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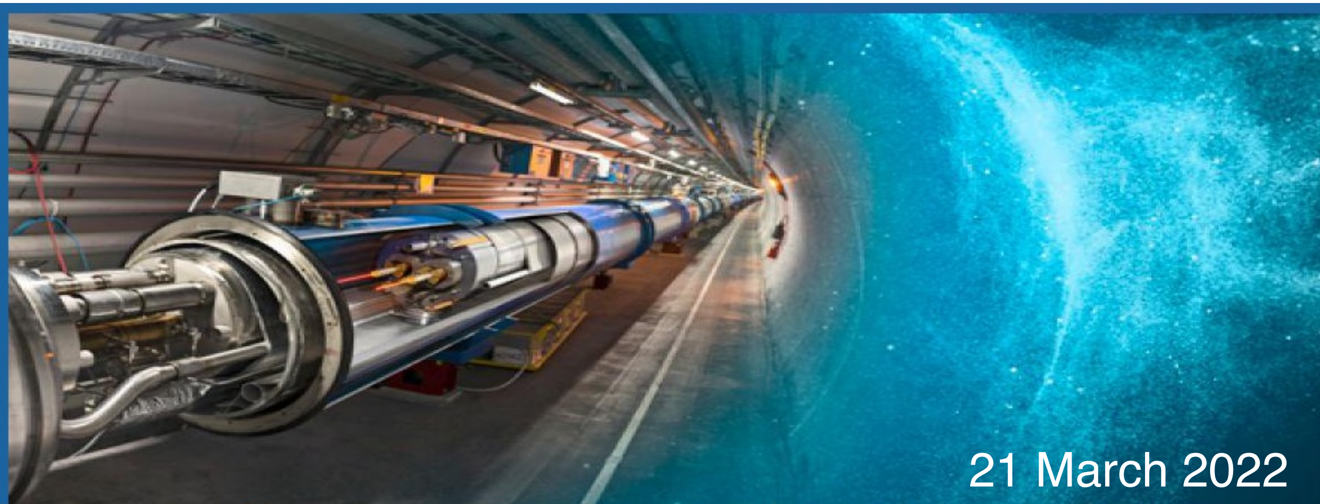
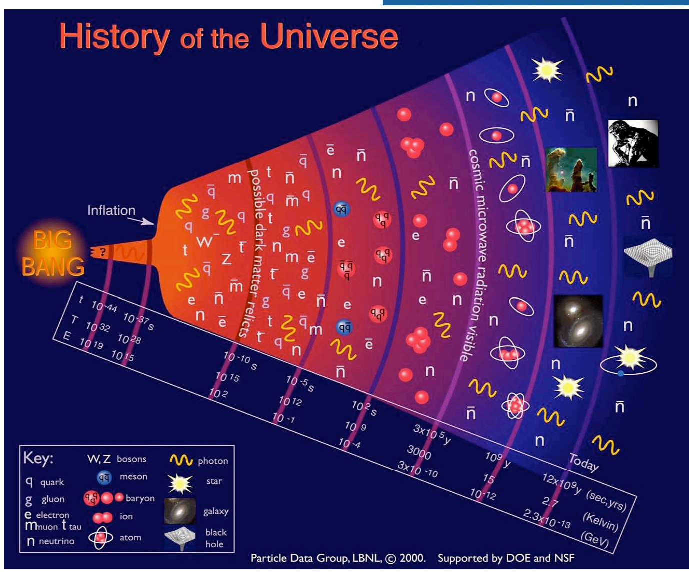
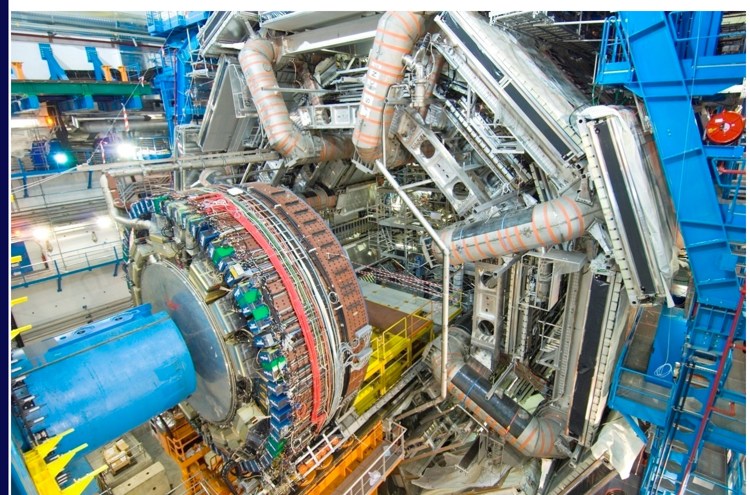
Discovery of the Higgs boson at the LHC

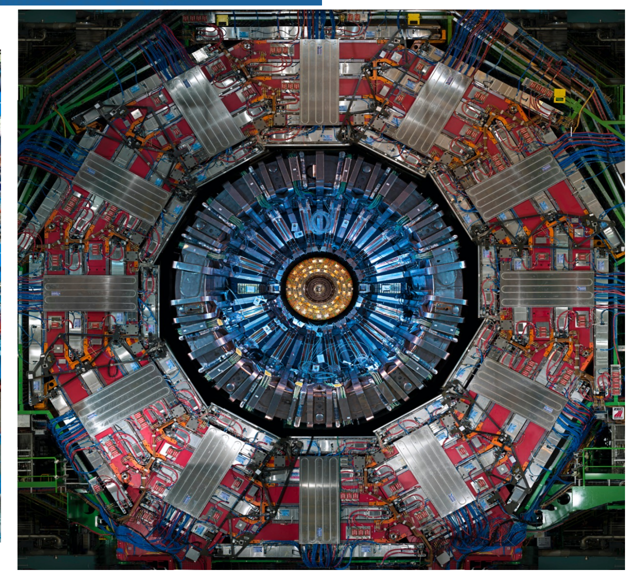


21 March 2022

First Pan-African Astro-Particle and Collider Physics Workshop







Tejinder S. Virdee, Imperial College London

Particle Physics

Particle physics is a modern name for centuries old effort to understand the laws of nature.

Aims to answer the two following questions:

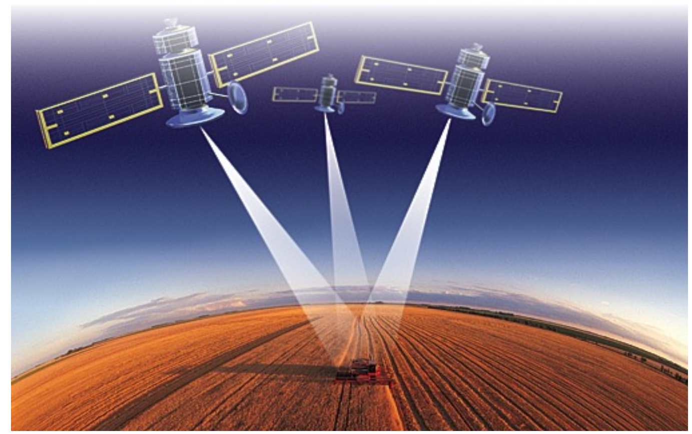
What are the elementary constituents that make up our universe?

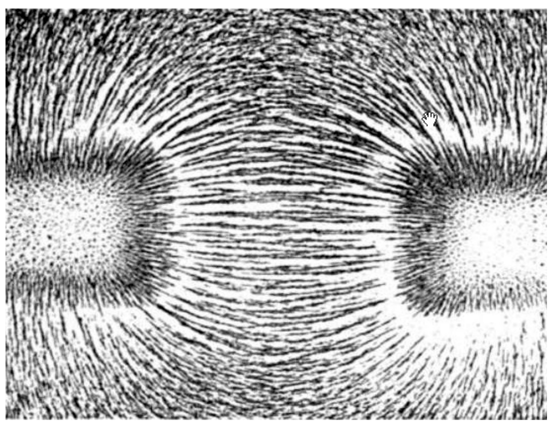
What are the forces that control their behaviour at the most basic level?

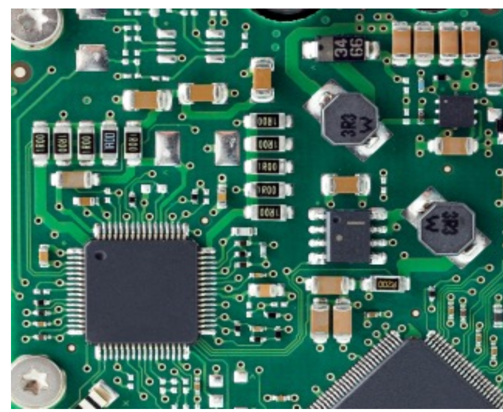
Experimentally:

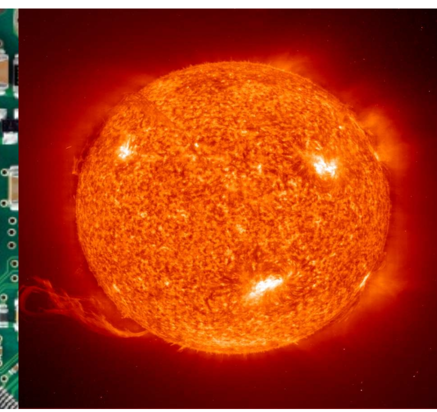
1. Make particles interact and study the products and properties of the result of the interaction
2. Measure the energy, direction and type of the products as accurately as possible
3. Reconstruct what happened during the collision

The Wonderful Variety of Nature









Can we understand this variety in a unified way?

