ON COLLIDER PHYSICS AND THE CMS EXPERIMENT

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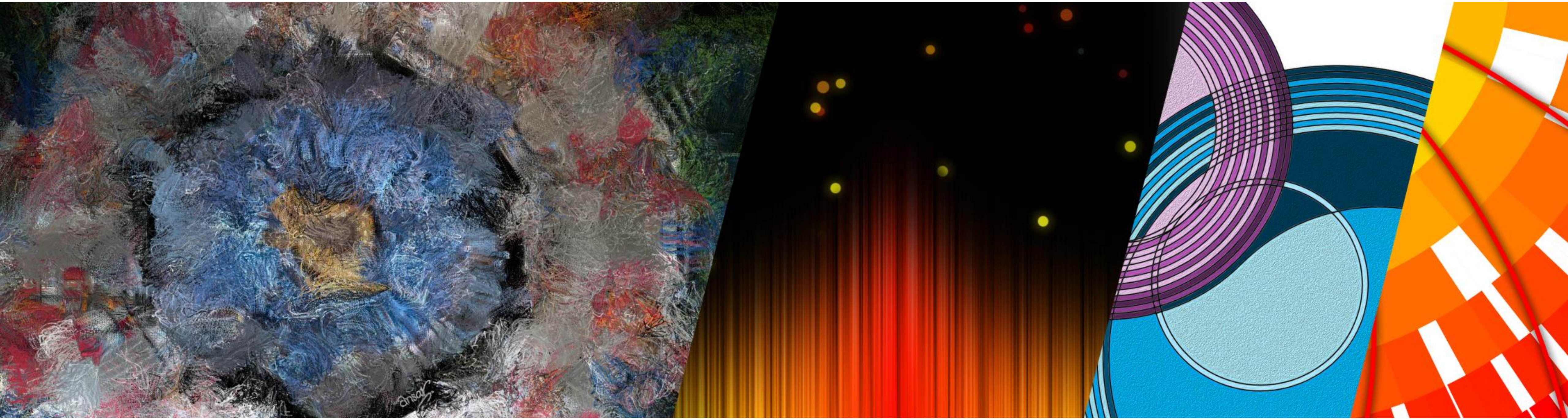
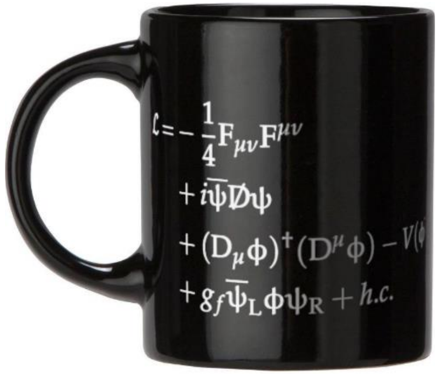
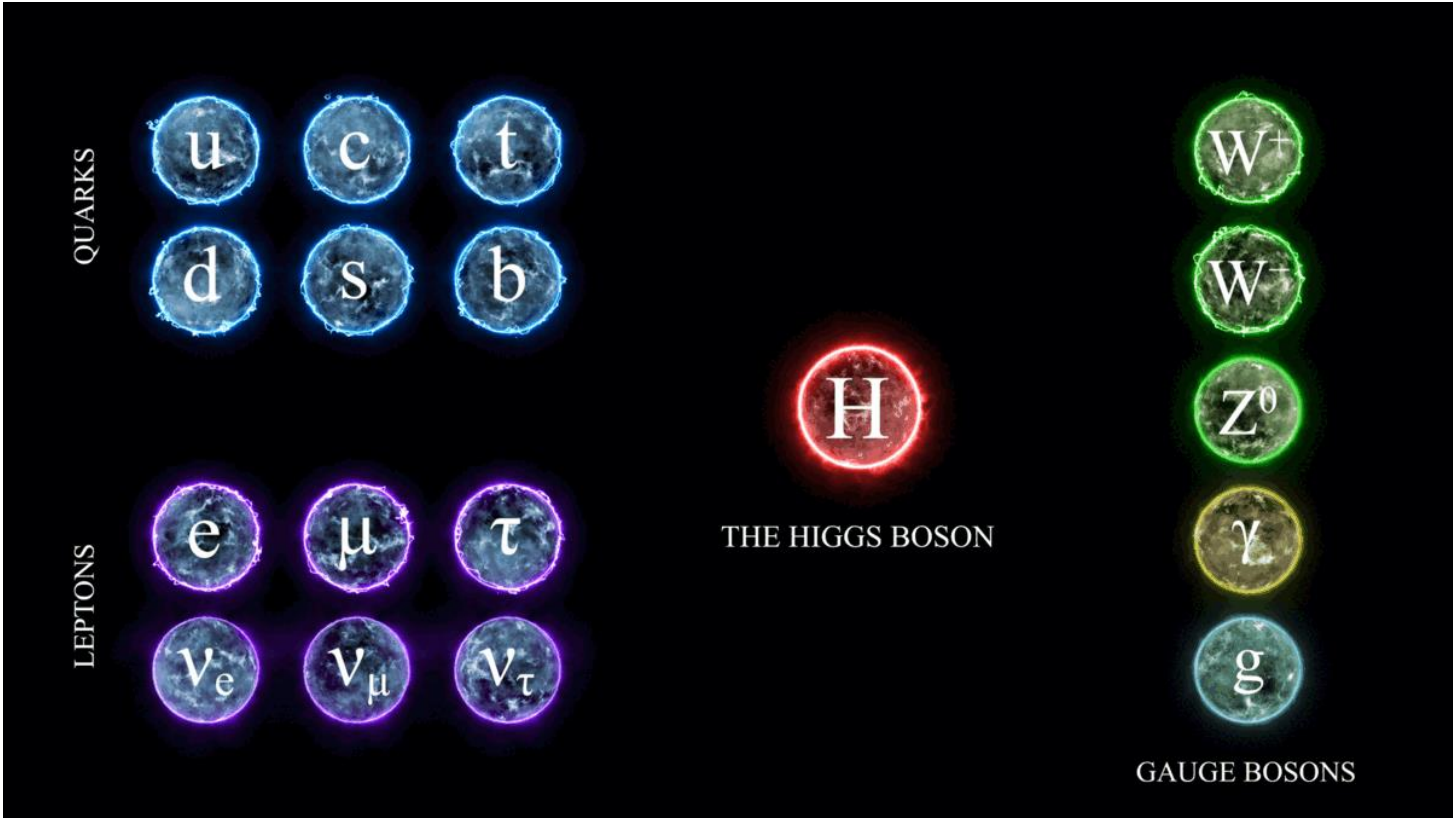


A (very) brief history of particle physics

Understanding the **building blocks of matter** has always been a holy grail for us.



The standard model of particle physics



CERN

In 1954, Conseil Européen pour la Recherche Nucléaire was established at the border of Switzerland and France.

Globe of science and innovation

Site of discovery of the W, Z, and Higgs bosons,

and birthplace of the world-wide web!

Today, scientists from **over 70 countries** work with CERN.

Pakistan is one of 6 associate members!

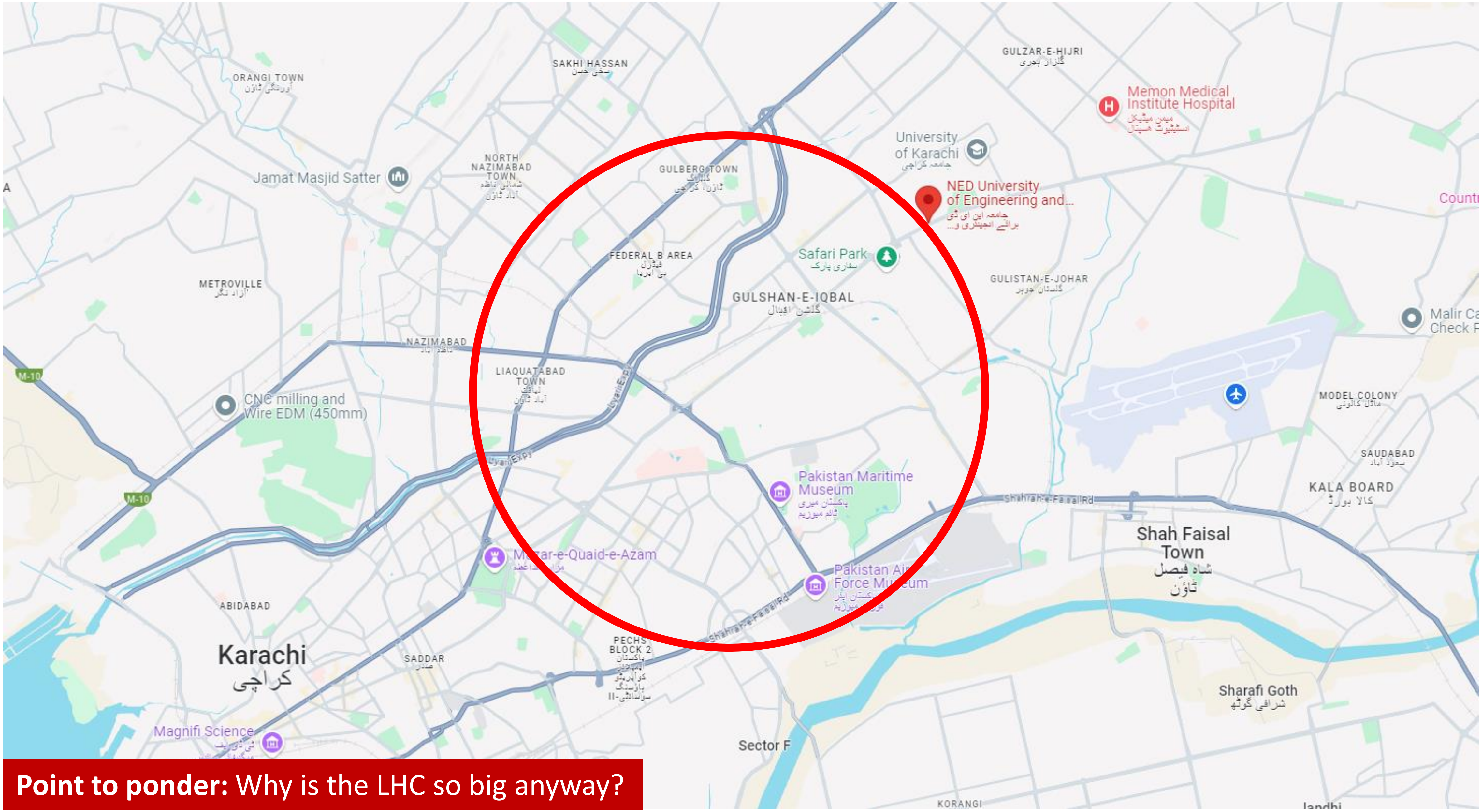
The Large Hadron Collider (LHC)

