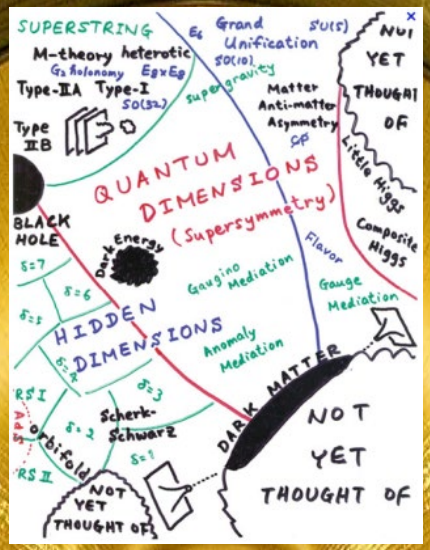
"What is Next in Particle Physics ?"– Experimental Perspective

Maxim Titov, CEA Saclay, Irfu, France



IEEE NPSS Educom International Summer School (REISS) Faculté des Science, University Mohamed V of Rabat, Morocco, July 1-10, 2024

The Aim of Particle Physics

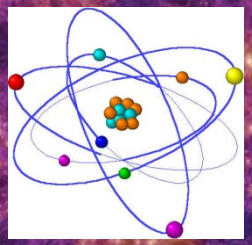
(*Elementary Particle Physics* and/or *High Energy Physics*)

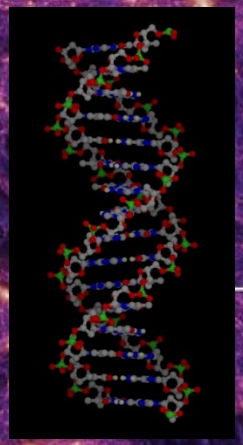
1. What is everything made of ?
2. What holds it all together?

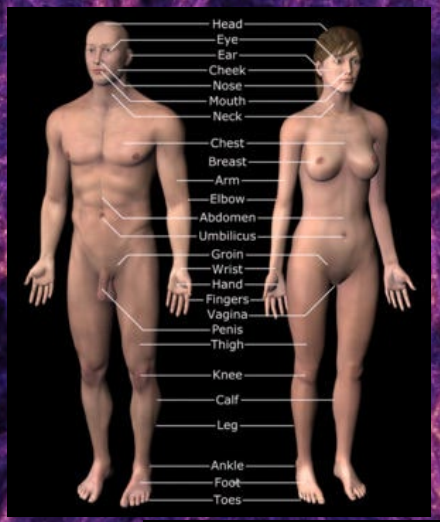
Particle physics is a modern name for centuries old effort to understand the laws of Nature

We are about to take a journey into the world of Higgs particle

What is everything made of ? What holds it all together ?

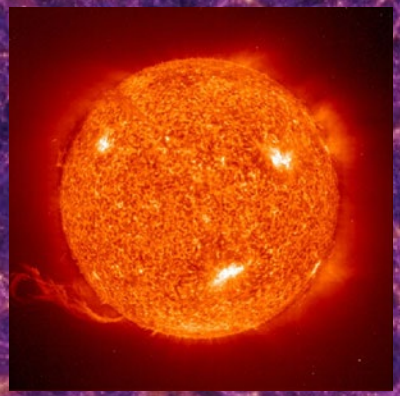






Where did we come from?

Why do we exist?