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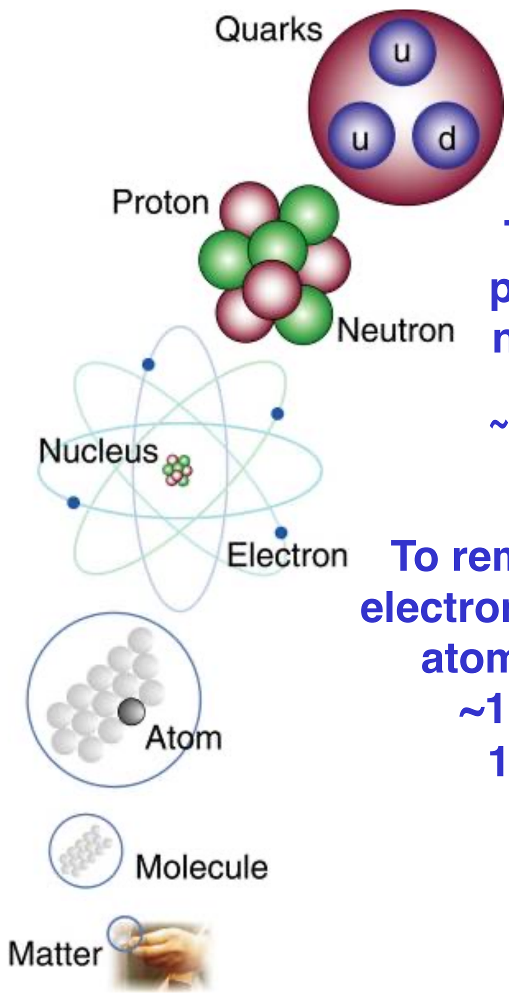
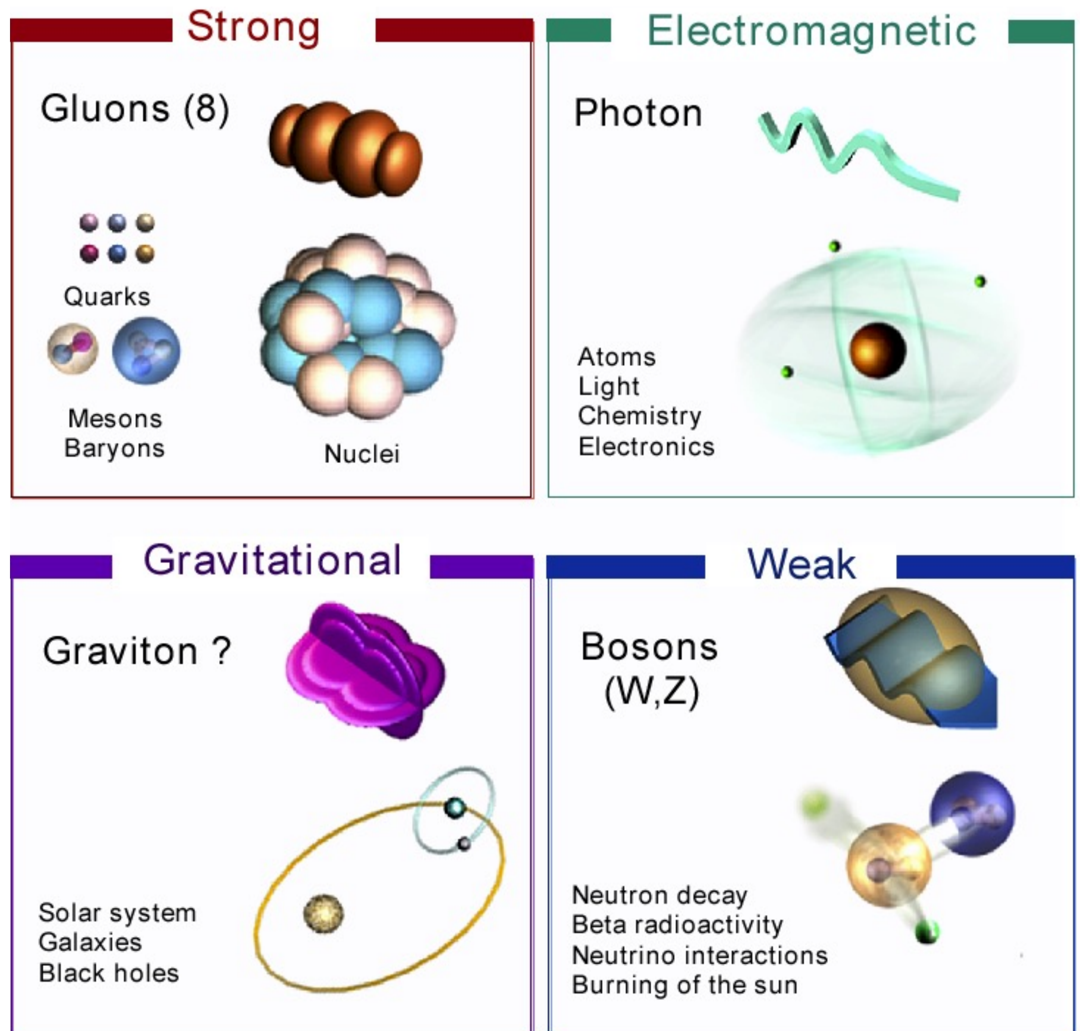
Matter and Forces



At LHC
~ 5 trillion ×

To remove a proton from a nucleus need ~10 MeV
~10 million ×

To remove an electron from an atom need ~10 eV
10 ×



All known forces in the world can be attributed to these four interactions

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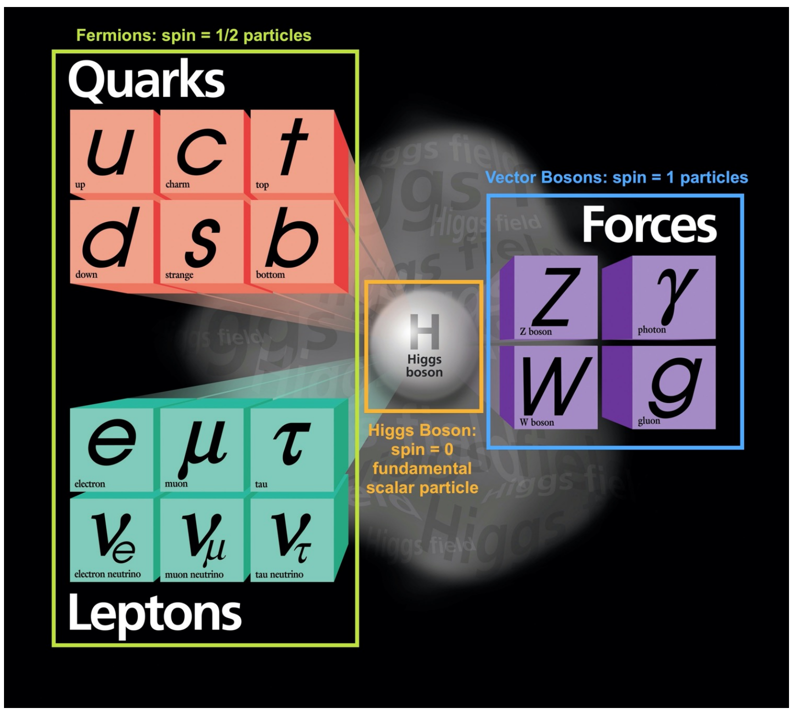
The Standard Theory of Particle Physics

Over the last 100 years: the combination of Quantum Mechanics and Special Theory of relativity along with the plethora of particles discovered has led to the Standard Model (Theory) of Particle Physics (SM).

The new (final?) "Periodic Table" of fundamental elements

Matter particles (fermions)



Force particles (bosons)

- Matter is composed of
- Three families of quarks
- Three families of leptons
- Interactions (strong nuclear, electromagnetic, weak nuclear) are carried by exchange of spin-1 bosons

The Standard Theory of Particle Physics

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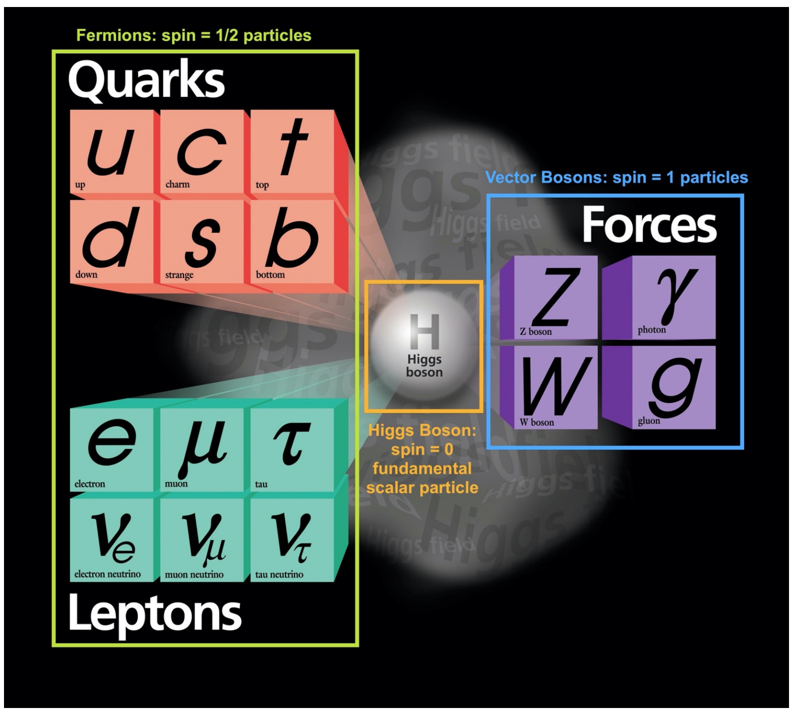
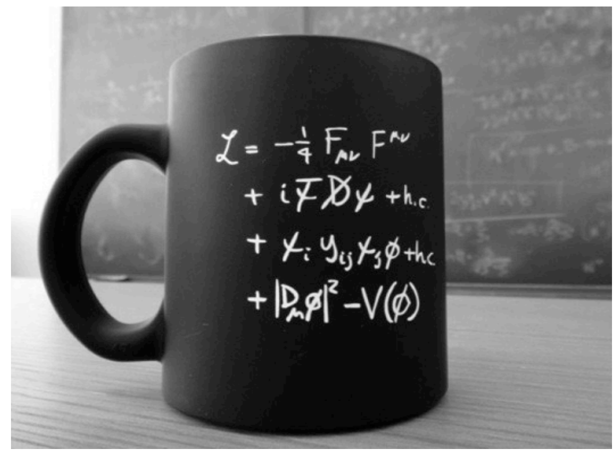
along with the plethora of particles discovered has led to the
Standard Model (Theory) of Particle Physics (SM).
The new (final?) "Periodic Table" of fundamental elements

Matter particles



Force particles

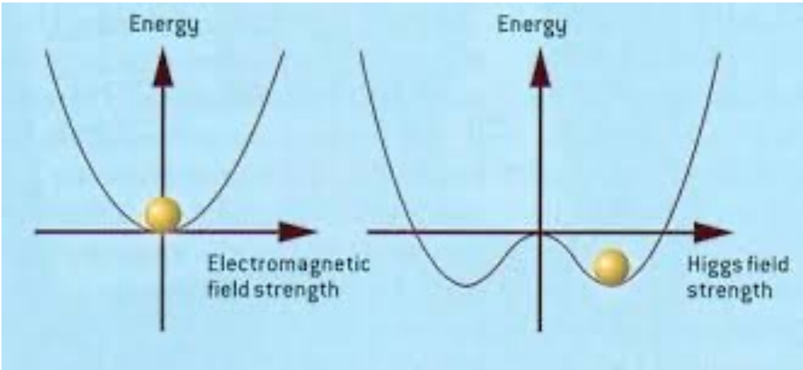


Quantum Field Theories of
3 of the 4 fundamental interactions
Very successful description of our visible universe (short distance)

The EW Spontaneous Symmetry Breaking Mechanism

✓The Higgs boson is a prediction of a mechanism (labelled the BEH mechanism) that took place in the early universe (< ps after the Big Bang) when the EM and weak interactions became distinct in their action. A complex scalar field is introduced that permeates the universe. Its quantum manifestation is the Higgs boson.

Before the phase transition
T >Tc; vacuum expectation value
$<v>=0$



After the phase transition
T <Tc (Tc ~ 100 GeV)
"Mexican hat" BEH potential
non-zero $<v>$
W an Z bosons acquire mass
Photons remain massless

$$V(h) = \frac{1}{2}m_{\mathrm{H}}^2 h^2 + \sqrt{\frac{\lambda}{2}}m_{\mathrm{H}} h^3 + \frac{1}{4}\lambda h^4$$

h-BEH field; $\lambda = m_H^2/v^2$

✓Nature possesses an EW symmetry that is spontaneously broken granting mass to W and Z bosons. In addition, via the so-called Yukawa interactions it grants mass to fermions.

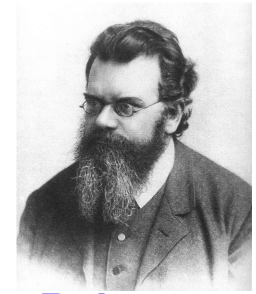
✓Thus elementary particles interacting with the BEH field acquire mass. The impact is far reaching, e.g. electrons acquire mass, allowing atoms to form and endowing out universe with the observed complexity.

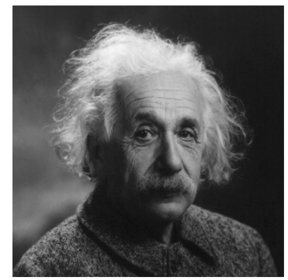
Particle Accelerators

accelerate particles to extremely high energies.

High energies allow us to

i) Study the young universe (E= kT)
Revisit the earlier moments of our ancestral universe
(look further back in time ➔“powerful telescopes”)


Boltzmann


Einstein


de Broglie

ii) Discover new particles with high(er) mass ($E = mc^2$)

iii) Look deeper into Nature ($E \propto 1/size$),
(look deeper ➔“powerful microscopes”)

Observe phenomena and particles normally no longer observable in our everyday experience.