A **27 km ring**, 100 m below the surface.

Protons accelerated to nearly the speed of light, and the **highest energies ever created by humans (∼14 TeV)**.

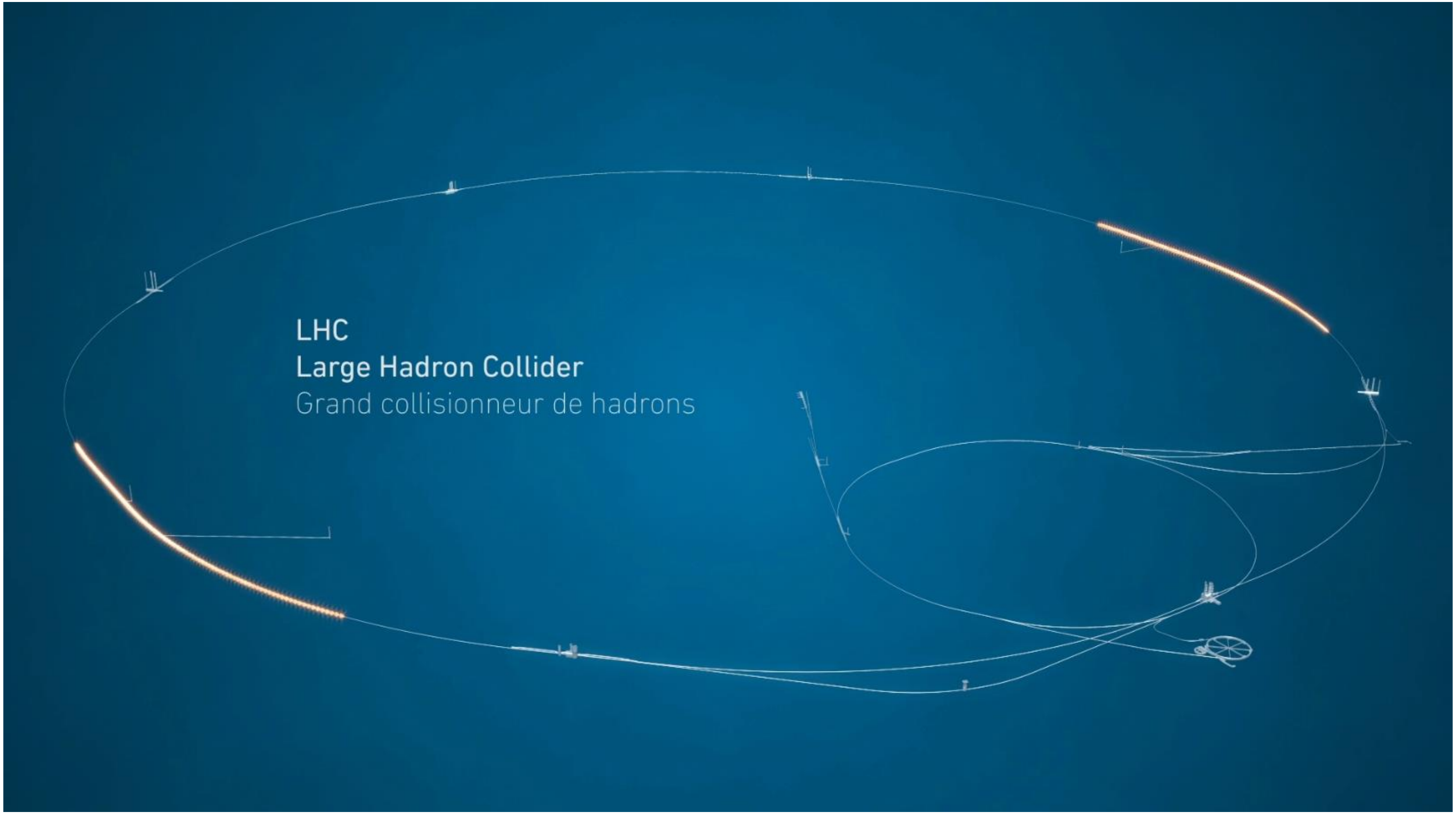
Bunches of **100 billion protons each collide 40 million times a second** at interaction points.

If the LHC were *here* ...



Point to ponder: Why is the LHC so big anyway?

The CERN accelerator chain

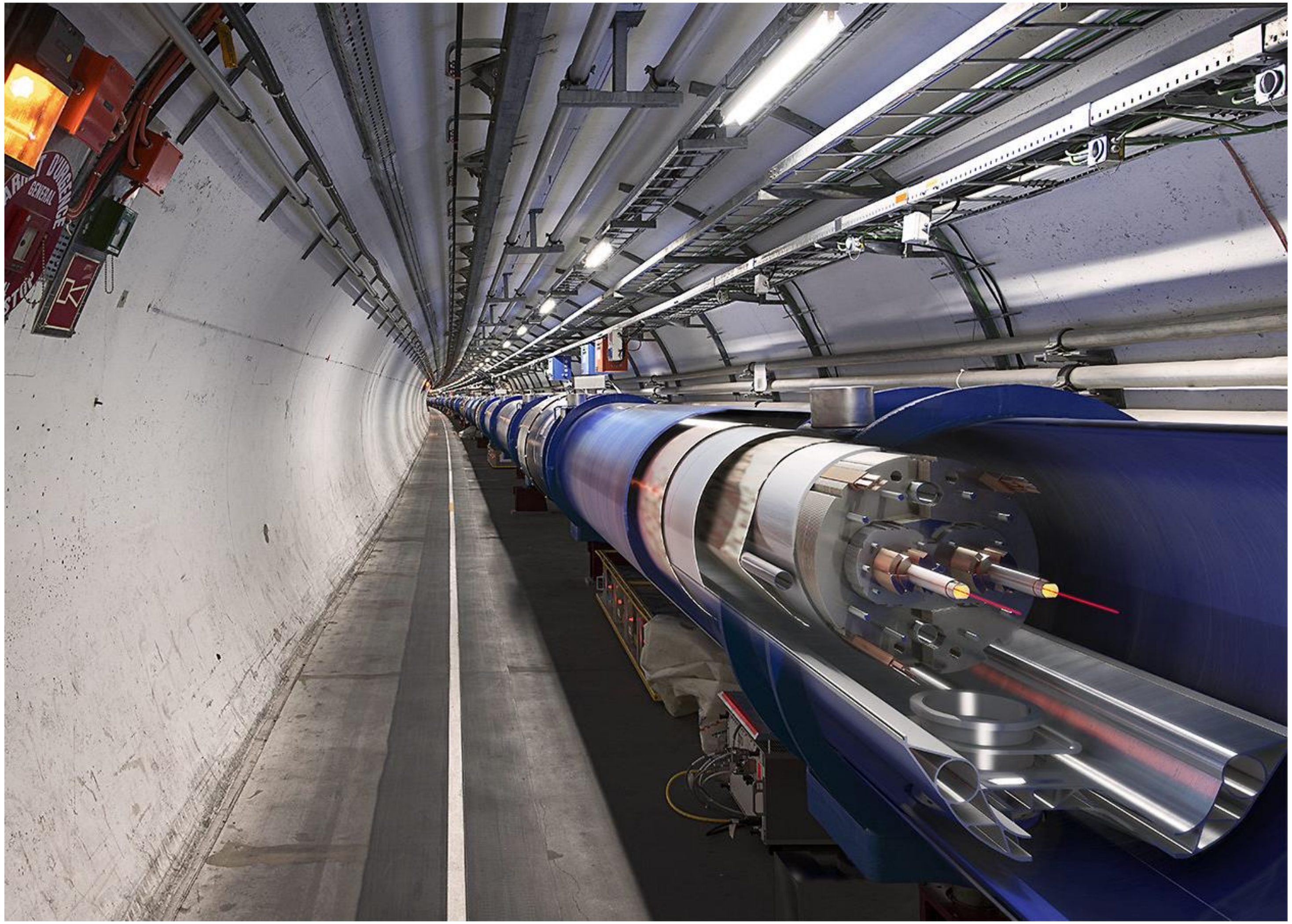


The LHC ring

- **The emptiest place in the solar system:**
  An extreme vacuum is needed inside the beam pipe. 10 times more atmosphere on the moon than in the LHC.