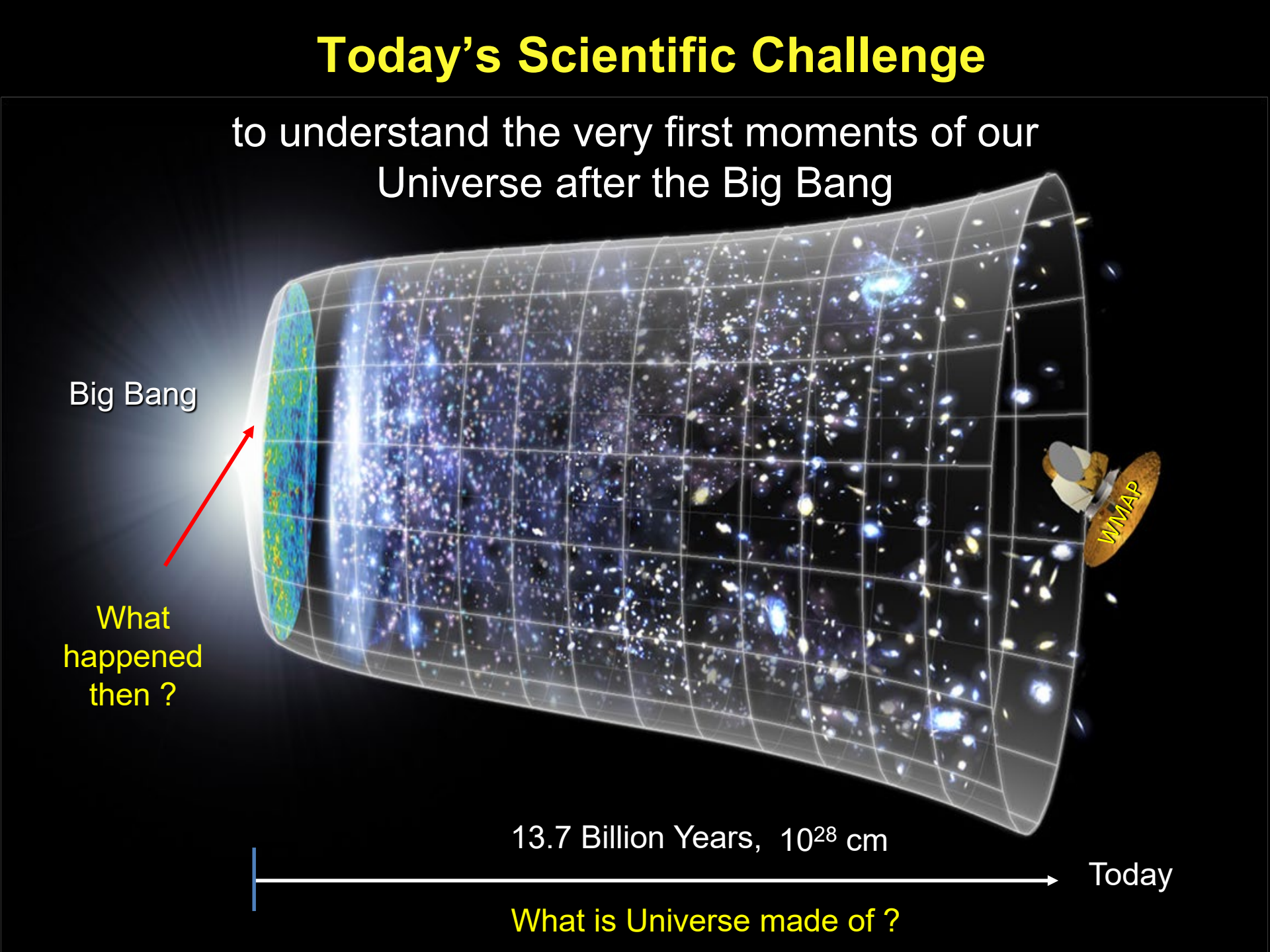


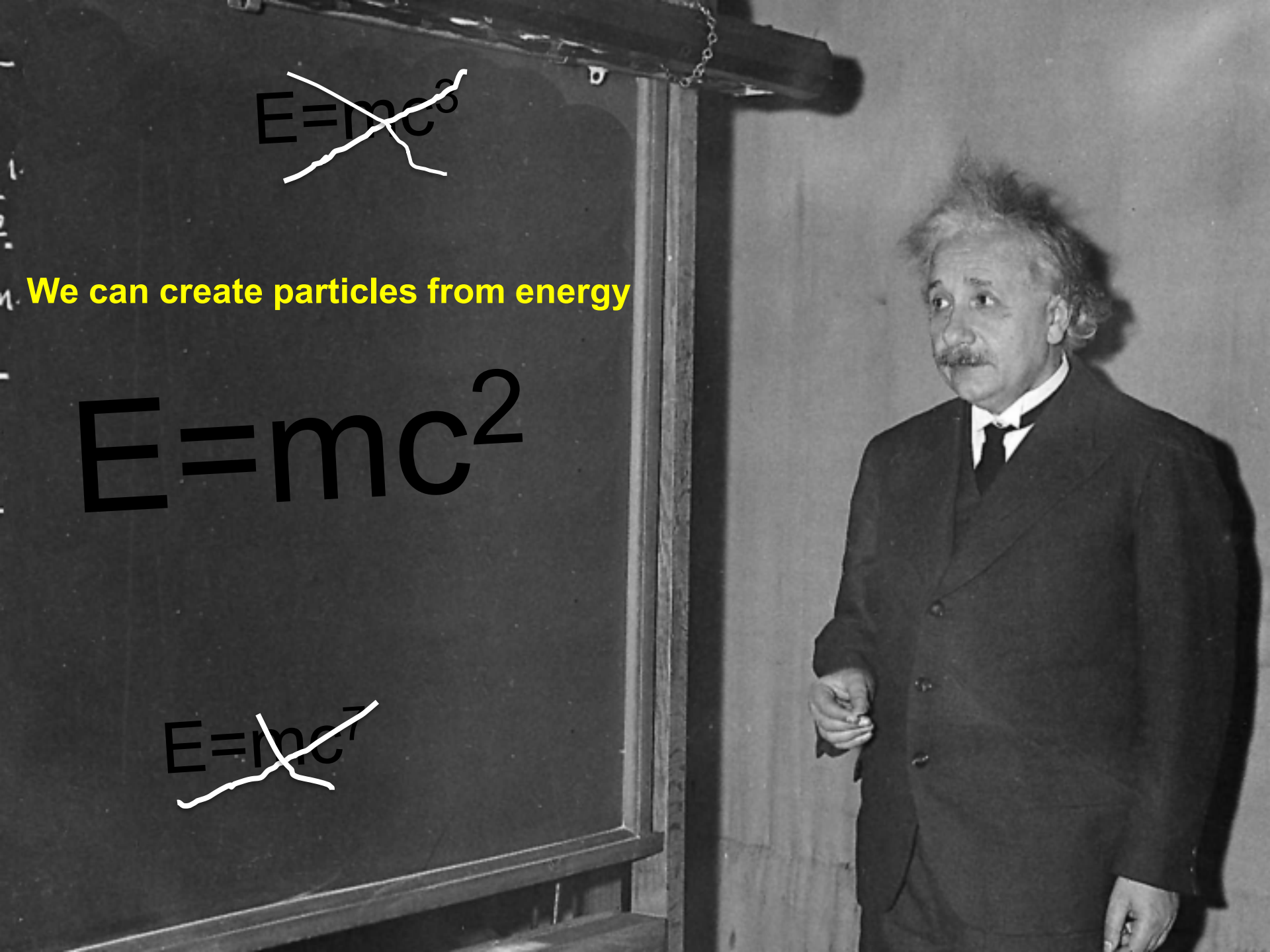
Matter Content of Our Universe

- ✓ **Dark Matter (27%)** → Can be detected only from its gravitational effects
- ✓ **Dark Energy (68%)** → Expansion of Universe is faster than "expected" (Big-Bang + relativity)