All in a controlled way - “in the laboratory”

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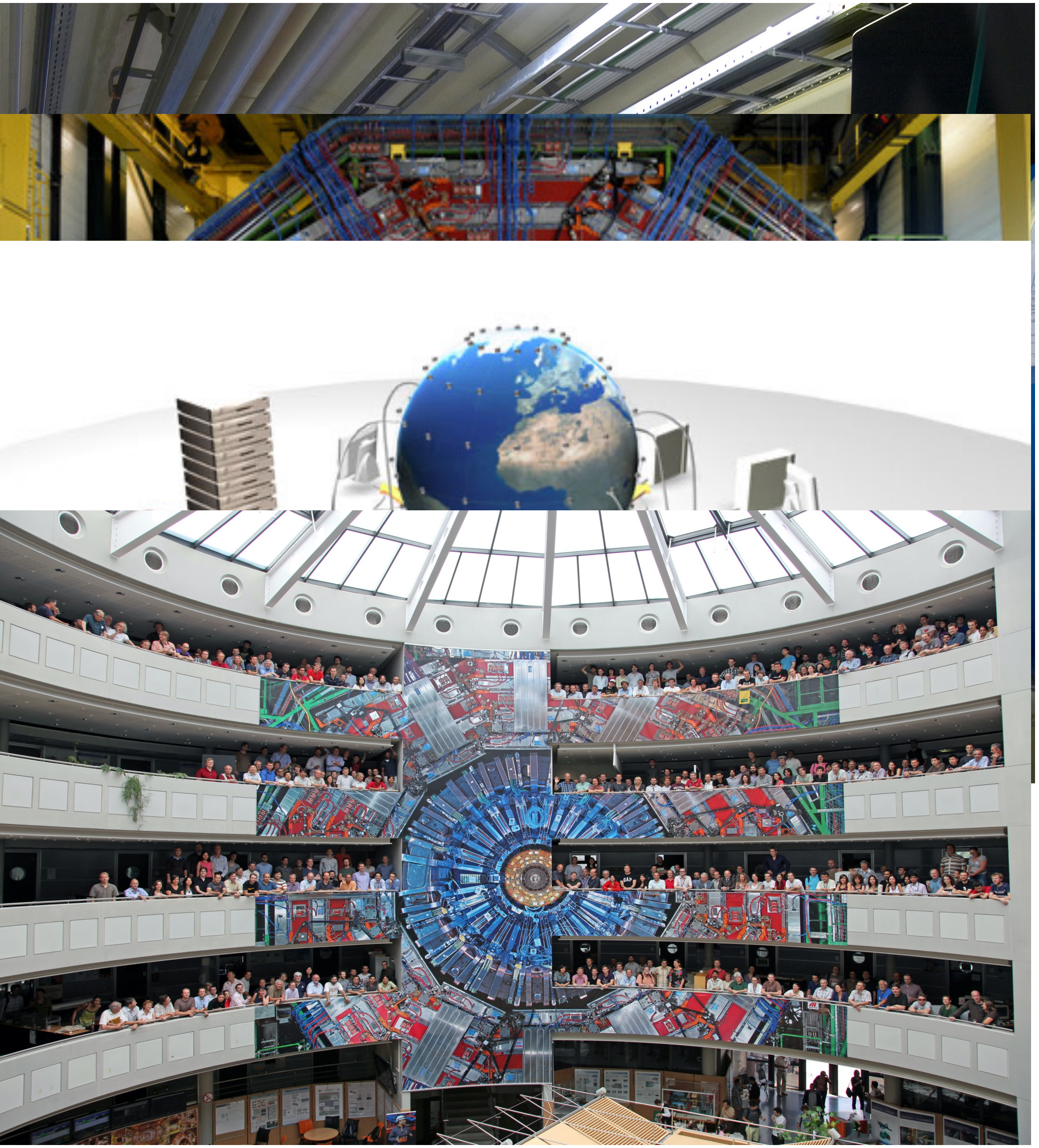
Studies in Particle Physics Require…….



1. Accelerators : powerful machines that accelerate particles to extremely high energies and bring them into collision with other particles

2. Detectors : gigantic instruments that record the resulting particles as they “stream” out from the point of collision.

3. Computing : to collect, store, distribute and analyse the vast amount of data produced by these detectors

4. Collaborative Science on a worldwide scale: thousands of scientists, engineers, technicians and support staff to design, build and operate these complex “machines”.

The Large Hadron Collider at CERN

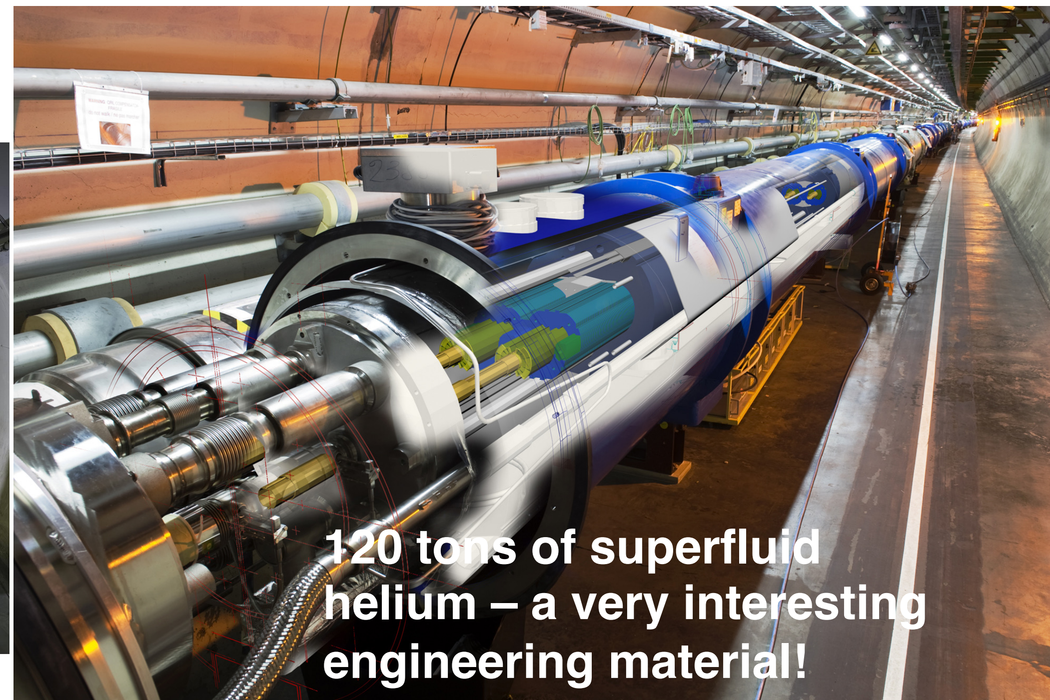
The LHC Accelerator

Protons are accelerated by powerful electric fields to very (very) close to the speed of light (superconducting r.f. cavities)

And are guided around their circular orbits by powerful superconducting dipole magnets.

The dipole magnets operate at 8.3 Tesla (200'000 x Earth's magnetic field) & 1.9K (-271° C) in superfluid helium.

Protons travel in a tube which is under a better vacuum, and at a lower temperature, than that found in inter-planetary space.

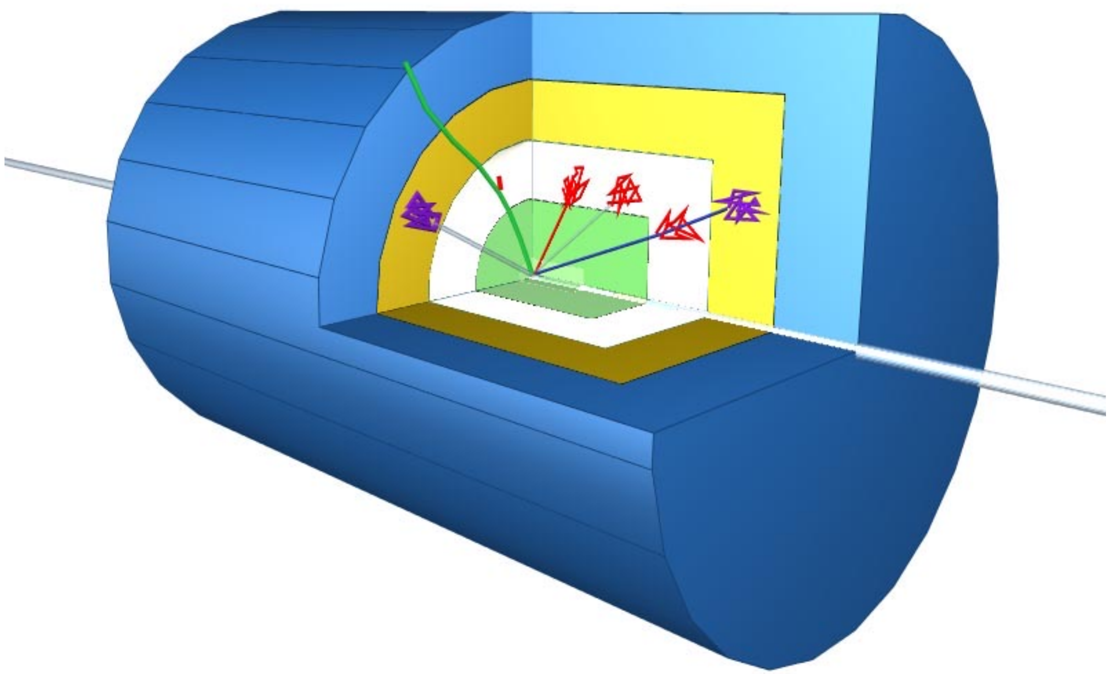


Schematic of an HEP Detector

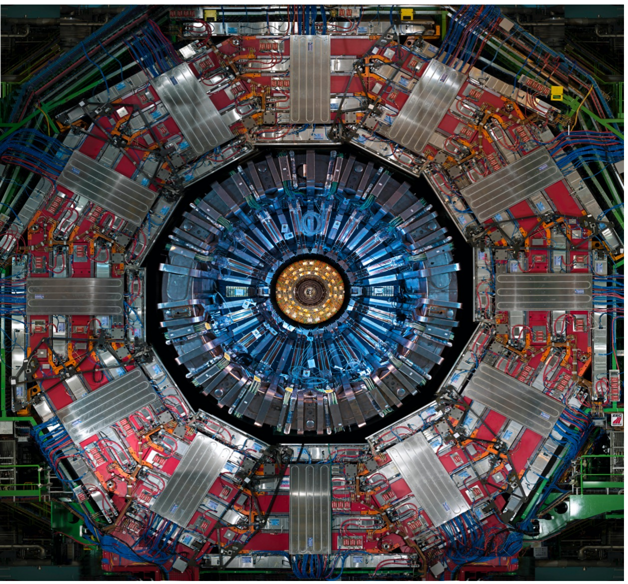
Physics requirements drive the design (e.g. search for the Higgs boson)