- **Colder than outer space:**
  8 Tesla superconducting magnets, needed to keep protons in the circular path; operate at 1.9 K.

- **Has some of the hottest temperatures in the galaxy:**
  When two beams of protons collide, a billion times hotter than the centre of the sun.

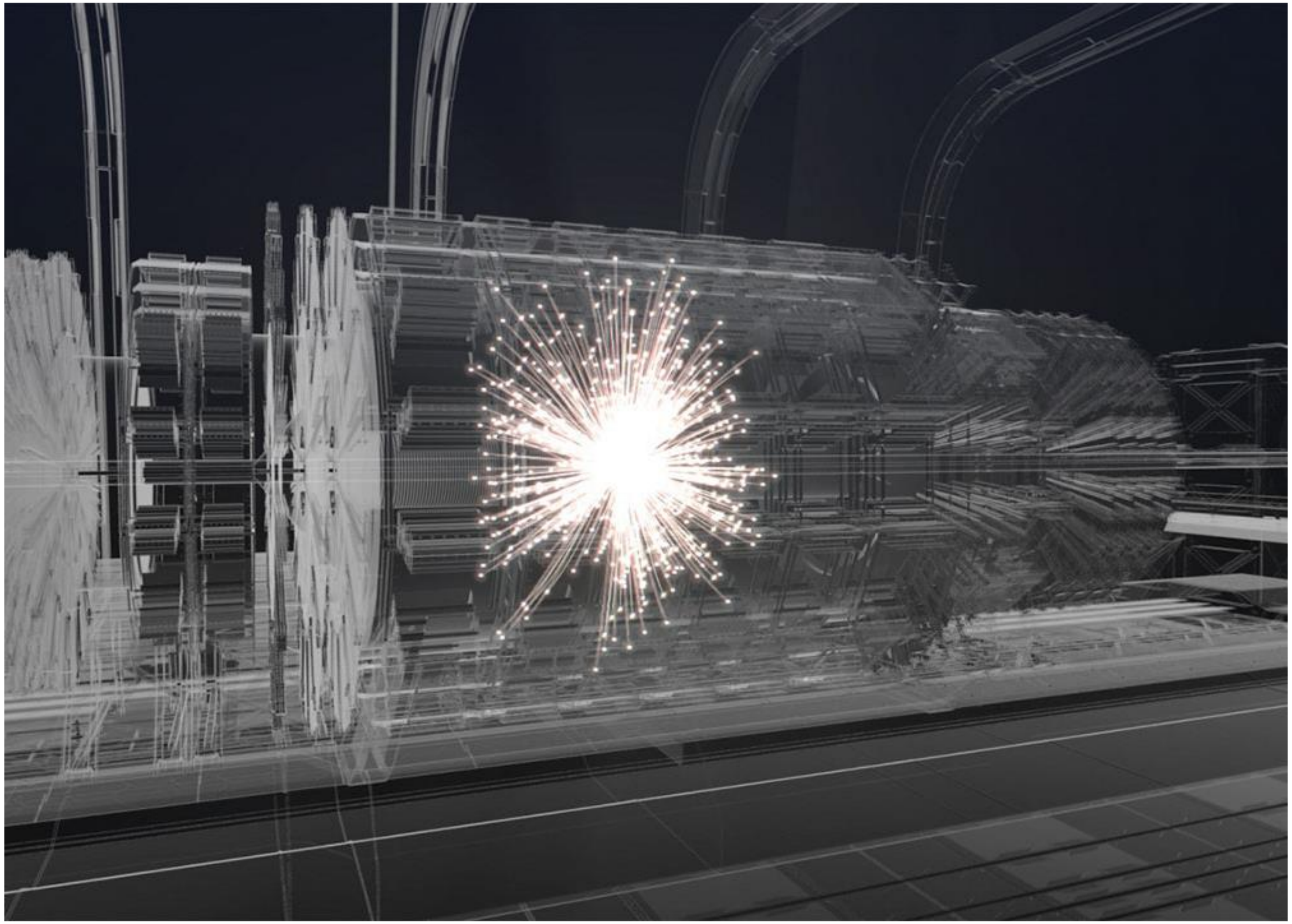


Point to ponder: What does the LHC beam taste like?

The LHC detectors (experiments)

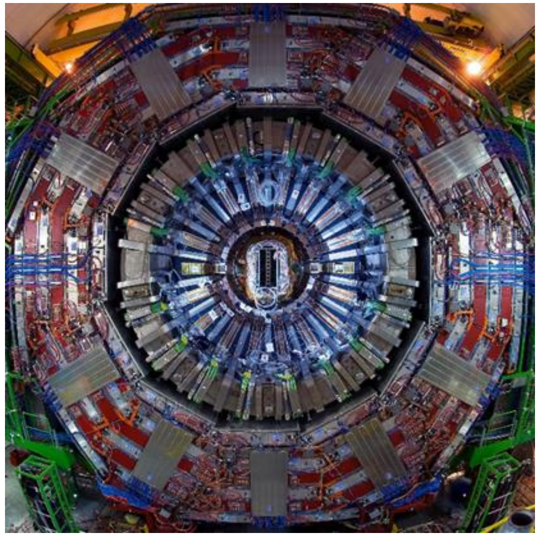
The LHC detectors act like **magic cameras** to record the debris from the collisions.

- ***"Photograph"*** some of the most elusive objects.
- ***"Number of megapixels"*** orders of magnitude greater than a normal camera.
- ***"Frame rate"*** of 40 million frames per second.
- ***"Select"*** the best 1000 pictures from these every second.



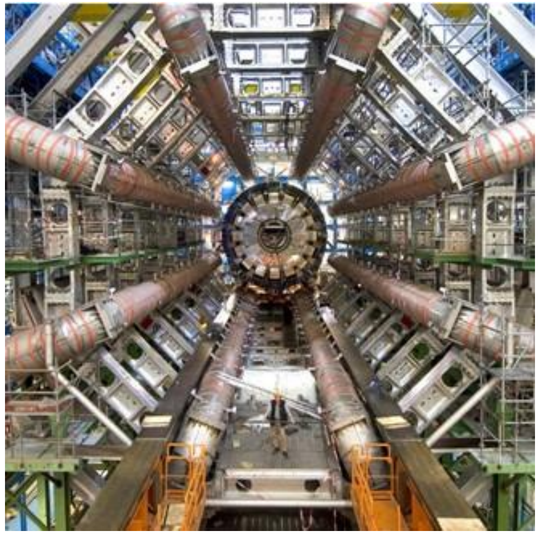
Point to ponder: Why are detectors for the *smallest* particles so big?

The LHC experiments



CMS

- **Largest detector by weight**, 14 k tonnes.
- **Wide range of physics goals**: Higgs, SM, exotica, supersymmetry, much more.

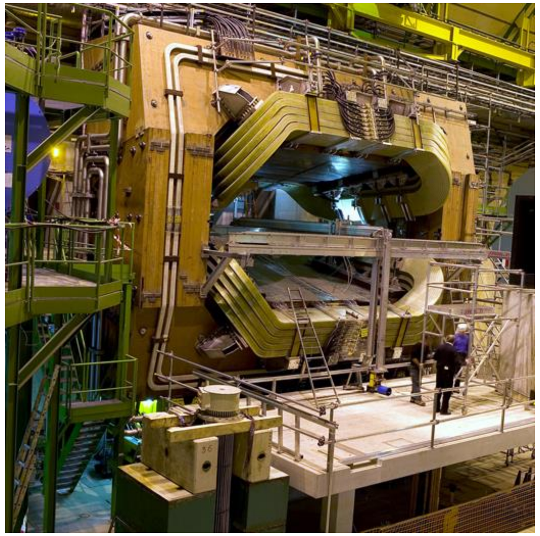


ATLAS

- **Largest detector by volume**, 46 m long.
- **Wide range of physics goals**: Higgs, SM, exotica, supersymmetry, much more.

ALICE

- **Specialised for heavy ion collisions**.
- Studies **quark-gluon plasma** – a state like the one found just after the Big Bang.



LHCb

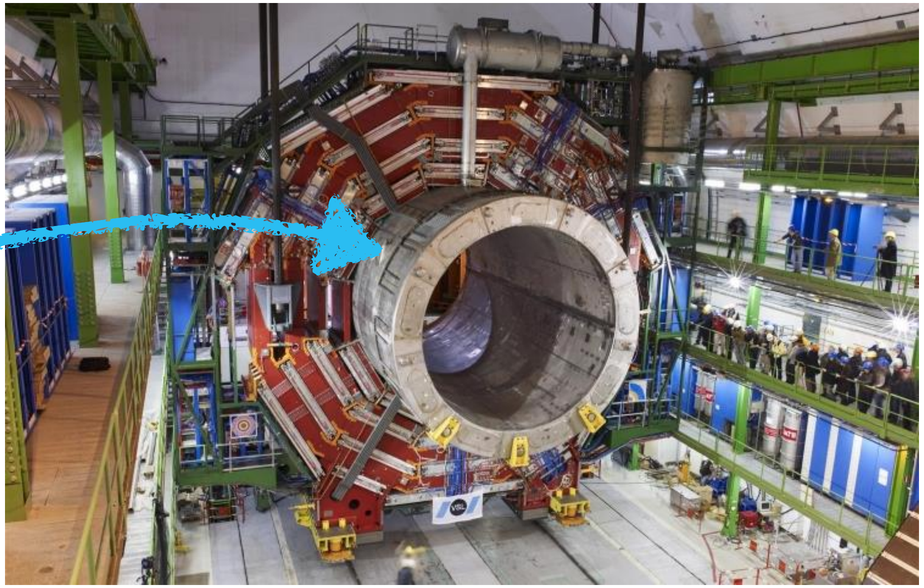
- Specialised to study **b-quark hadrons**.
- Insight into **matter-antimatter asymmetry**.