Today's Scientific Challenge

to understand the very first moments of our Universe after the Big Bang



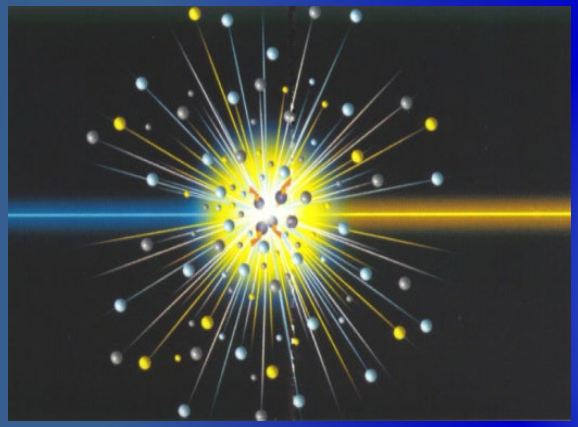

$E=mc^3$
We can create particles from energy
$E=mc^2$
$E=mc^7$

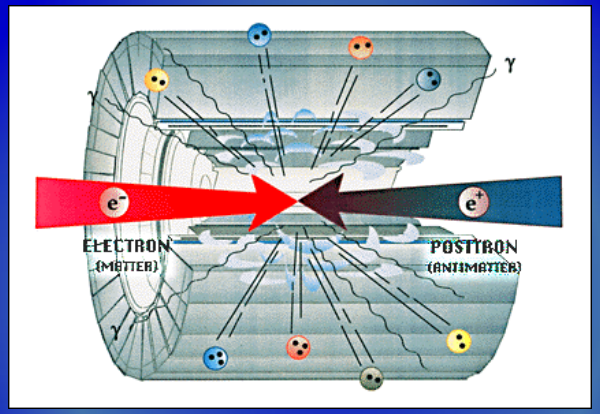
Tools of the Trade → Particle Accelerator

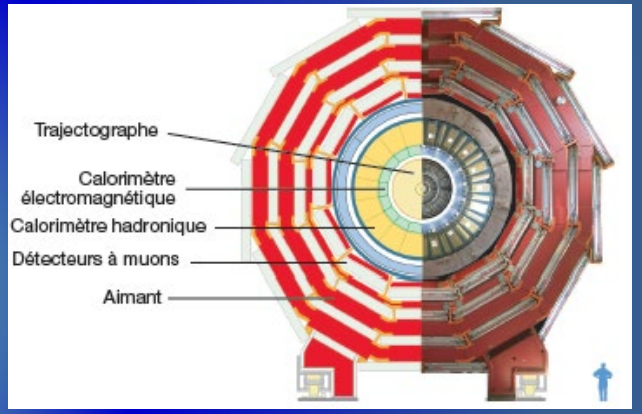
Collision of accelerated particles → "Grain" of energy → New Particles

High energies are needed to produce massive particles & look into smaller distances E ~ 1/λ