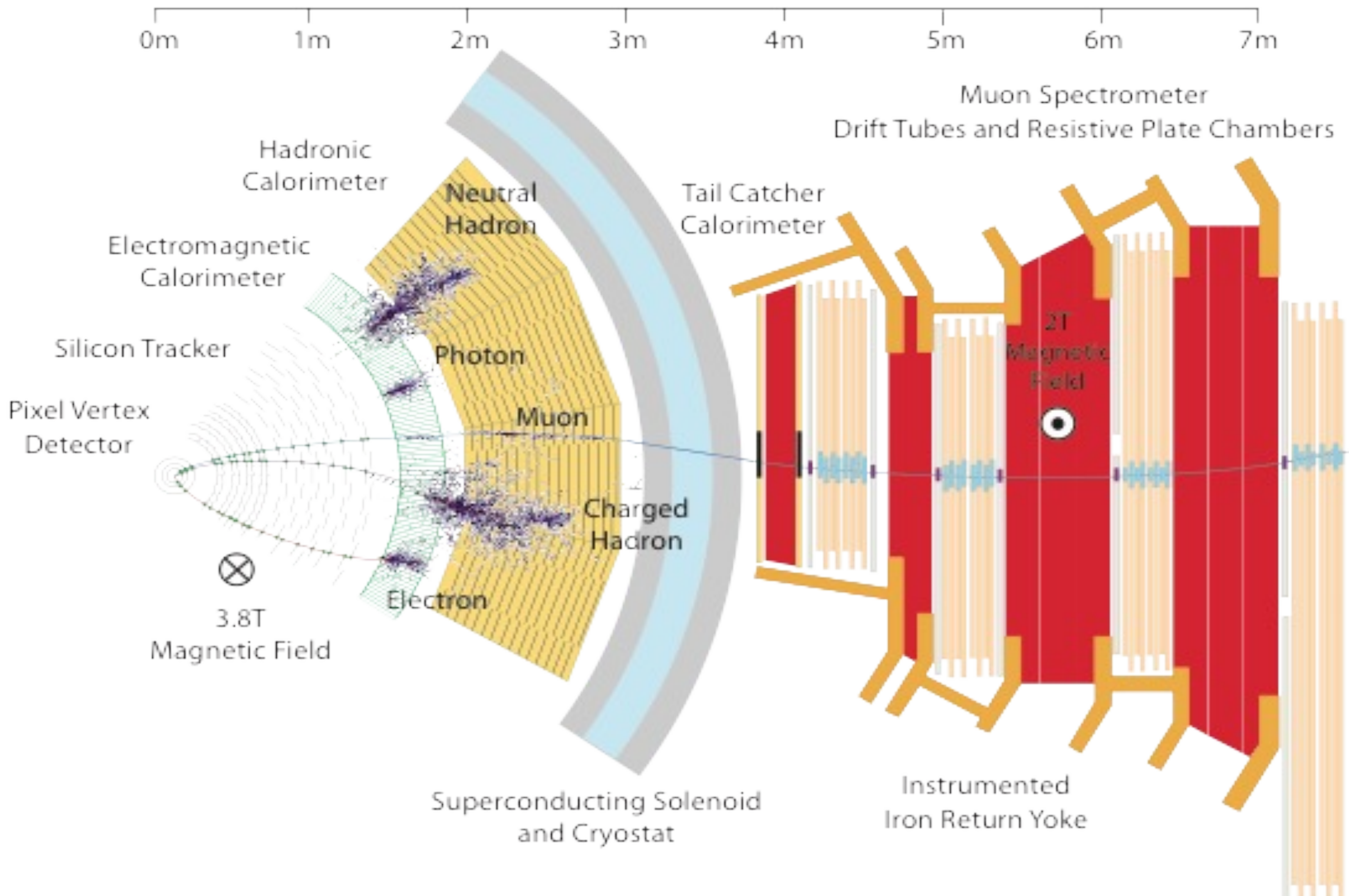
Analogy with a cylindrical onion:

Technologically advanced detectors comprising many layers, each designed to perform a specific task.
Together these layers allow us to identify and precisely measure the energies and directions of all the particles produced in collisions.



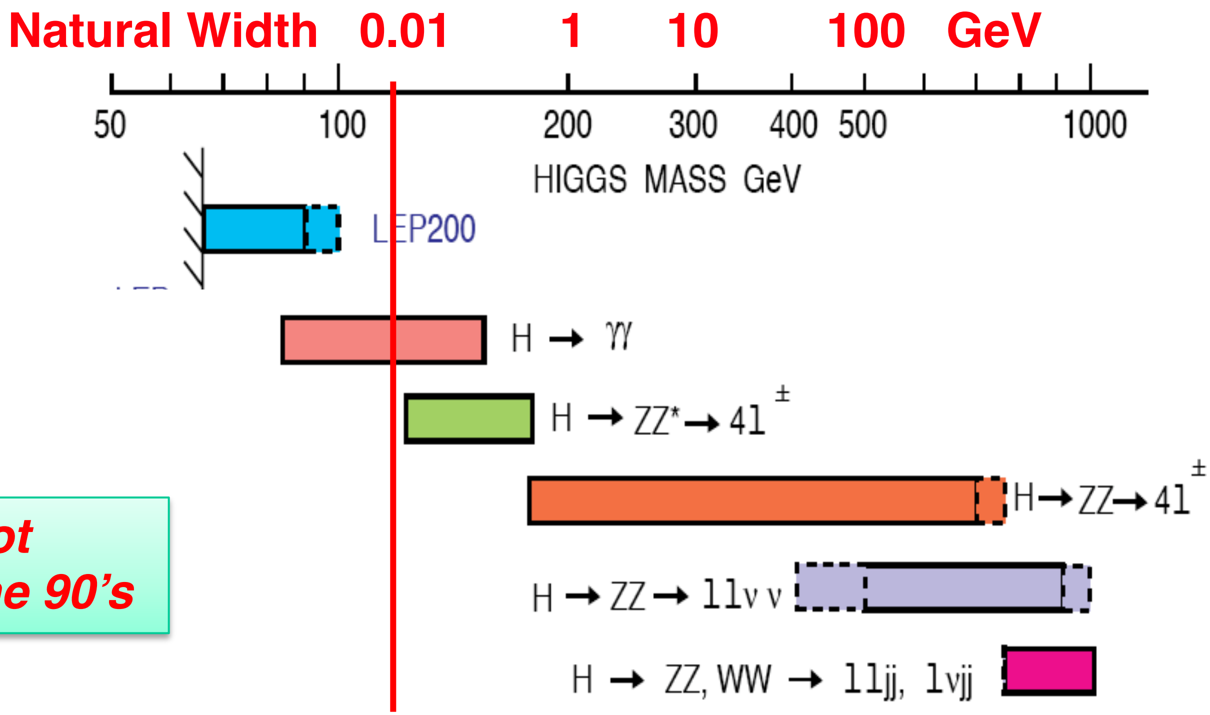
Measuring & Identifying Particles





Search for the Higgs boson: A physics driver for ATLAS/CMS detector design

The possibility of detection of the SM Higgs boson over the wide mass range, and its diverse manifestations, played a crucial role in the conceptual design of the ATLAS and CMS experiments



Natural width
$\Gamma \sim h/\tau$

Plot from the 90's

Search for a low mass Higgs boson (e.g. H→γγ, H→ZZ→4l) placed stringent performance requirements on ATLAS and CMS detectors (especially measurement of momenta (in the tracker) and ECAL energy resolution).

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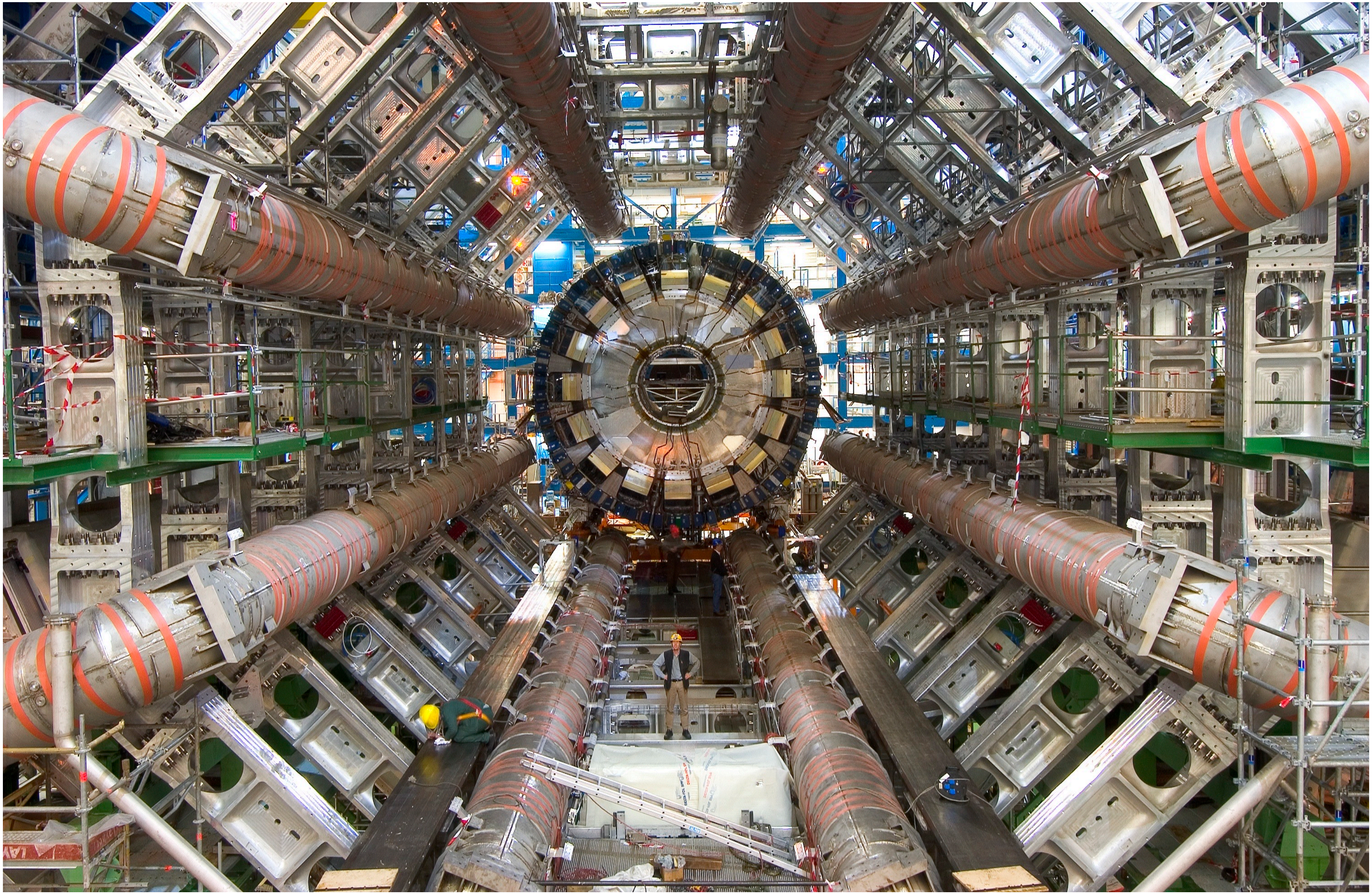
The ATLAS Experiment



CMS: Concept to Data Taking took ~ 20 Years!

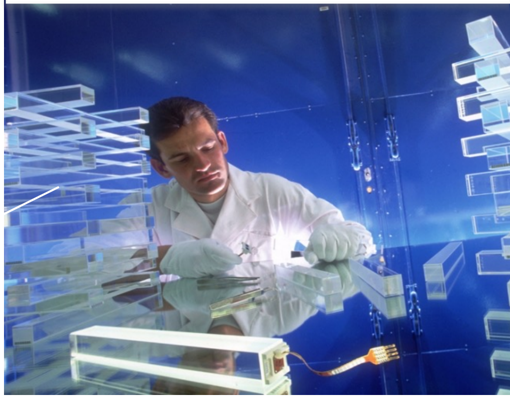
Silicon Tracker

Gas ionization chambers

3000 scientists from 40 countries
800 Ph. D. Students!

CMS cut in mid-plane

Scintillating Crystals



Brass plastic scintillator

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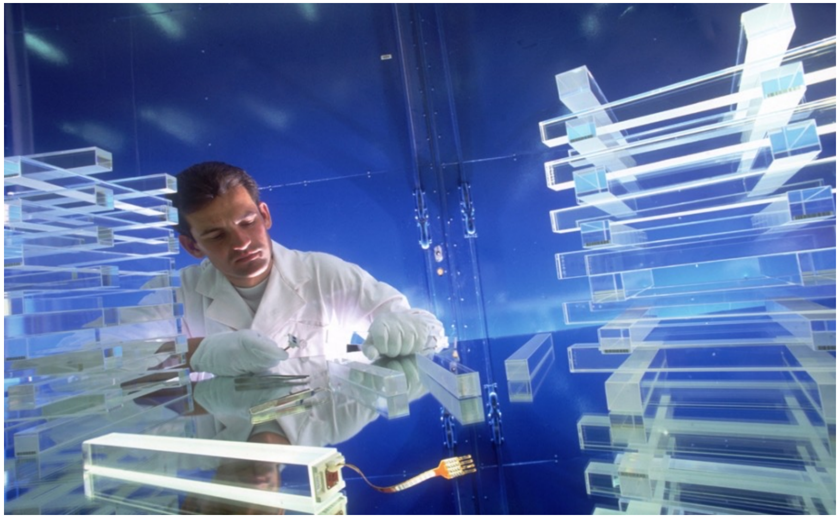
Example of Challenging Technologies: ECAL: Lead Tungstate Crystals

Physics Driving the Design
Measure the energies of photons from a decay of the Higgs boson to a precision of ≤ 0.5%.