Point to ponder: Why does CERN have two experiments (ATLAS and CMS) for the same goal?

The Compact Muon Solenoid (CMS) detector

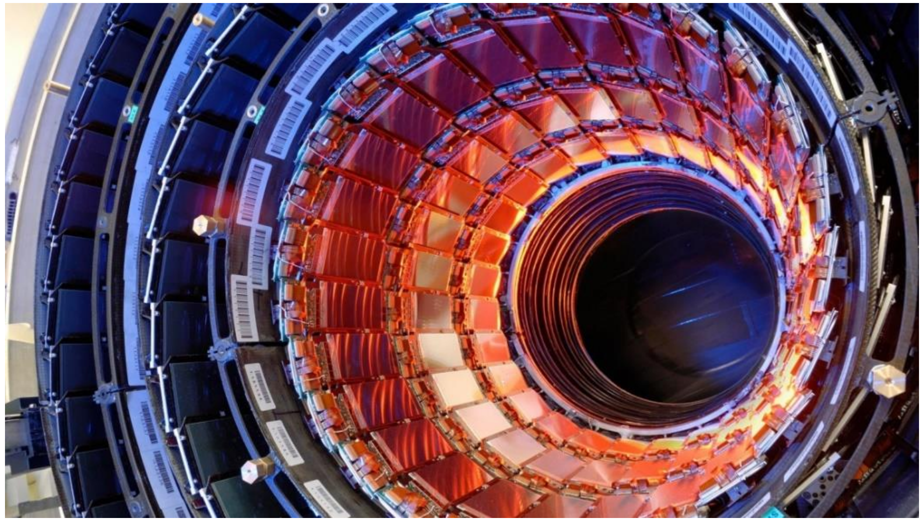
Solenoid magnet

- A strong magnetic field **(4 Tesla)** for bending particles.
- **Largest superconducting magnet** ever built – operating at ~4 K.
- **100,000 times stronger** than the Earth's magnetic field.



Tracker

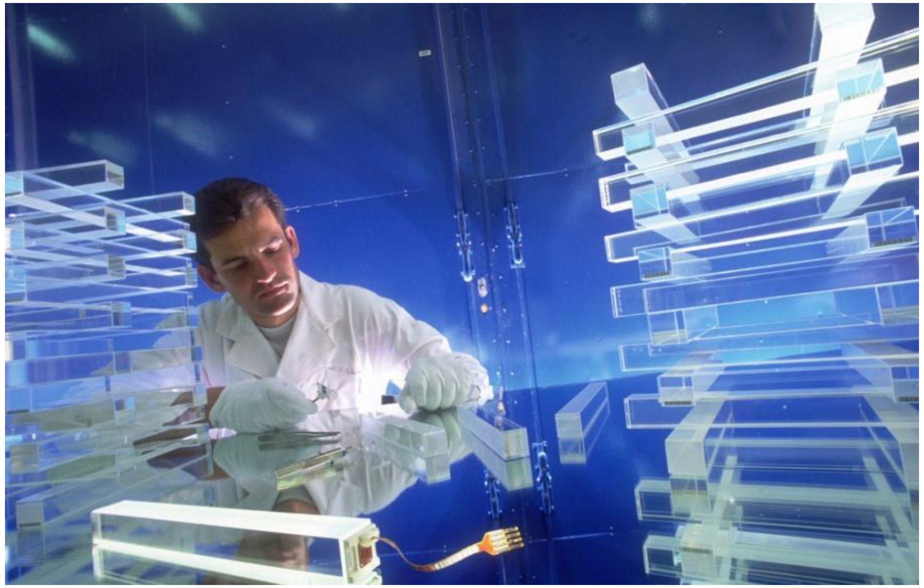
- Innermost detector; **detects tracks** of charged particles.
- Consists of two parts: **pixel and strip trackers.**
- Based on the principle of a **p-n junction diode**.



The Compact Muon Solenoid (CMS) detector

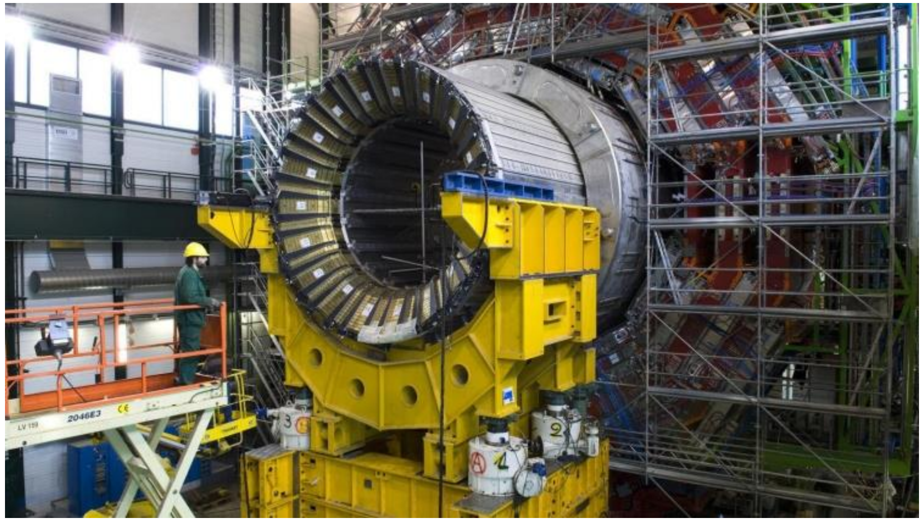
Electromagnetic calorimeter

- Used to detect **electrons and photons**.
- **Scintillator** composed of Lead Tungstate ($PbWO_4$) crystals.
- **Charged particles produce light** in the crystals, which is detected by the detector electronics.

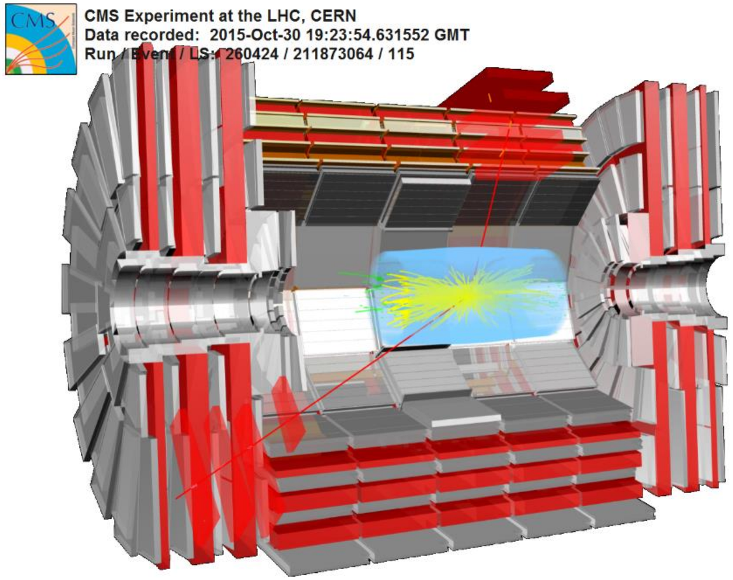


Hadronic calorimeter

- Used to detect **hadrons** (particles formed from quarks).
- Consists of alternating layers of **brass and plastic scintillators**.
- Hadrons produce charged particles via **strong interaction**. These charged particles produce light which is detected.

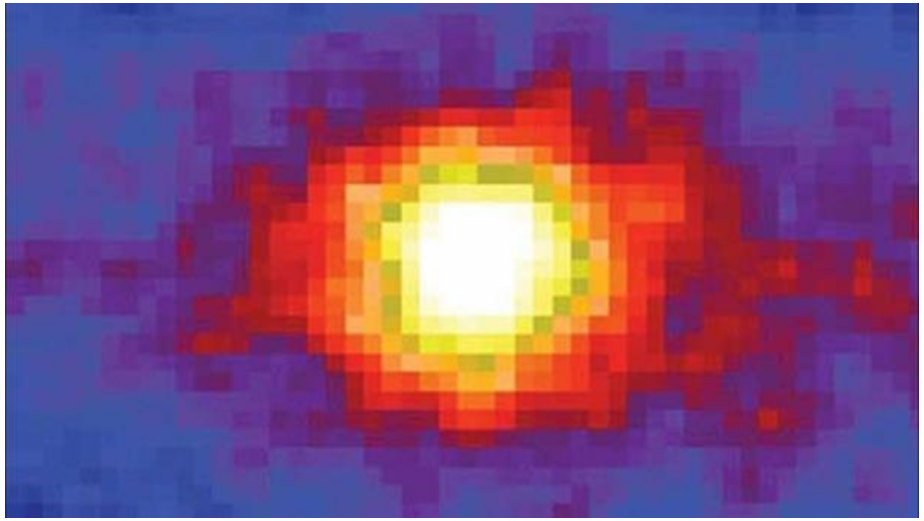


The Compact Muon Solenoid (CMS) detector



Muon detectors

- **Outermost detectors** in the CMS experiment.
- Different types: Cathode strip chambers (**CSC**), drift tube (**DT**), resistive plate chambers (**RPC**).
- **Gaseous detectors**, observe ionisation caused in the gas by the passing muons.