Accelerators **$E = mc^2$** **Detectors**



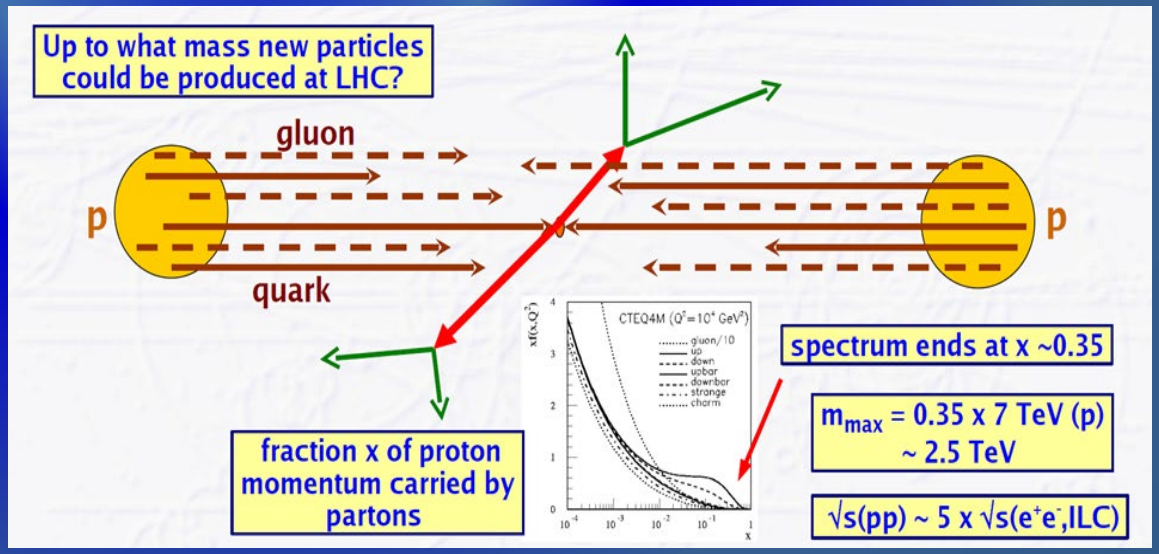




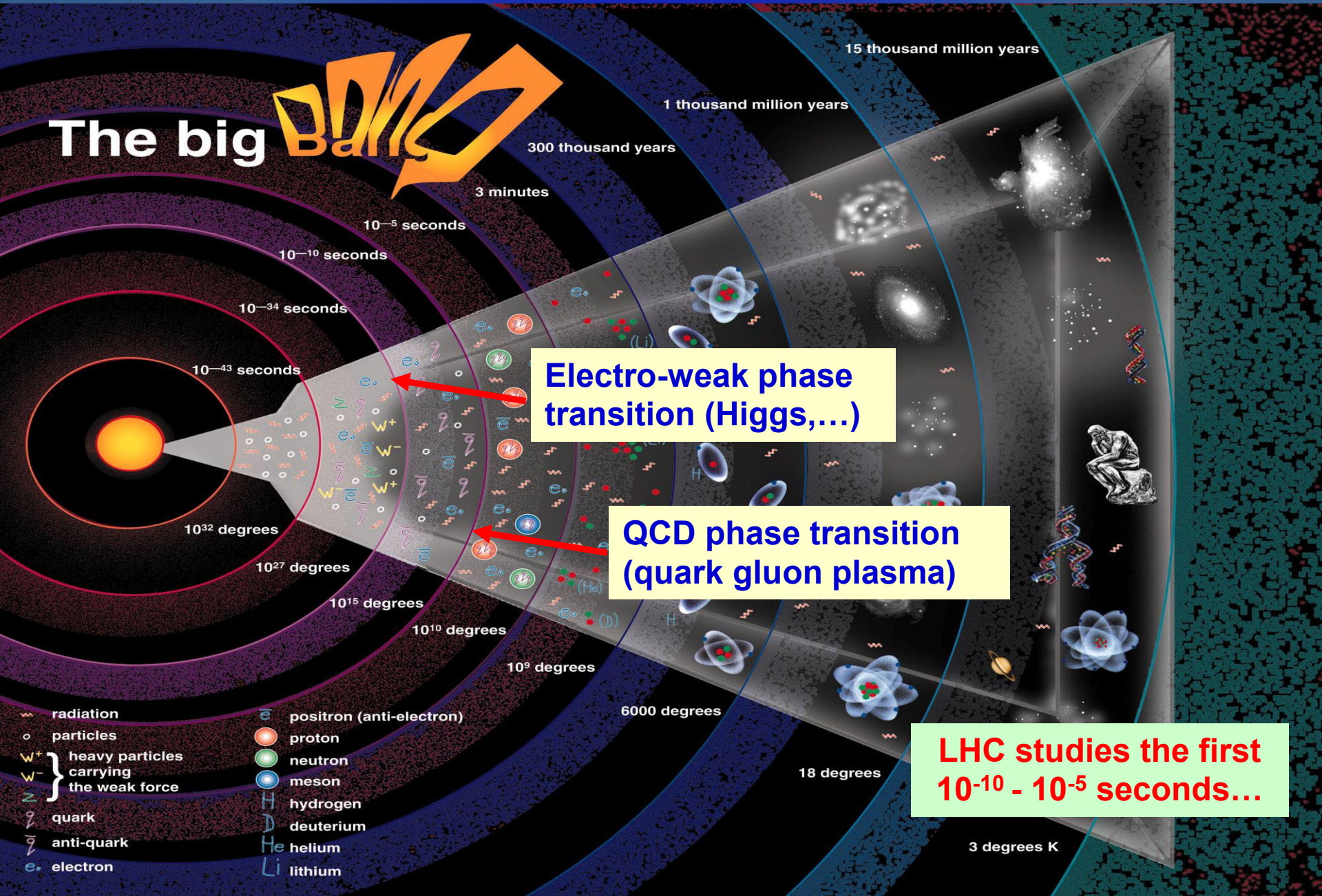
Power of resolution:

