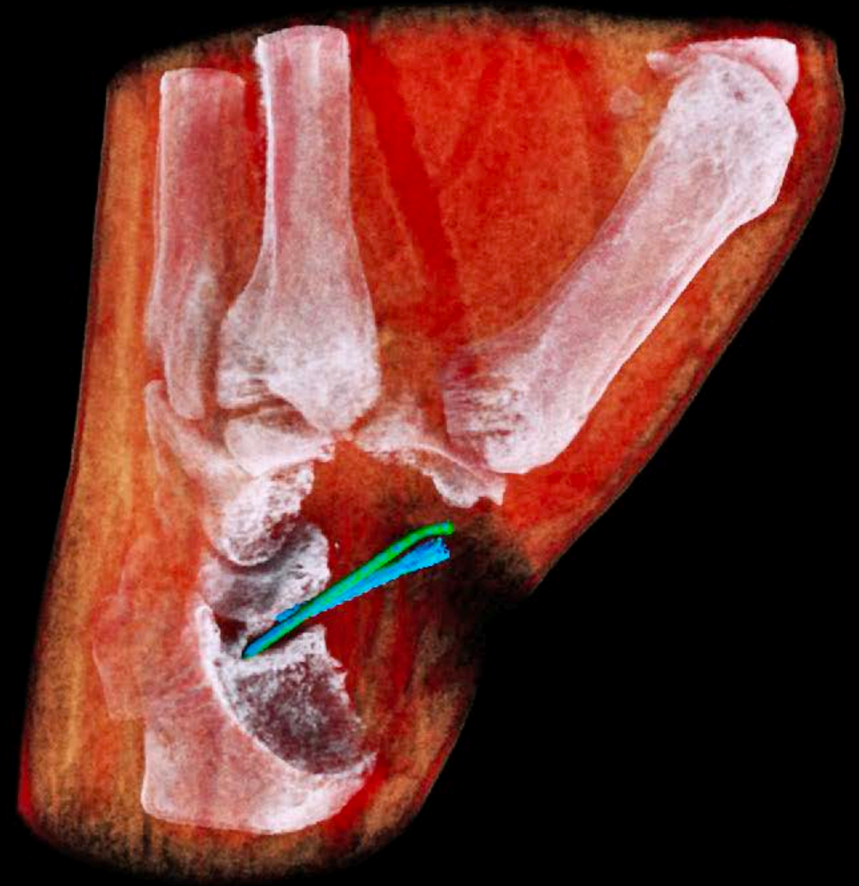
Blue skies research ... not with imaginations/ideas



100,000 Kilometres (km)
Radio/TV waves
10 Centimetres (cm)
Microwaves
1 Millimetre(mm)
Infrared (IR)
700 Nanometres (nm)
Visible spectrum
400 Nanometres (nm)
Ultraviolet (UV)
10 Nanometres (nm)
X-rays
1 Nanometre (nm)
Gamma rays
1 Picometre (pm)



Medipix3; a CMOS pixel detector readout chip designed to be connected to a segmented semiconductor sensor.