Ghost particles (neutrinos)

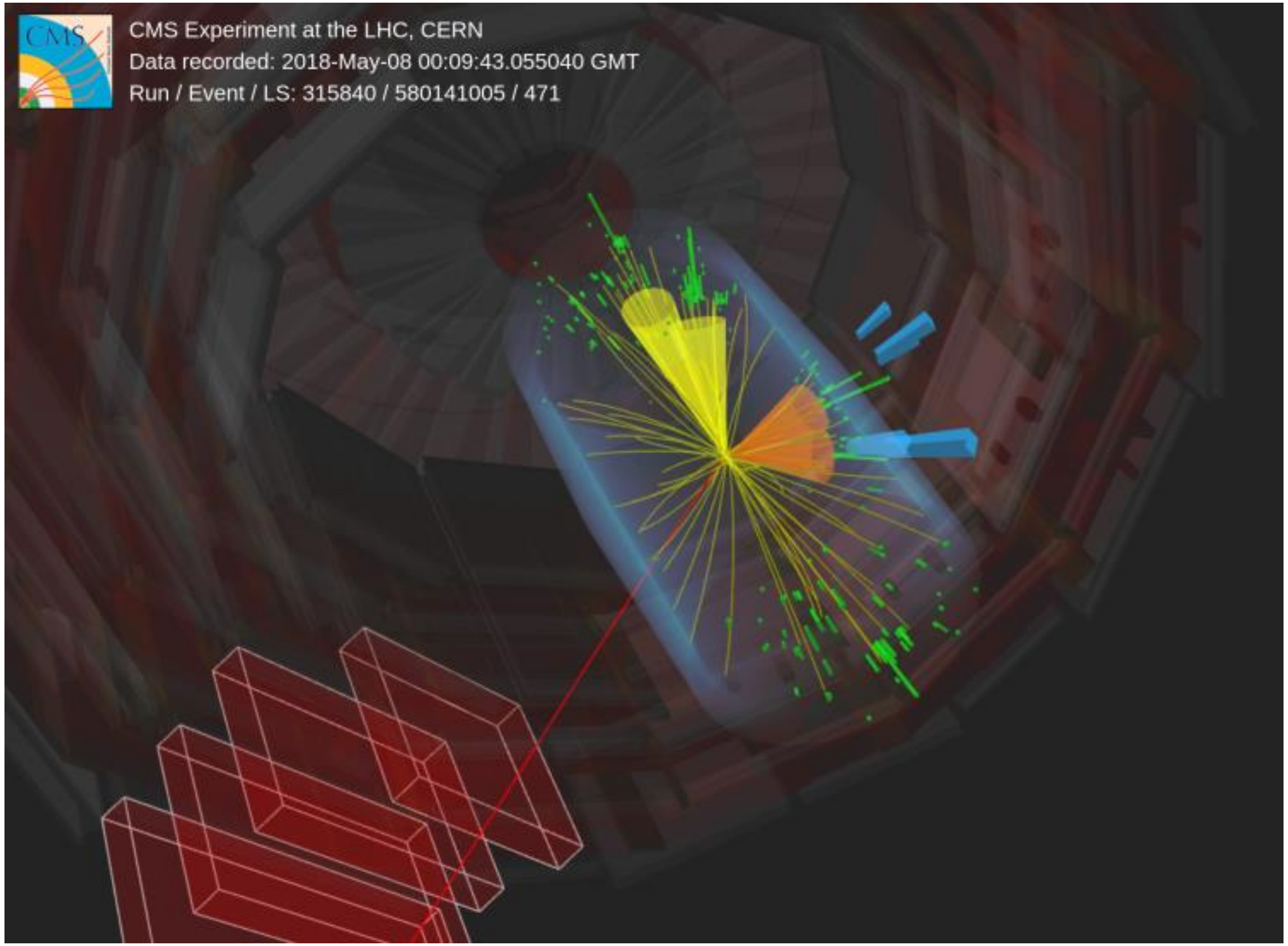
- Neutrinos interact only very **weakly**; hence they don't get detected in CMS at all!
- The presence of neutrinos is **inferred using conservation of momentum**.

From raw data to physics results

- Data collected by CMS is **filtered** in multiple steps to retain only ***interesting*** **collisions**.

- The data is then stored and processed in a **world-wide computing grid** (tens of petabytes of data every year).

- The data is analysed in multiple steps: Firstly, particles are ***"reconstructed"*****,** and kinematic properties deduced.



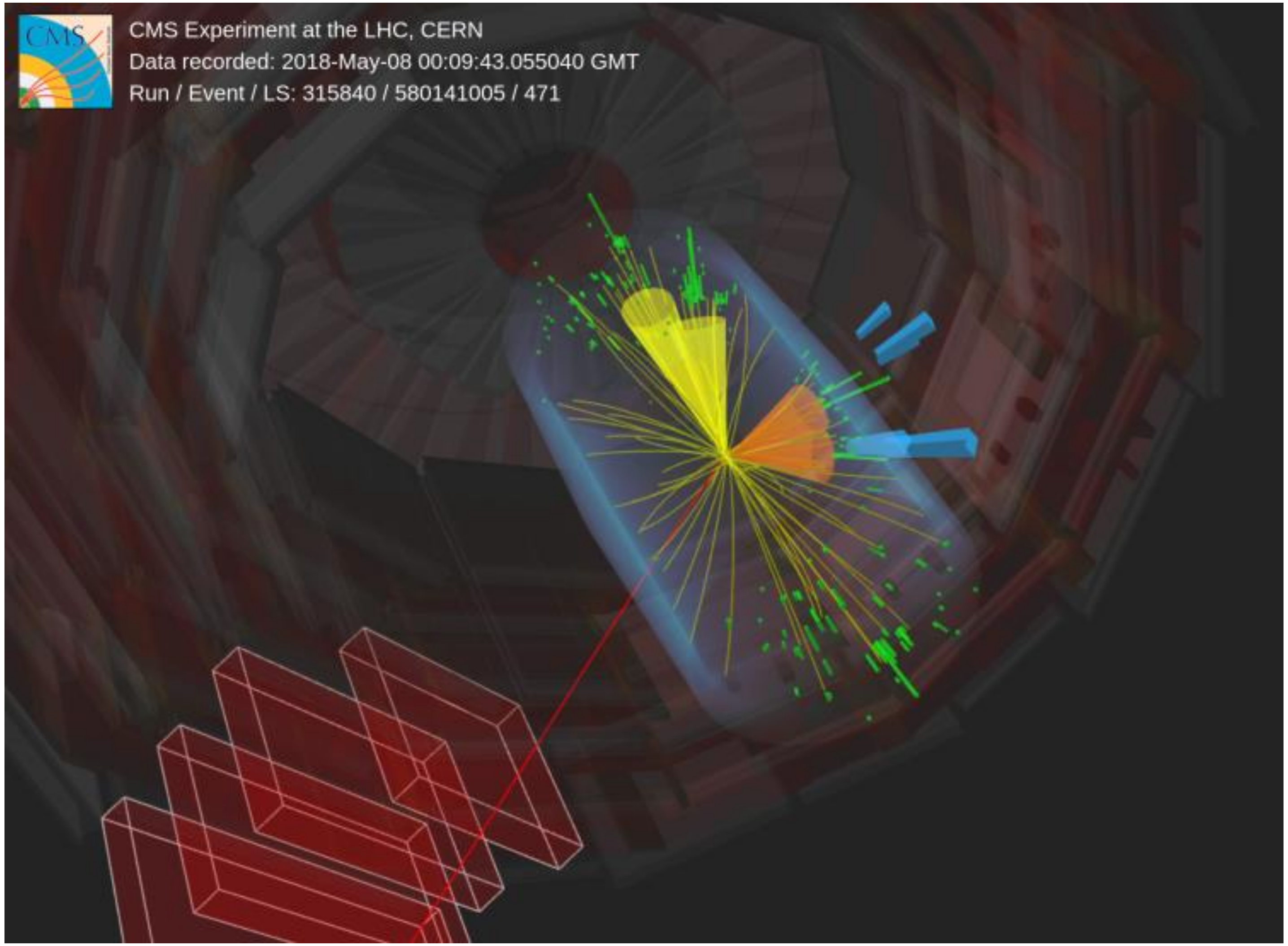
Display of a collision event consistent with top quark anti-quark pair production at CMS.

From raw data to physics results

- We need to differentiate the process we are interested in (***signal***) from imposters that can give similar final state particles (***background***).

- A plethora of techniques, including **Monte-Carlo simulations** and **machine learning**.

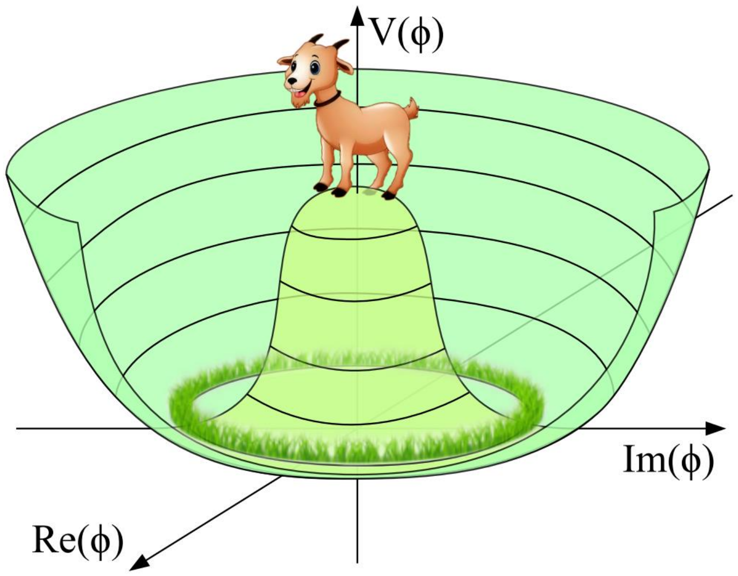
- **Statistical inferences** are deduced.