$$\lambda(m) = 1.24 \ 10^{-15} / P(GeV/c)$$

LHC (14TeV) → 9×10^{-17} m



Brief History of Our Universe and Physics of LHC



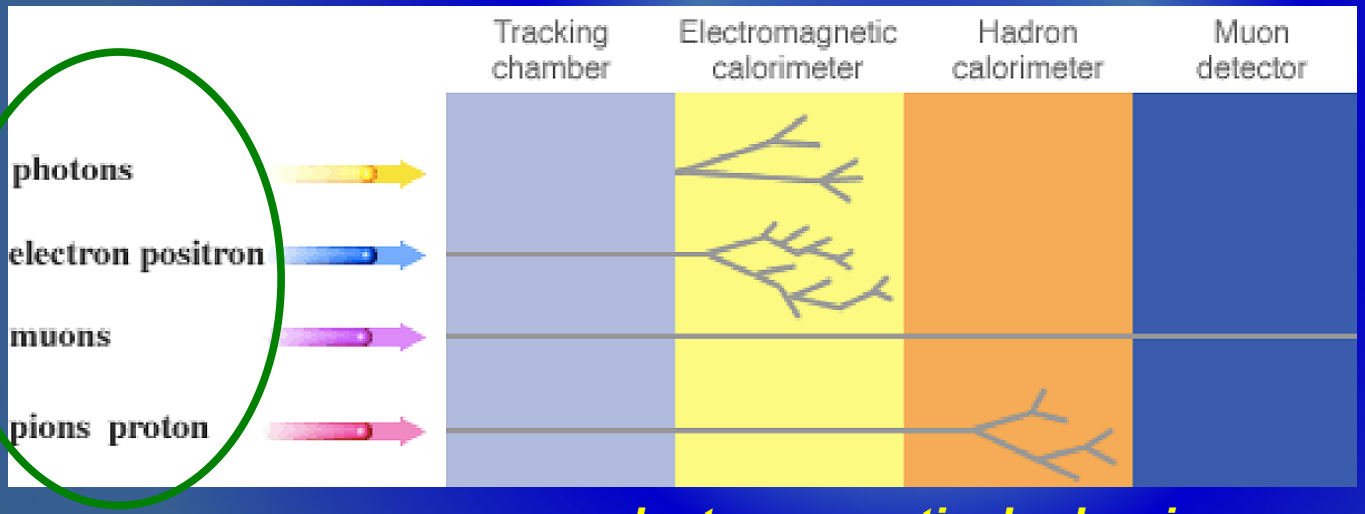
13,7 billion years ago there were other things in the Universe – that we can "create" at the Large Hadron Collider (LHC) at CERN

Particles at LHC - very small "objects" of high energy – are instruments to go back in time

So we have built a Time Machine!