3D colour human X-ray, clinical trial

High resolution spectroscopic radiography

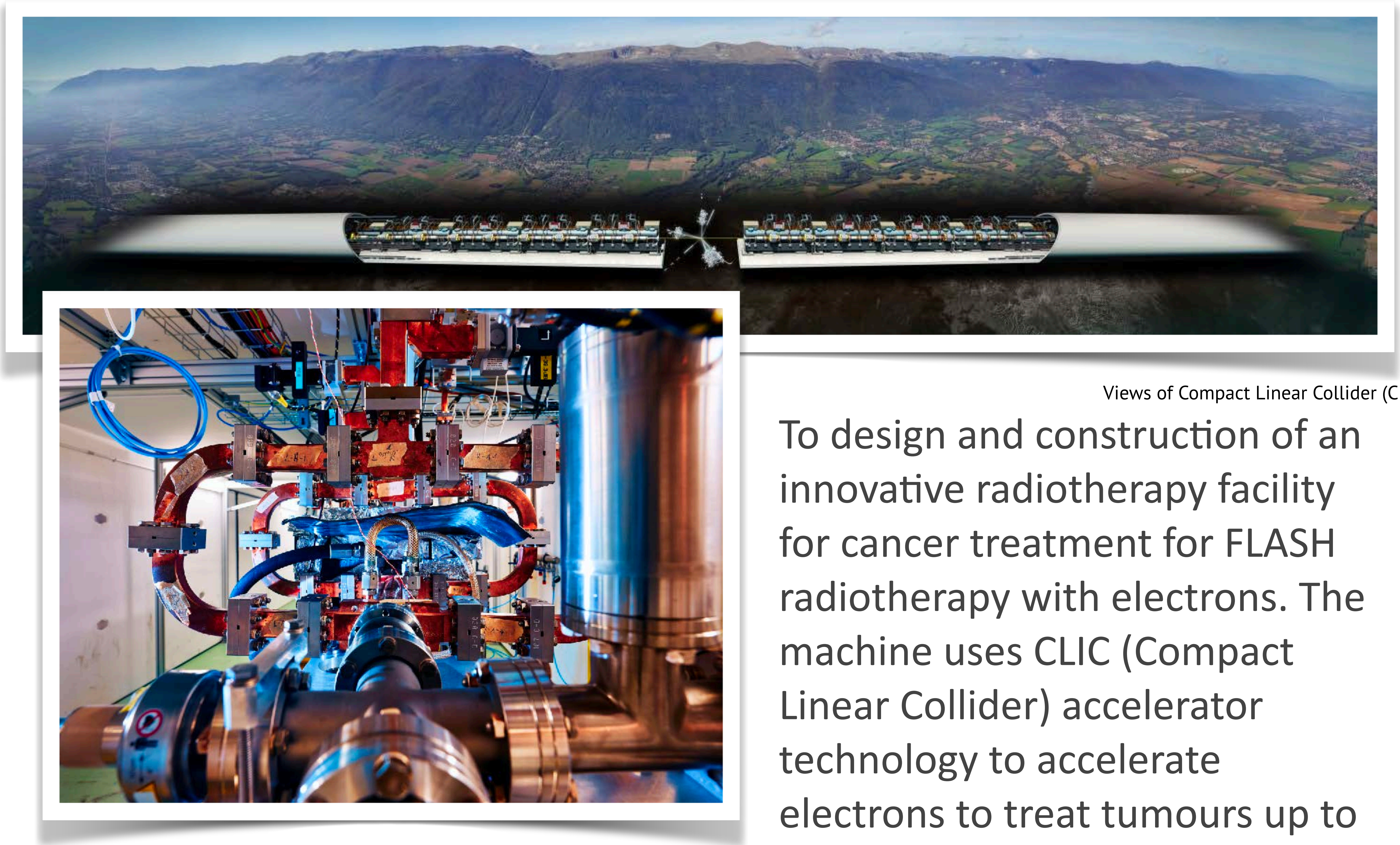
Blue skies research … not with imaginations/ideas

The irrigation system will use fibre optic sensors designed to measure parameters such as temperature, humidity, concentration of pesticides, fertilisers and enzymes in the soil of cultivated fields. This is the same fibre optic sensors developed by CMS experiment in order to monitor the environment in the CMS tracking system.

https://cms.cern/news/how-can-high-energy-physics-help-water-shortage

Blue skies research ... not with imaginations/ideas

[Wikipedia] **Blue skies research** (also called blue sky science) is scientific research in domains where "real-world" applications are not immediately apparent. It has been defined as "research without a clear goal"[1] and "curiosity-driven science". It is sometimes used interchangeably with the term "basic research".