Display of a collision event consistent with top quark anti-quark pair production at CMS.

The Higgs boson

- Mathematical symmetries dictated that **all particles should be massless!**
- 1964: **Brout, Englert, and Higgs** proposed a mechanism, and predicted a field (and a corresponding particle) that gives mass to all particles.
- 2012: **The discovery of the Higgs boson** was announced by CMS and ATLAS experiments.
- 2013: Englert and Higgs received a **Nobel prize.**

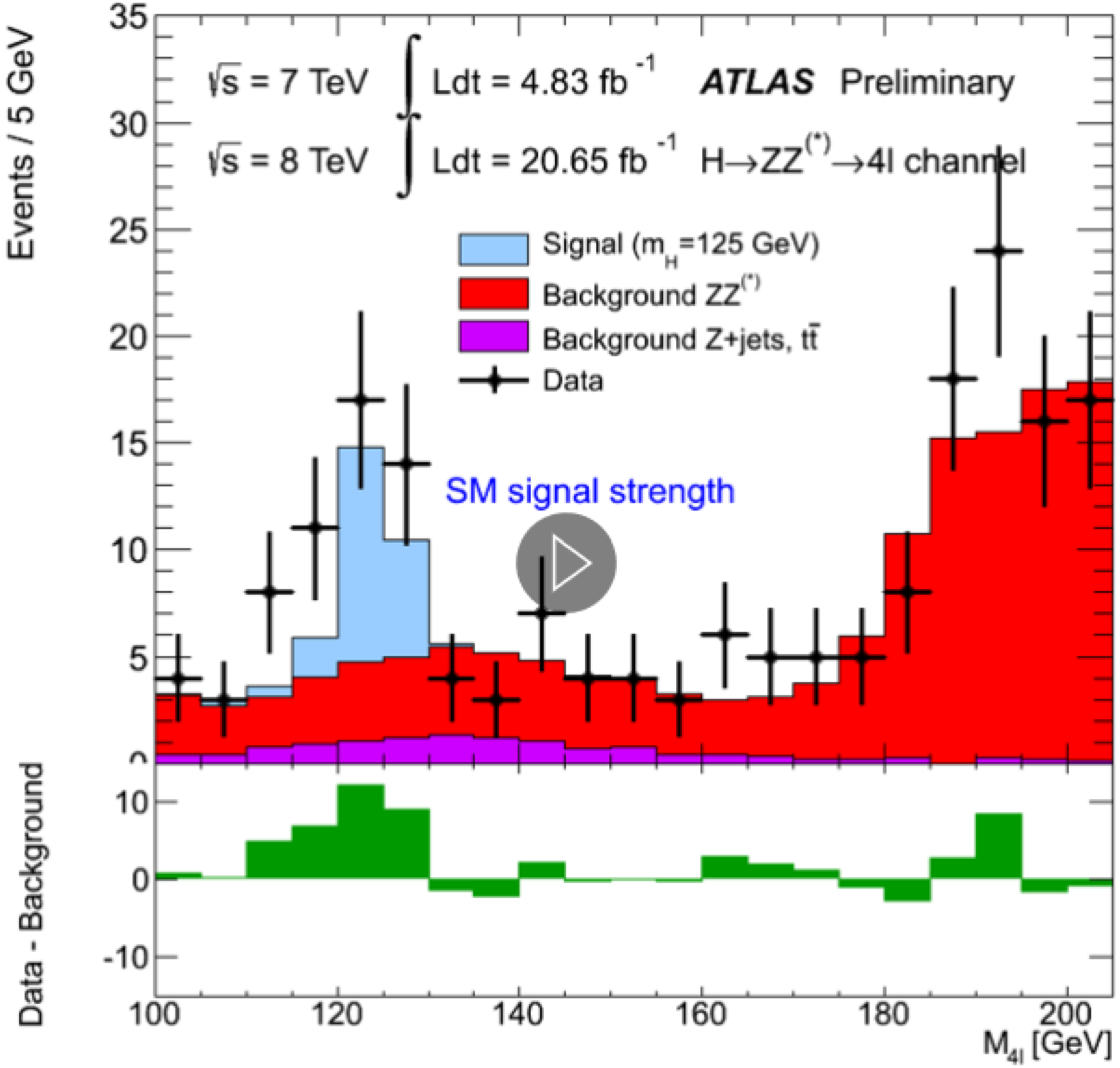


Analogy for spontaneous symmetry breaking.

Discovery of the Higgs boson

CMS and ATLAS experiments analysed **millions of events**, in different *channels*.

Announced discovery after confirming *an excess of 5 standard deviations*.

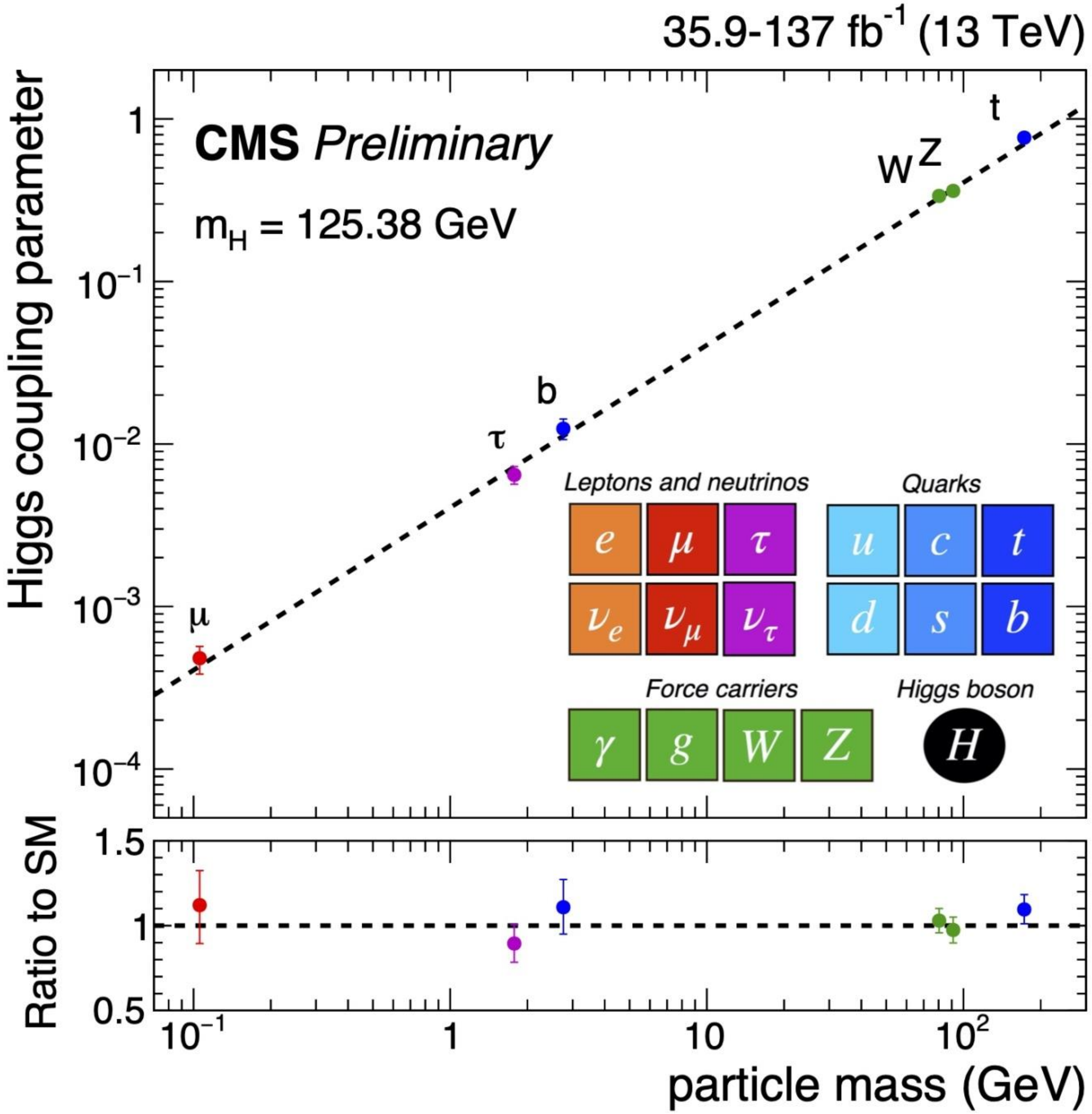


Recent results: Higgs boson couplings with fermions

- Since its discovery, studying **properties of the Higgs boson** in great detail.