Idea (1993 – few yellowish cm³ samples)

→ **R&D (1993-1998: improve rad. hardness: purity, stoechiometry, defects)**

→ **Prototyping (1994-2001: large matrices in test beams, monitoring)**

→ **Mass manufacture (1997-2008: increase production, QC)**

→ **Systems Integration (2001-2008: tooling, assembly)**

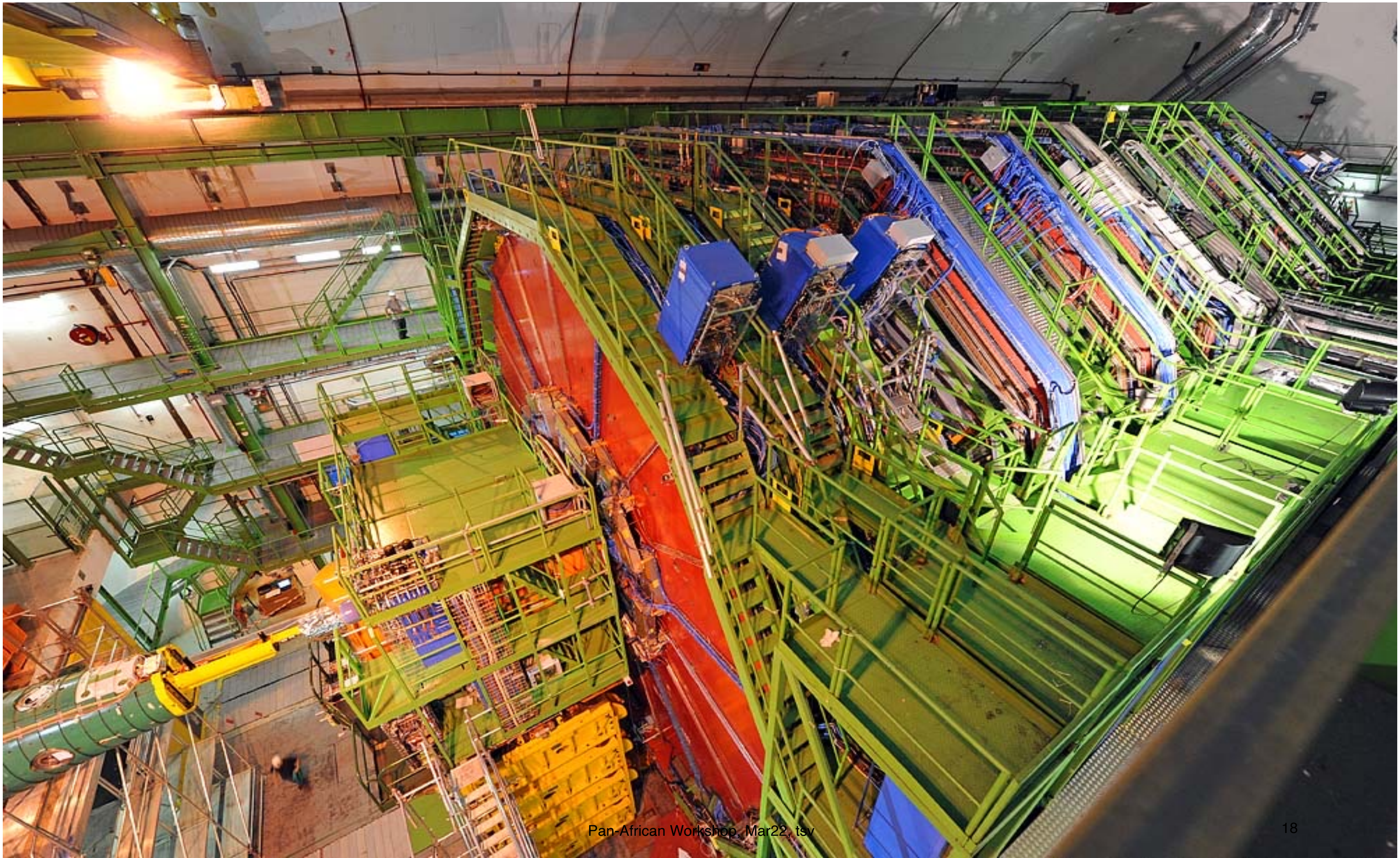
→ **Installation and Commissioning (2007-2008)**

→ **Collision Data Taking (2009 onwards)**

→ **Discovery of a new heavy boson (2012)**

Idea to Discovery
Δt ~ 20 years !!!

CMS Detector Closed (Sept 2008)



Africa in ATLAS and CMS Experiments

ATLAS

South Africa—since 2010

5 institutes: Univ. of Cape Town; Johannesburg; Witwatersrand; iThemba Labs.

18 Physicists, 20 PhD, 26 Masters, 12 Engineers

Physics analyses (e.g. Higgs Physics) & Muon perf.

Hardware (Silicon Tracker, Tilecal and Muon System

Morocco—since 1996

7 institutes: Univ. of Hassan II; Ibn-Tofail; Cadi Ayyad; Mohammed I, Mohammed V, Mohammed VI.

16 Physicists, 26 PhD, 4 Masters, 7 Engineers

Physics analyses (e.g. Higgs Physics, HI phsyics)

Hardware (TRT, LAr Calo, HGTD)

Algeria—Technical Associate member 2019

1 institute: ENSInformatique, Algiers

5 Engineers in Software & Computing)

CMS

Egypt—since 2012

6 institutes: Zewail City, Universities (British, Cairo, Helwan, Ain Shams, Suez Canal; Fayoum, Mansoura.)

23 Physicists

Physics analyses

Hardware (GEM and RPCs)

Tunisia—since 2022

1 institute: UTM Tunis.

2 Physicists, 2 PhD, 4 Masters, 5 Engineers

Hardware (MTD and DAQ)

Nigeria—since 2022

1 institute: Univ. Benin

4 Engineers in Software & Computing)

Going to the Science

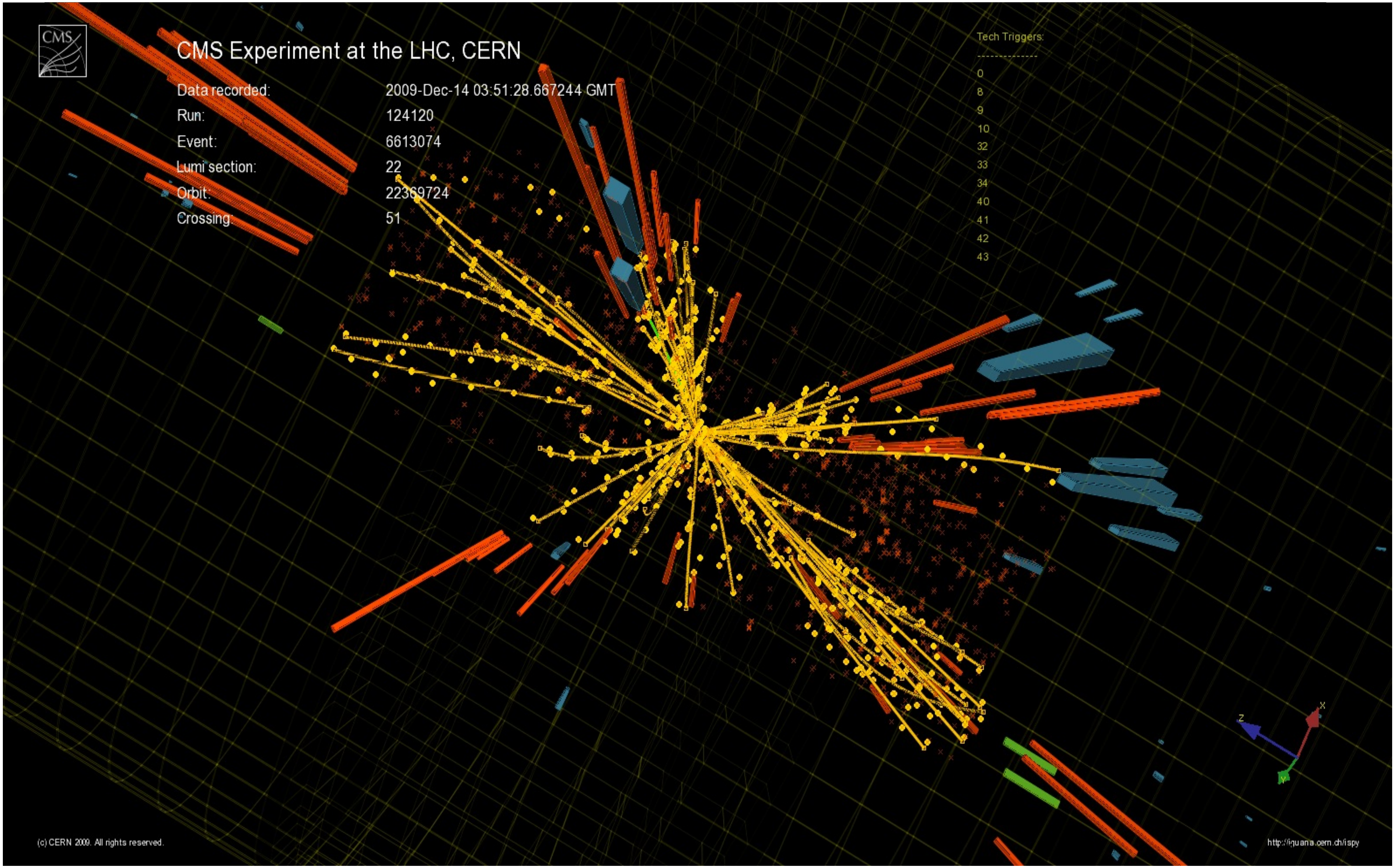
1. Do the experiments perform as designed?

2. Is known physics correctly observed?

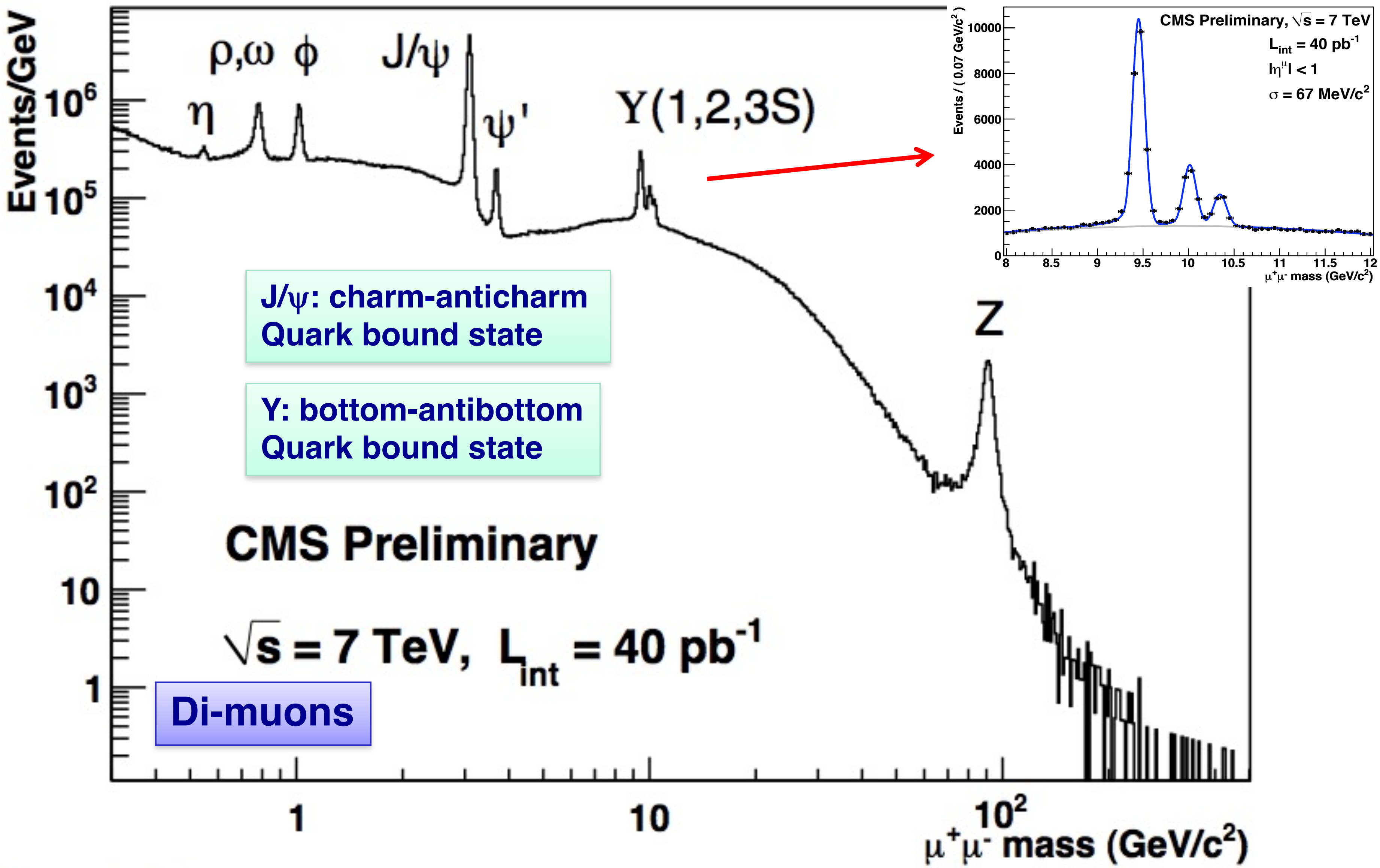
3. Then look for new physics

We can only claim signals of new physics after having made measurements of already known physics that are consistent with the precise predictions of the Standard Model.