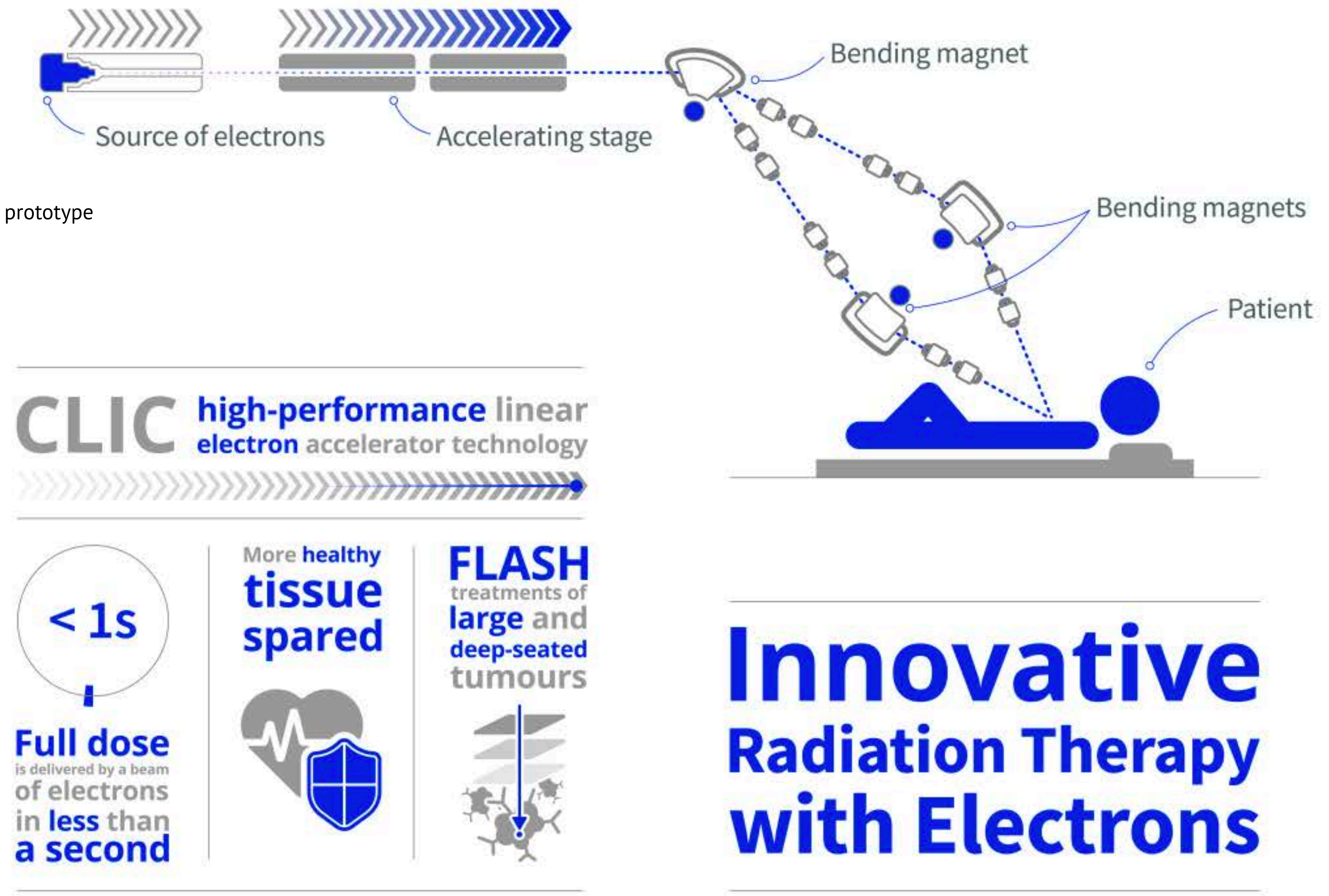


Views of Compact Linear Collider (CLIC) prototype

CLIC prototype

To design and construction of an innovative radiotherapy facility for cancer treatment for FLASH radiotherapy with electrons. The machine uses CLIC (Compact Linear Collider) accelerator technology to accelerate electrons to treat tumours up to 15 to 20 cm in depth.

Compact Linear Collider (CLIC)



https://cds.cern.ch/record/2728727