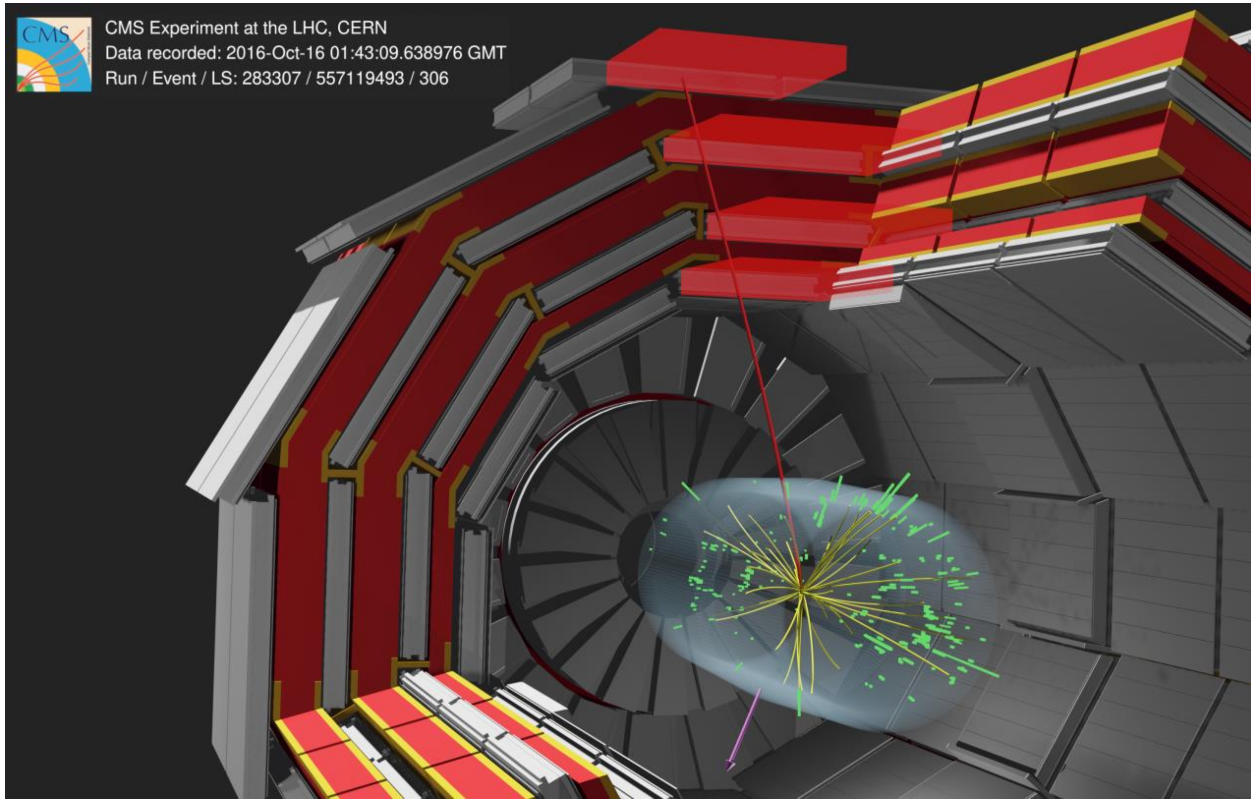
- **2018:** The CMS and ATLAS collaborations announced the discovery of Higgs boson **couplings with the third-generation fermions**.

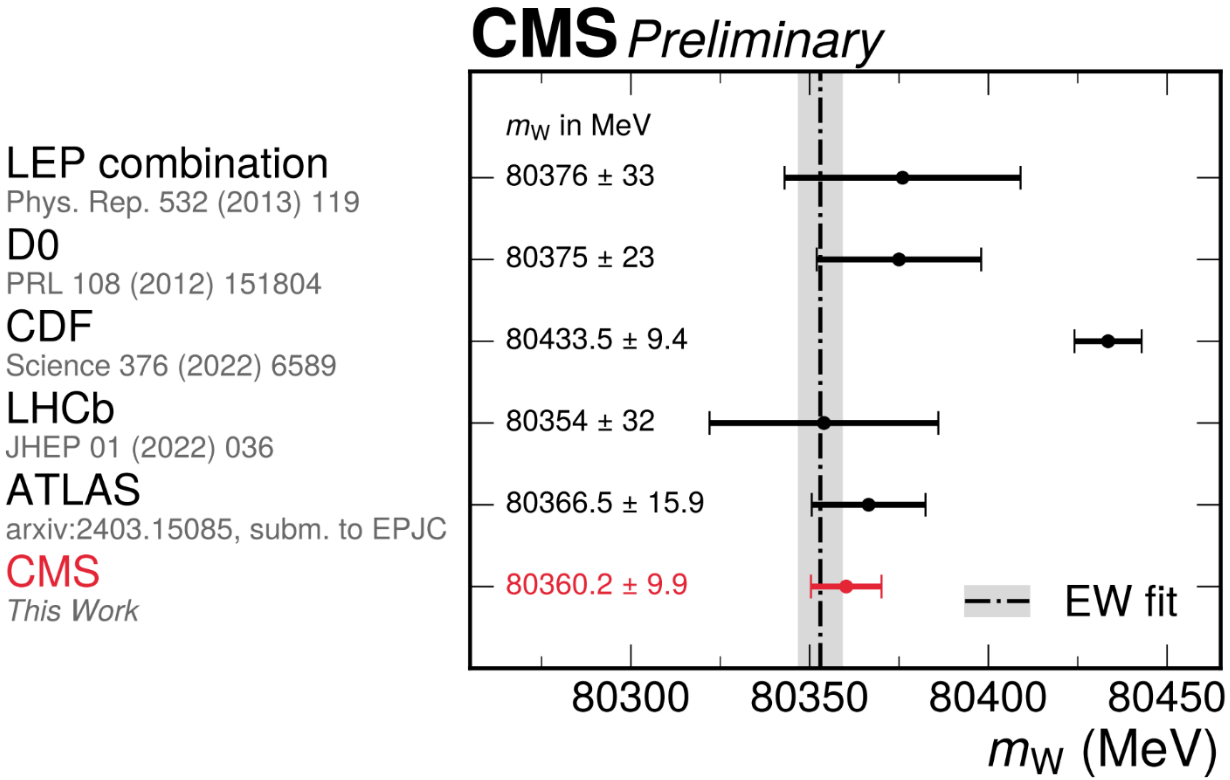
- **Recent result:** Higgs boson **couplings with the second-generation fermions**.



Recent results: W boson mass

- The mass of the W boson is a **fundamental prediction of the standard model**.
- The CMS experiment very recently announced an **extremely precise measurement – with a 0.012% uncertainty!**
- **Agrees with the standard model prediction.**

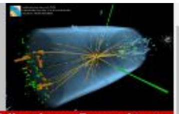




Full physics programme of the CMS experiment

Compact Muon Solenoid
LHC, CERN

Visit us: CMS Public Website, CMS Physics ; Contact us: CMS Publications Committee



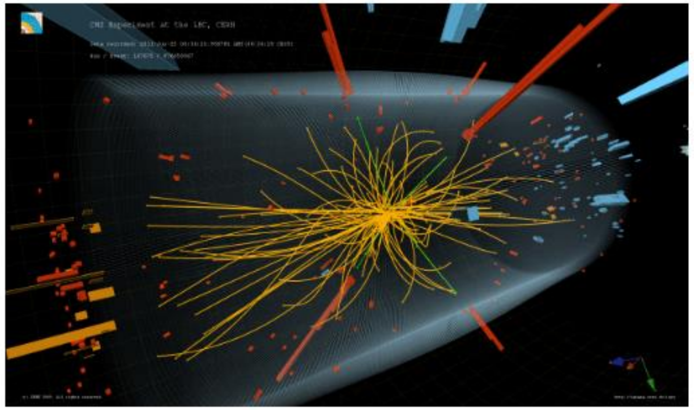
CMS Publications

CMS Publications
- Run 3 data
- Run 2 data
- Run 1 data
- Cosmics data
- The CMS Experiment at the CERN LHC

CMS Physics Publications
- Forward and Small-x QCD Physics
- B Physics and Quarkonia
- Standard Model Physics
- Top Physics
- Higgs Physics
- Supersymmetry
- Exotica
- Beyond 2 Generations
- Heavy-Ion Physics

CMS Physics Object Publications
- Tracking
- Vertexing and B Tagging
- Electron Photon
- Muon
- Tau
- Jet and Missing ET
- Generators
- Luminosity