Quarks/gluons Production at the LHC



Performance of Experiments: CMS



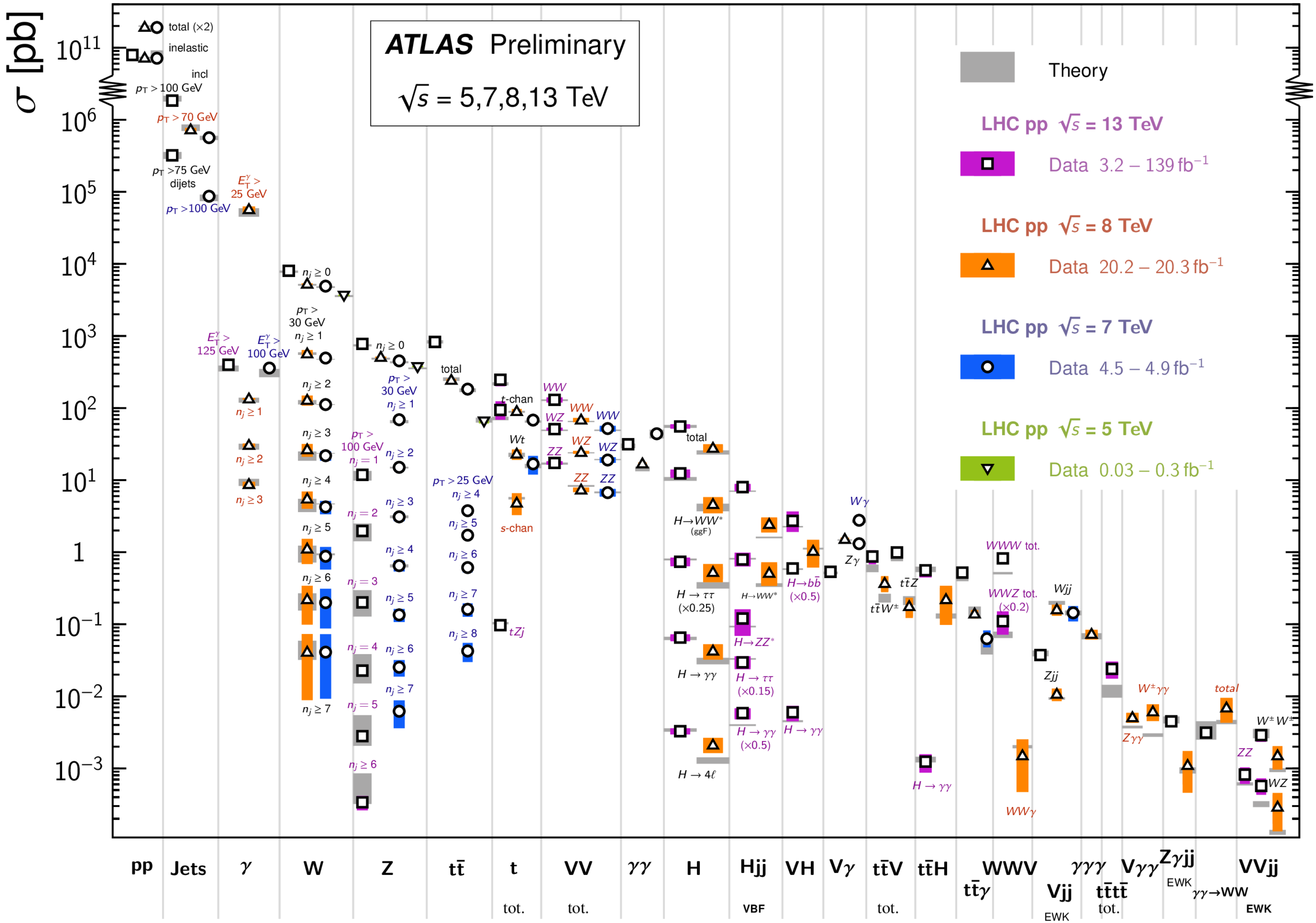
J/ψ: charm-anticharm Quark bound state

Υ: bottom-antibottom Quark bound state

Di-muons

Standard Model Production Cross Section Measurements

Status: February 2022



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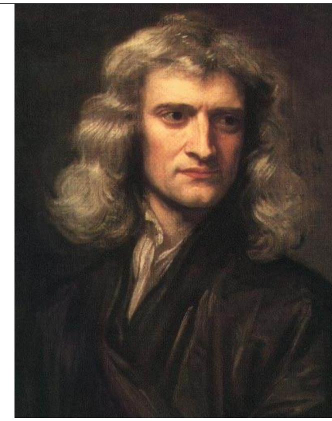
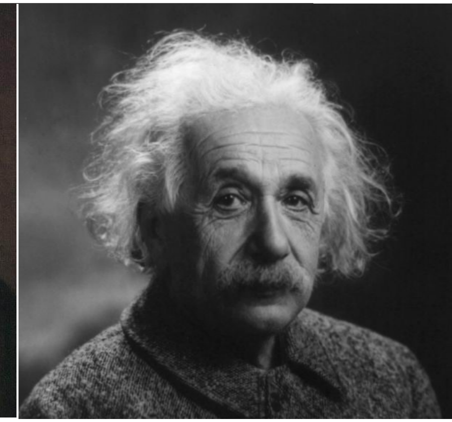
Mass gives our Universe substance!

To Newton: F= ma, w = mg
To Einstein: $E = mc^2$
Mass curves space-time

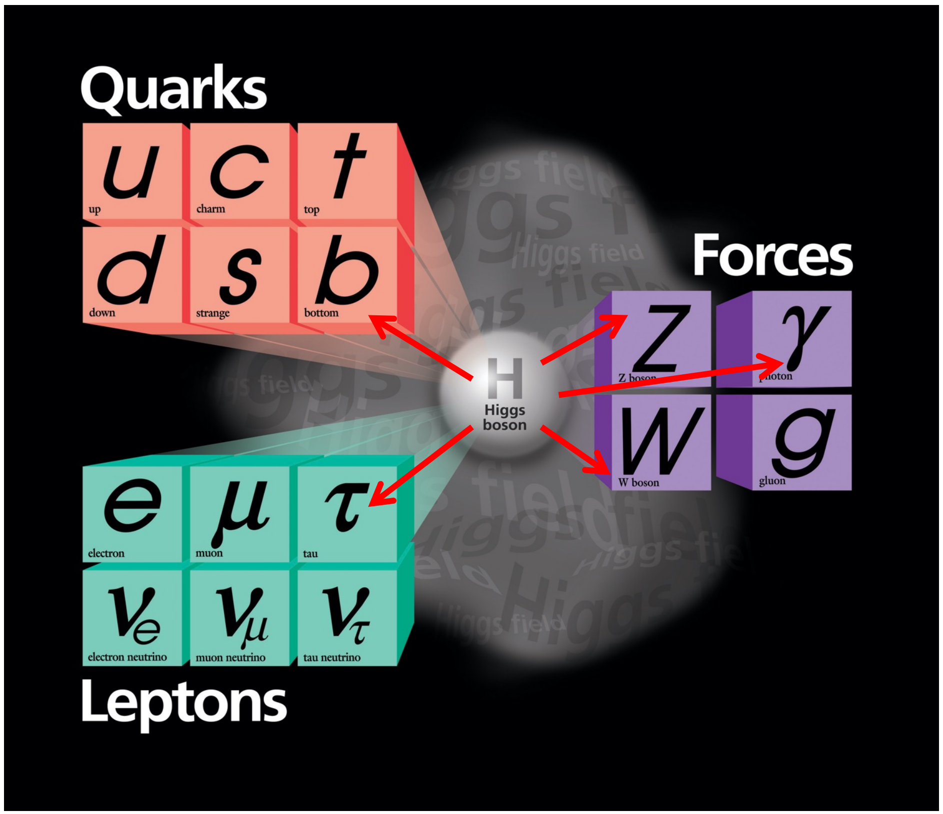
All of this is correct.
But how do fundamental objects become massive?
Simplest theory – all fundamental particles are massless !!

A bold intellectual conjecture (1964): a field pervades our entire universe. Particles interacting with this field acquire mass, the stronger the interaction the larger the mass

The field is a quantum field – its quantum is the Higgs boson. Finding the Higgs boson establishes the existence of this field.

So, how do we look for the Higgs boson?

The SM Higgs boson leaves very characteristic fingerprints with well-defined couplings, decay rates and angular distributions of final products



Higgs lifetime (125 GeV): 10^{-22} s

So decay immediately so only see decay products in the detector

Higgs couples to mass:

Coupling to fermions (quarks and leptons)

$H \to b\bar{b}$, $H \to \tau^+\tau^-$ $H \to \gamma\gamma$ $H \to ZZ \to 4l$

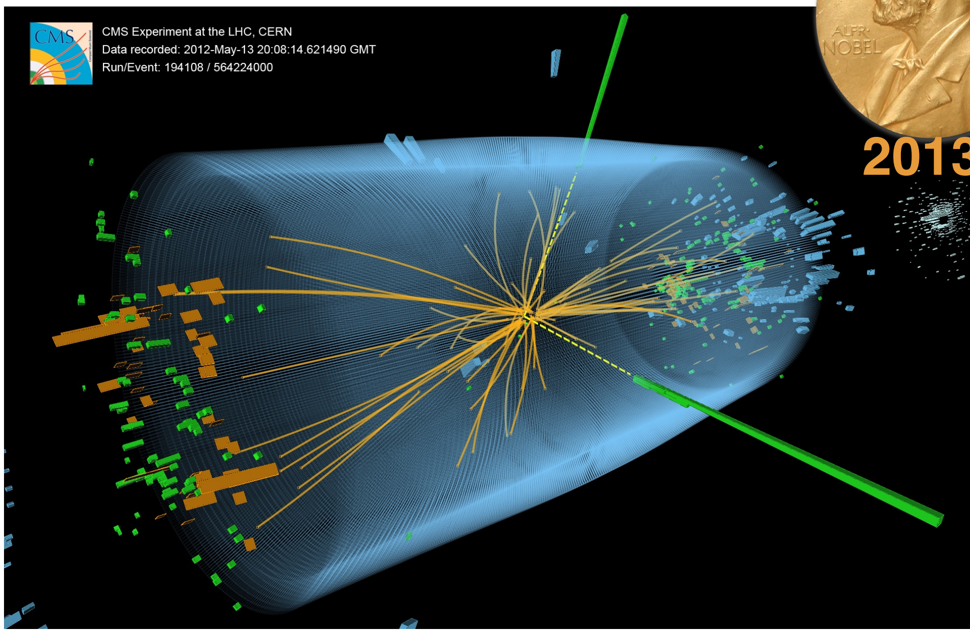
~58 % **~10%** **~2/mille** **~10^{-4}**

at a mass of ~125 GeV
many decay modes are detectable
Makes it easier to establish whether or not it is a SM Higgs boson

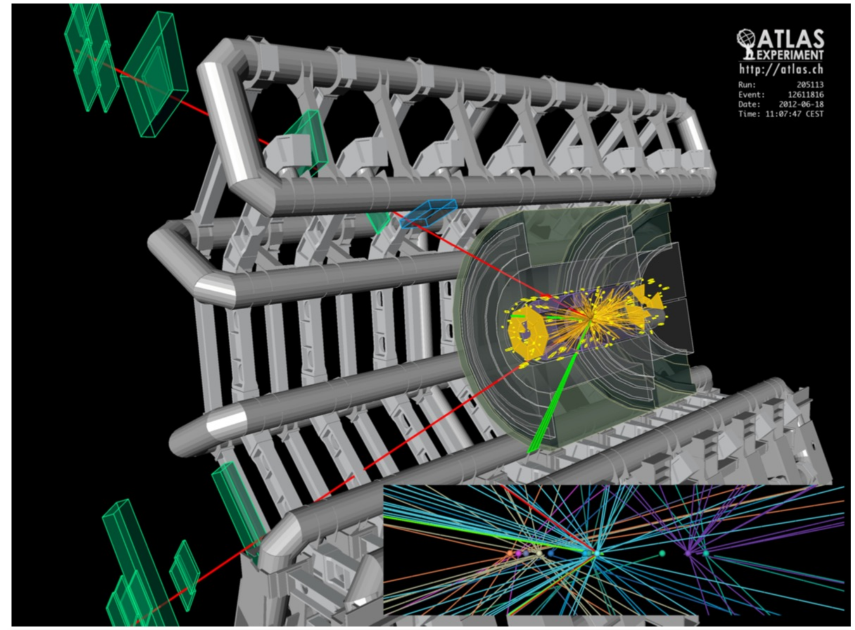
Discovery (2012): Higgs boson

CMS: H→γγ Channel

ATLAS: H→Z→e⁺e⁻ μ⁺μ⁻ Channel



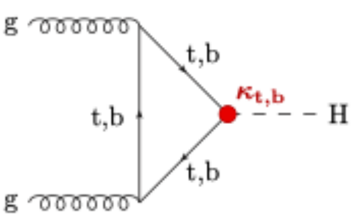
Expected: 450 events S/B ~ 3%



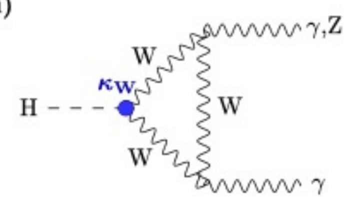
Expected: 20 events S/B ~ 1.5

Production; ggF
via t-quark loop

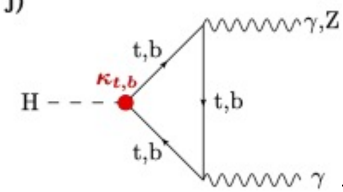
γγ decay via t-quark, W loops



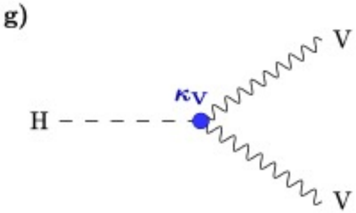
i)



j)



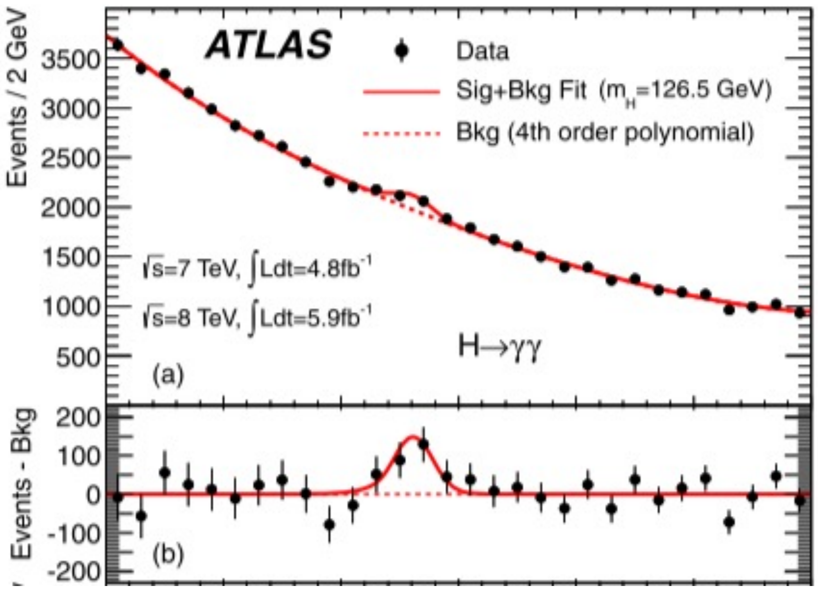
g)

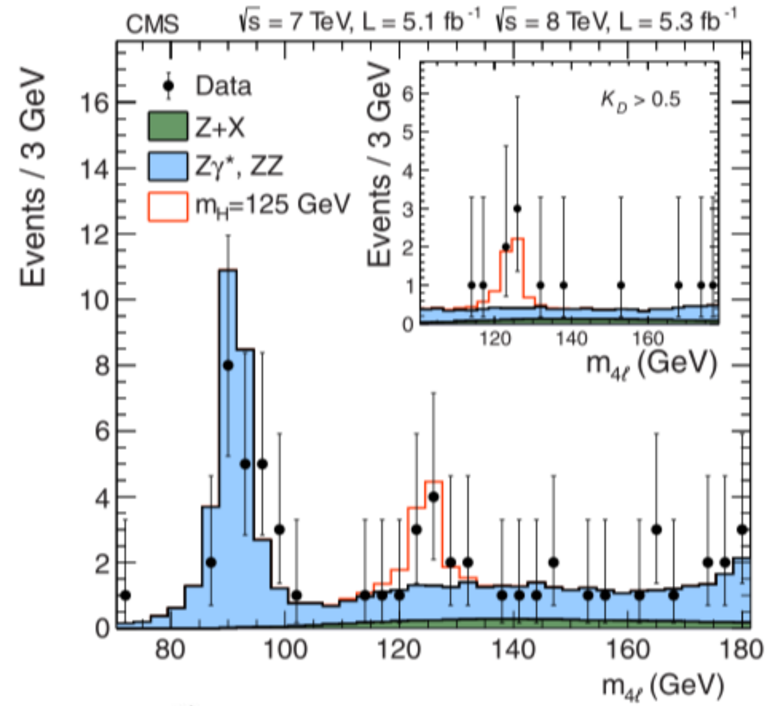


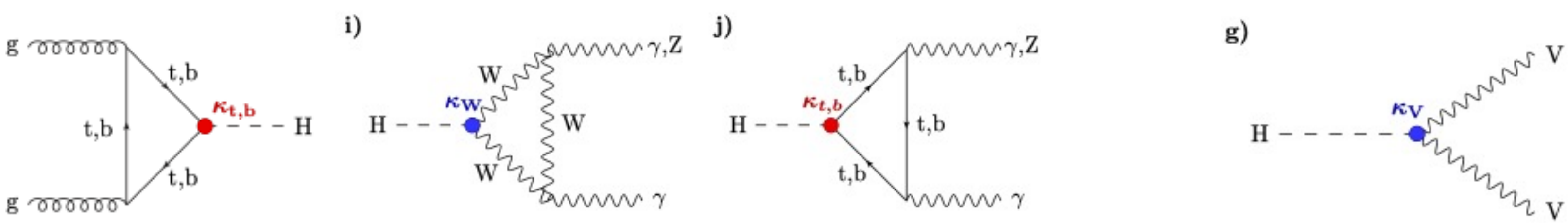
Discovery (July 2012): H boson

H→ 2γ Channel

H→Z→4*l* Channel







Discovery of the Higgs boson

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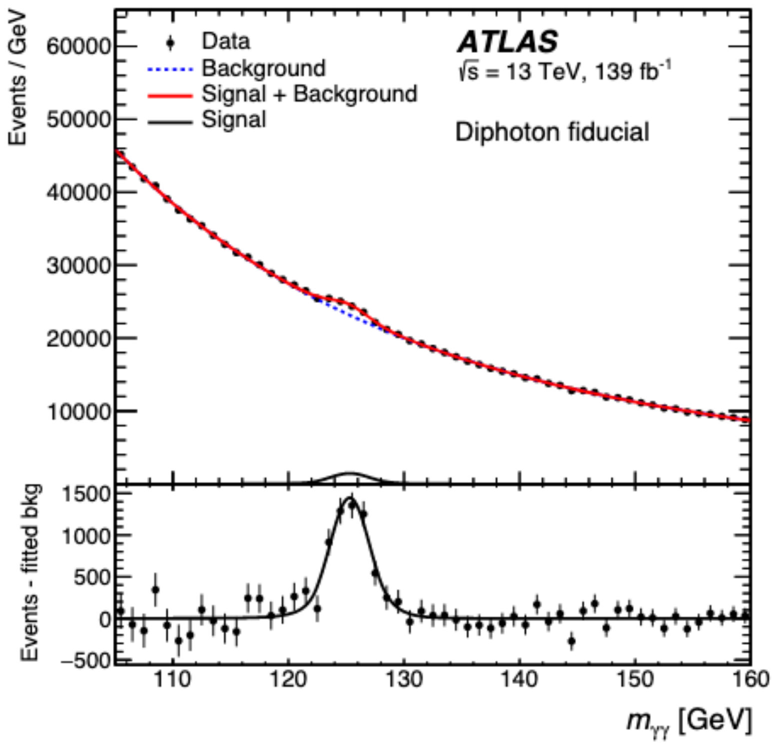
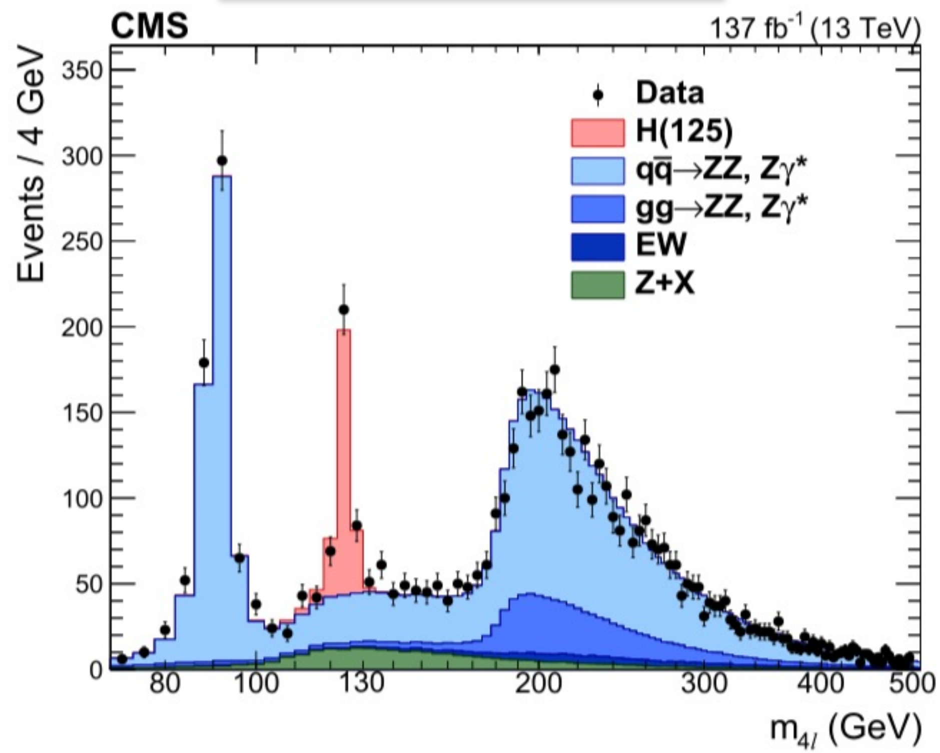
H boson Today