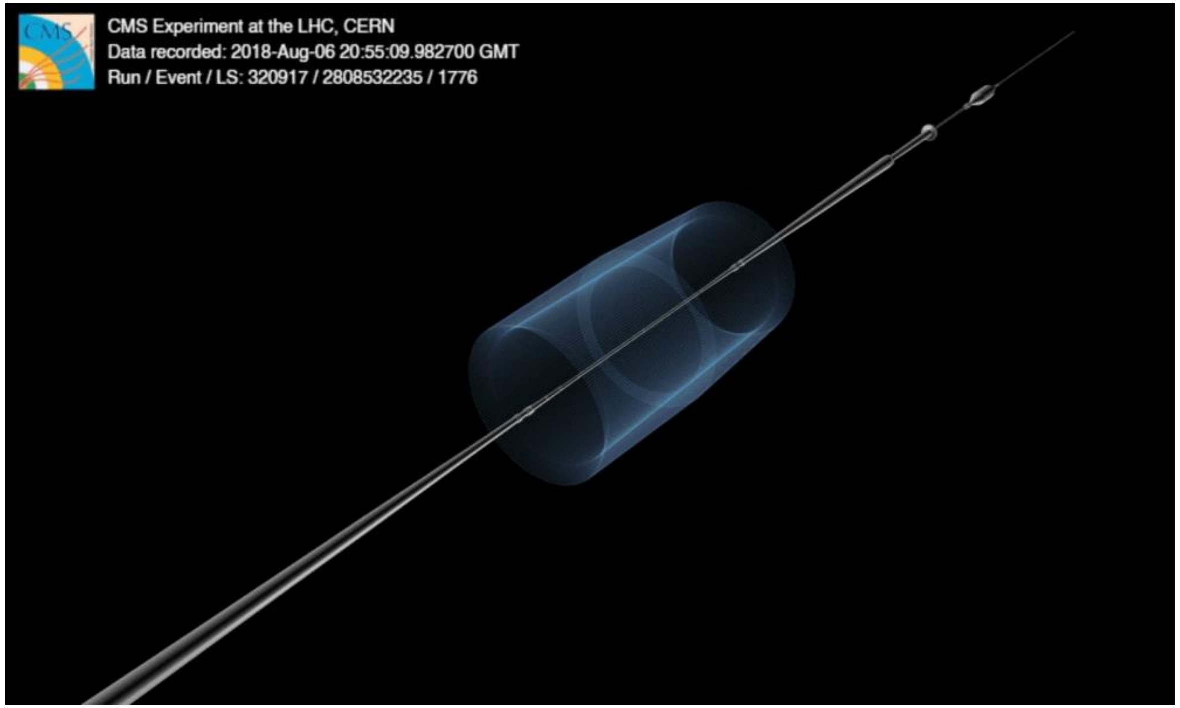
CMS Publication Search Page

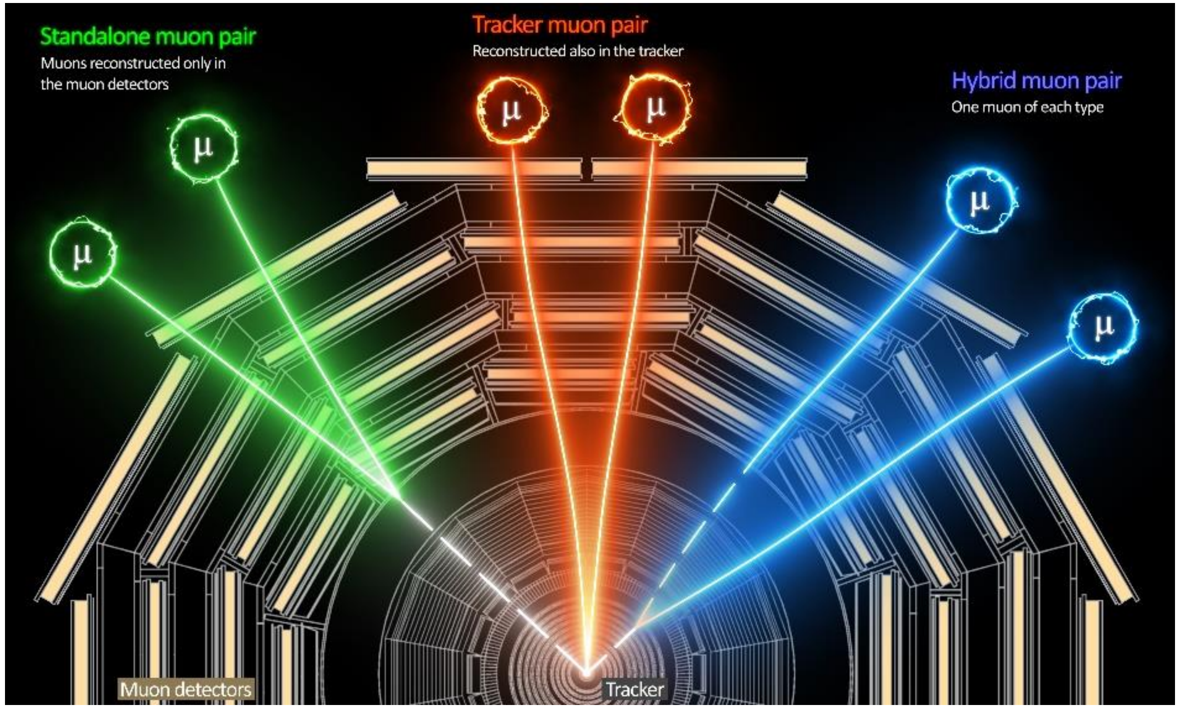


http://cms-results.web.cern.ch/cms-results/public-results/publications/

Exotic long-lived particles

- Most particles we are interested in **decay at the point of collision**.
- Searching for **exotic *long-lived* particles**, e.g. **dark photons**, using muons.
- Sensitive to a very **wide range of displacements** that the long-lived particles cover before decaying.



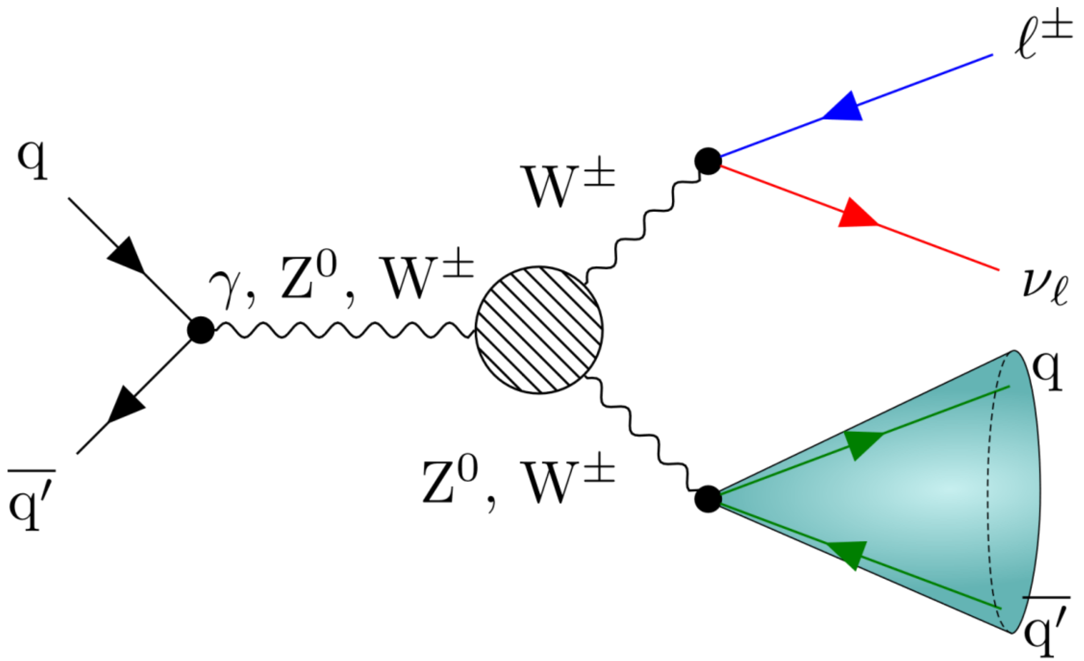


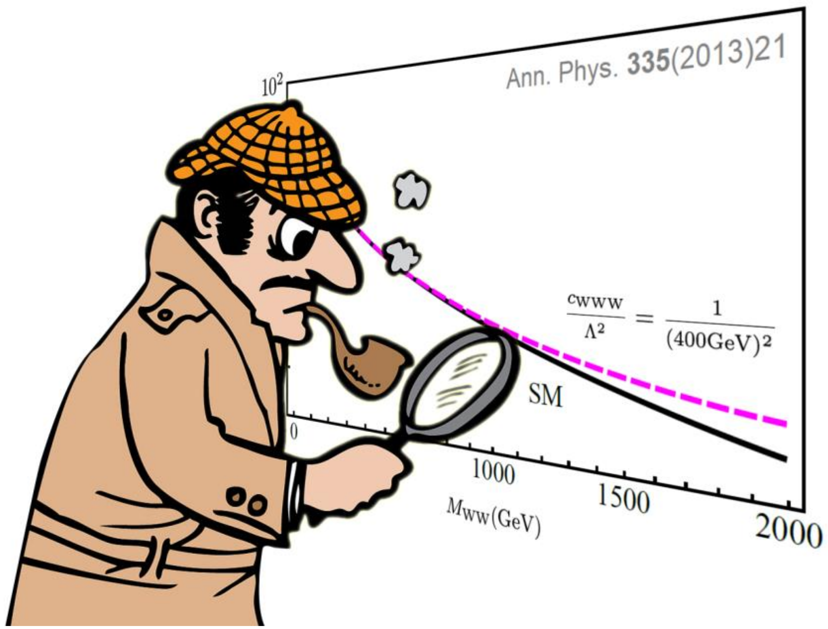
Model-independent indirect searches

- Study production of **pairs of vector bosons ($W^{\pm}$, Z^{0})** and **anomalous couplings**.
- Theoretical framework: **model-independent effective field theory**

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_1 + \frac{c_{\rm WWW}}{\Lambda^2}\mathcal{O}_{\rm WWW} + \frac{c_{\rm W}}{\Lambda^2}\mathcal{O}_{\rm W} + \frac{c_{\rm B}}{\Lambda^2}\mathcal{O}_{\rm B} + \ldots$$

- Non-zero $c_{\rm WWW}$, $c_{\rm W}$, $c_{\rm B}$ would indicate **physics beyond the standard model**.





Conclusion and outlook

- The LHC and CMS experiment are a true **technological marvel**, and a testament to **human ingenuity and perseverance**.

- Physicists here are pushing the boundaries of **our understanding of the basic building blocks of the universe**.

- Planning already in full swing for **upgrades and advancements decades into the future**.