10 years after discovery with ten times more data

H→ 2γ Channel



H→Z→4*l* Channel



Now also seen in bb, ττ, μμ decay channels, determined $J^P=0^+$, $\delta m/m_H \sim 0.1\%$

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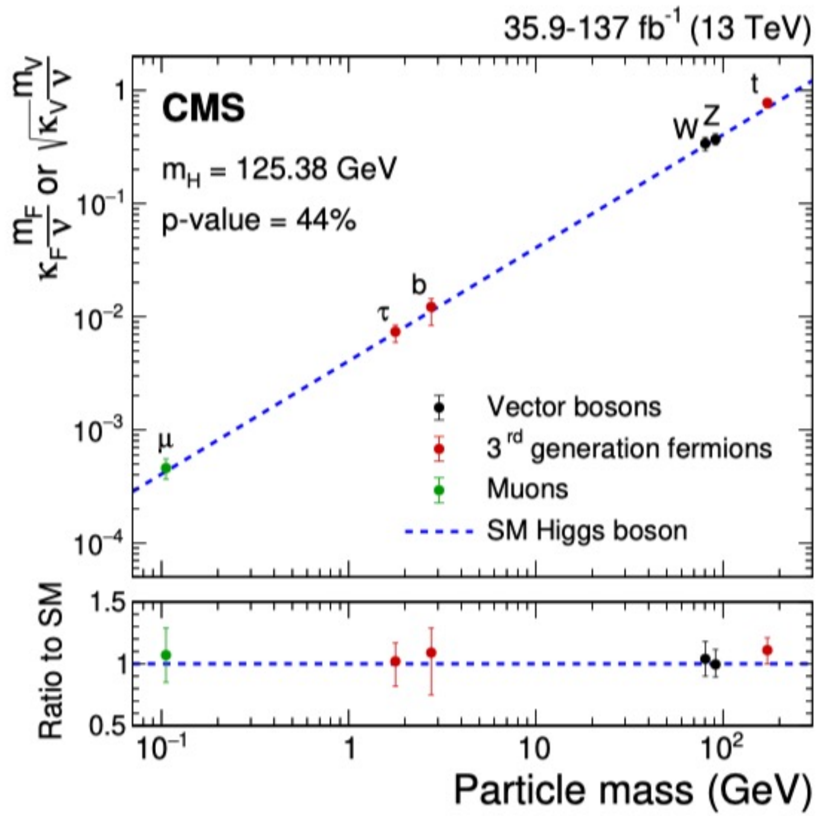
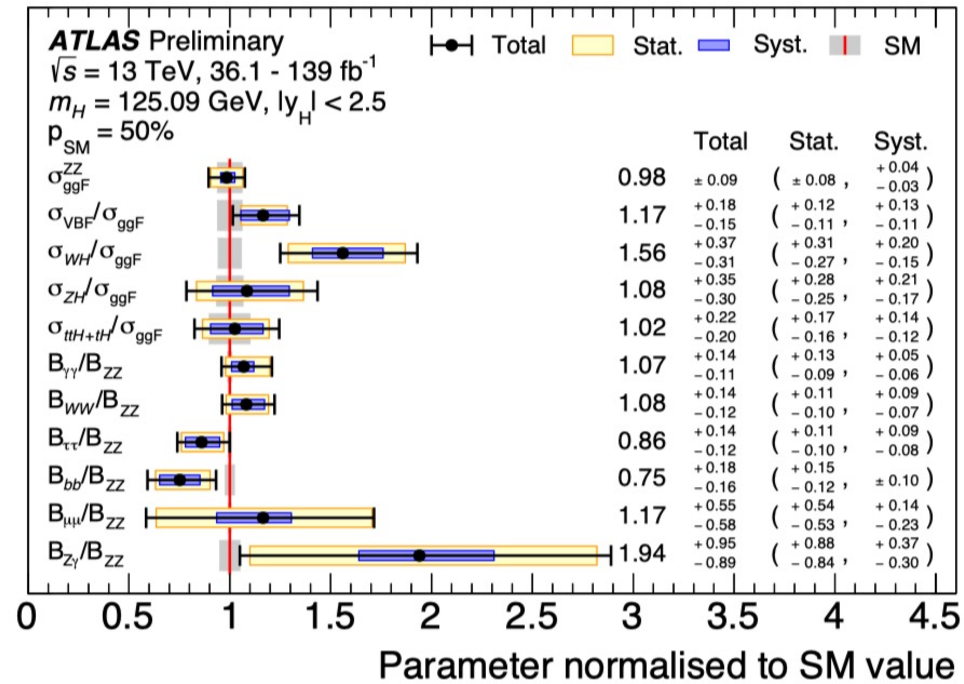
Today: H boson in various production modes and decay channels





H coupling amplitudes for
Fermions α m_f
Bosons α M_V^2

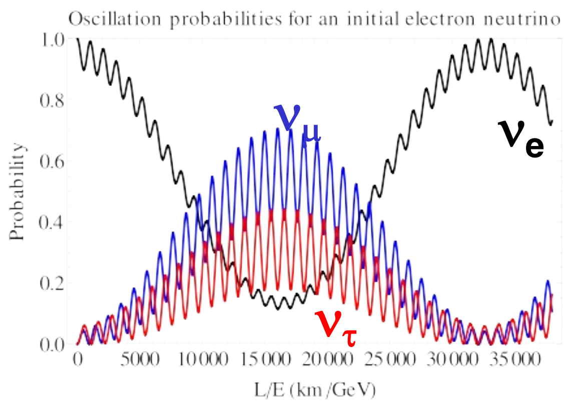
e.g. ATLAS: Global strength μ [= $(\sigma_i.B_i)/\sigma_i.B_i)_{SM}$]
At Discovery: μ= 1.4 ± 0.3
Today: μ= 1.06 ± 0.06
Uncertainties are 5 times smaller. Xpts performed better than implied by increased statistics alone.

Moving Forward
Should we really expect new physics ?

Ample observational evidence for physics Beyond the SM

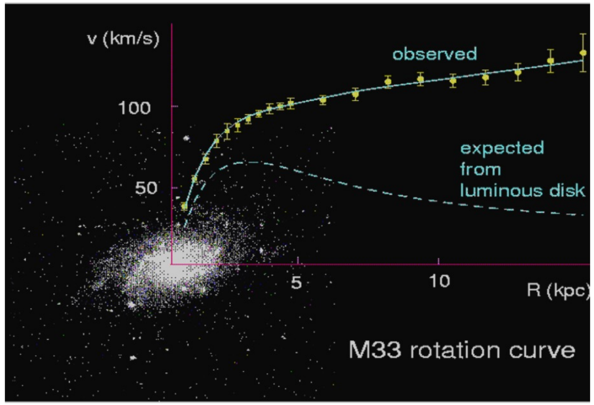
Neutrino mass (oscillations)

a QM phenomenon

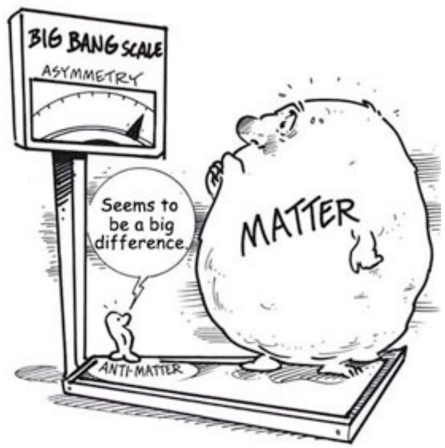


2015

Dark Matter

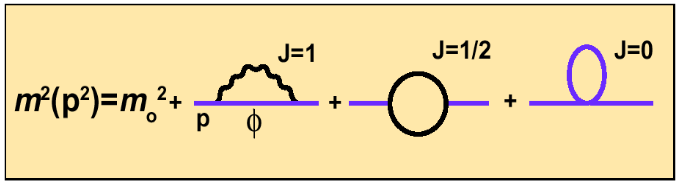


Matter-antimatter asymmetry



The lightness of the Higgs boson?

In absence of new physics up to a scale Λ
m_H gets correction of the order of Λ^2 !



Future Prospects:
Run-3 → High Luminosity LHC (2030s)

S. Cittolin

140fb^{-1} → **300 fb^{-1}** → **3000 fb^{-1}**
Today — Mid'20s — 2030s

1. **Higgs boson and EWSB physics**

   (Examine 8 → 16 → 150 million Higgs bosons)

- Experimentally → make precision measurements of the properties (couplings etc. at a percent level) and self couplings in a new sector. Higgs boson is a "special" particle
- Theoretically → need precise predictions (~1%)

2. Search for physics beyond the SM

- Extend mass reach for possible high mass objects predicted by BSM
- Dark matter & weakly interacting BSM phenomena
- Ensure coverage and sensitivity to elusive signatures

3. Precision (sensitive) SM measurements

- Look for (significant) deviation from SM predictions
- Intrinsic value of knowledge acquired independent of discovery

Summary

- Over the last 50 years, the "construction" of the Standard Model (SM) represents a towering intellectual achievement of humankind.
- This has allowed us to trace in much detail the evolution of our universe from moments after the Big Bang.

- At the LHC we have discovered the keystone of the SM – the Higgs boson – it appears to be the one predicted by the SM. Now being studied in great detail.
- No evidence has yet been found for physics BSM.
- However, we are just at the start of the exploration of the Terascale.

- What further discoveries await us?
- Several of the open questions today are just as profound as those a century ago. LHC is the foremost place to look for new physics.

- Discoveries in fundamental science invariably lead to paradigm shifting technologies

Only experiments reveal/confirm Nature's secrets

Translation to Phase 2 Experiment Design

New higher granularity more radiation hard inner trackers

x10 more channels; sensors, fe electronics, 10 Gb/s data-links have to withstand doses of up to 500 Mrad and fluences of 10^{16} n/cm^2. |η| coverage up to 4. Introduce Track Trigger in L1.

Replacement of components affected by radiation

Electromagnetic calorimeter - new electronics

CMS: Endcaps calorimeter: new high granularity "imaging" calorimeter with timing info. (HGCAL) withstand doses of up to 500 Mrad and fluences of 10^{16} n/cm^2

Higher bandwidth L1 triggers and DAQ

- Introduce Track Triggers in L1
- Higher L1 output rate [e.g. 100→750kHz and latency (>10μs)]
- Enhanced trigger processors (ASIC-based → FPGA-based).
- DAQ recording rate 1000→10k evts/s

Replacement of front-end electronics

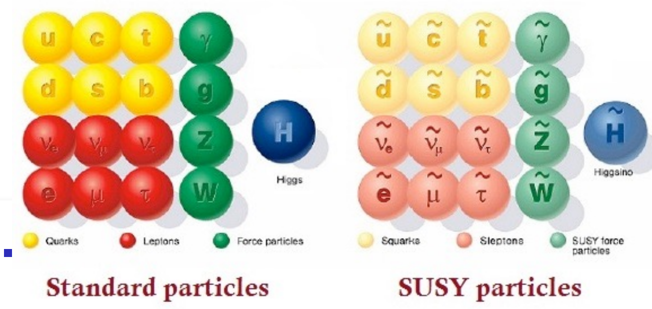
Deal with higher rates, longer pipelines (e.g. >10 us)

Introduction of precision timing (e.g. CMS MTD)

Vertex localization, pileup suppression, slow charged tracks, …

New Physics: Some Conjectures

Supersymmetry (SUSY)



Intimately relates matter particles and force particles.

SUSY predicts the existence of a partner for every known SM particle with spin differing by half a unit and 5 Higgs bosons!

The lightest particle of this species is a candidate for dark matter
Would address the issue of the "lightness" of the Higgs boson.

Superstring Theory

Can gravity be unified with the other forces? Supersymmetry helps.

Extra Dimensions

Number of space-time dimensions determines the observed form of a force
Tell-tale signs are new heavy Z-like particles.