Schematic View of a Particle Collider Detectors

- *There is not one type of detector which provides all measurements we need -> "Onion" concept -> different systems taking care of certain measurement*
- Detection of collision production within the detector volume
  - → resulting in signals due to electro-magnetic interaction
  - → exceptions: strong interactions in hadronic showers (hadron calorimeters)
  - → weak interactions at neutrino detection (not discussed here)



undetected ***neutrinos...***

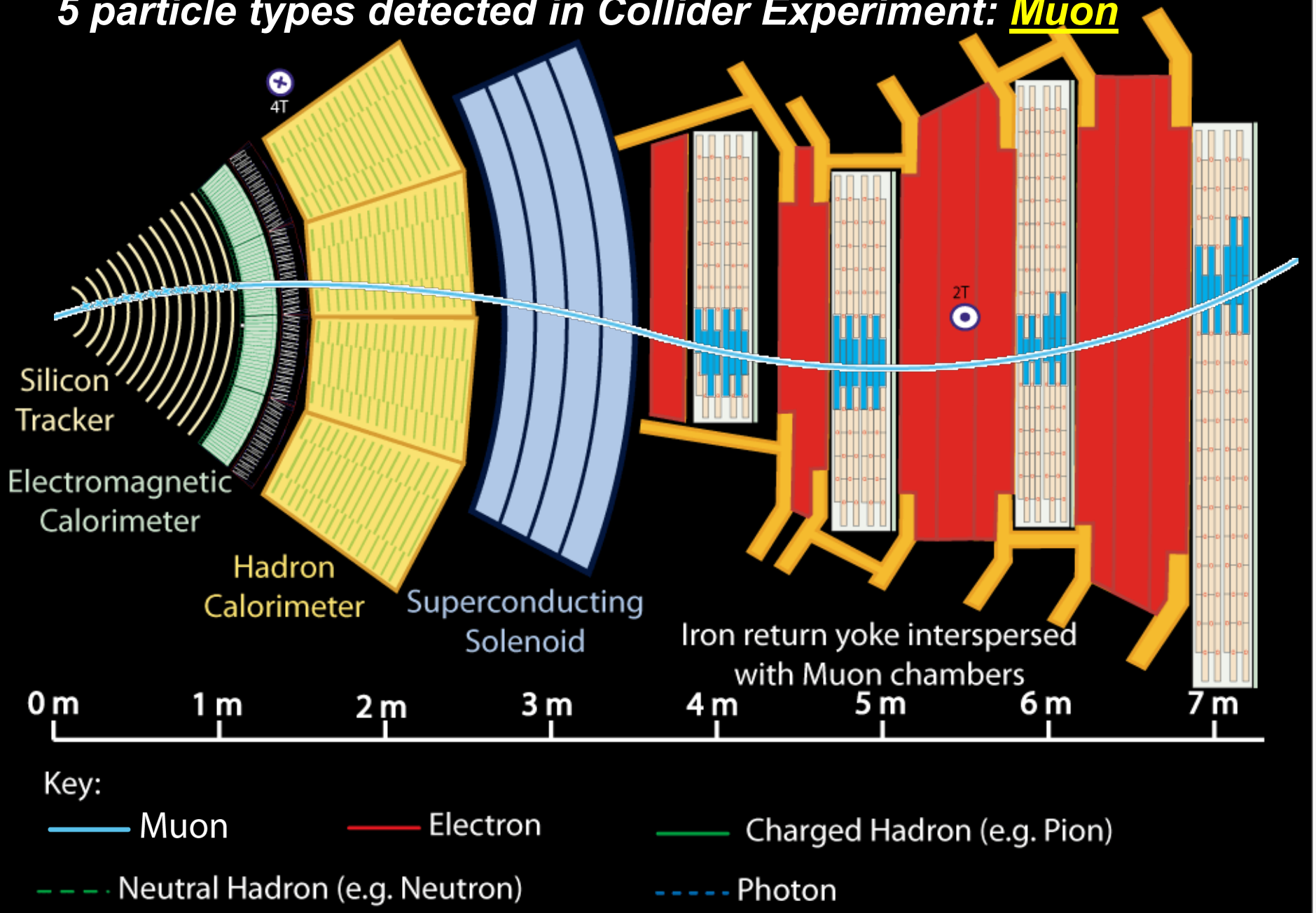
electromagnetic hadronic showers

momentum *measurement by curvature in magnetic field*

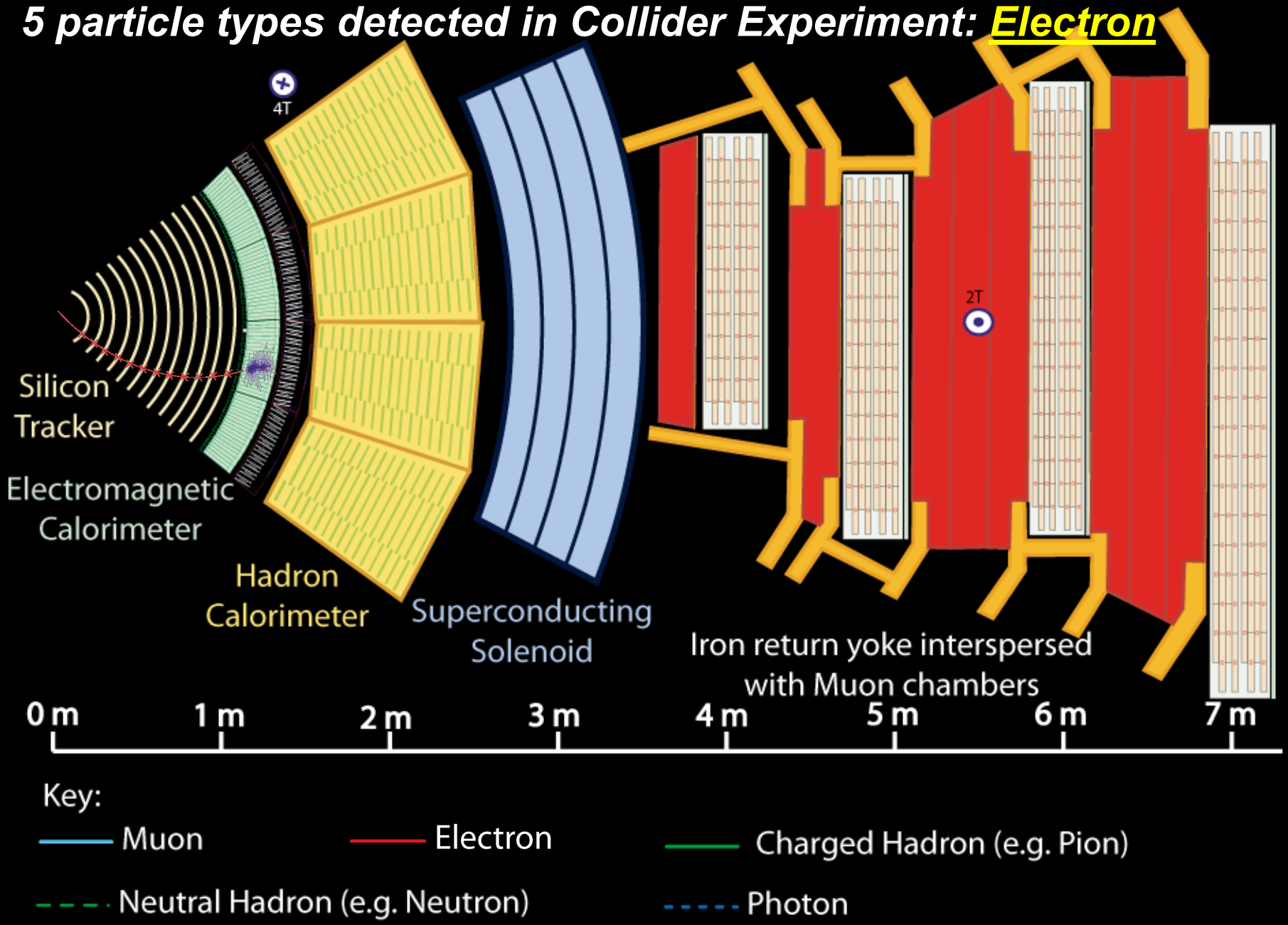
energy *measurement by creation and total absorption of showers*

muon detection with improved momentum measurement (long lever arm)

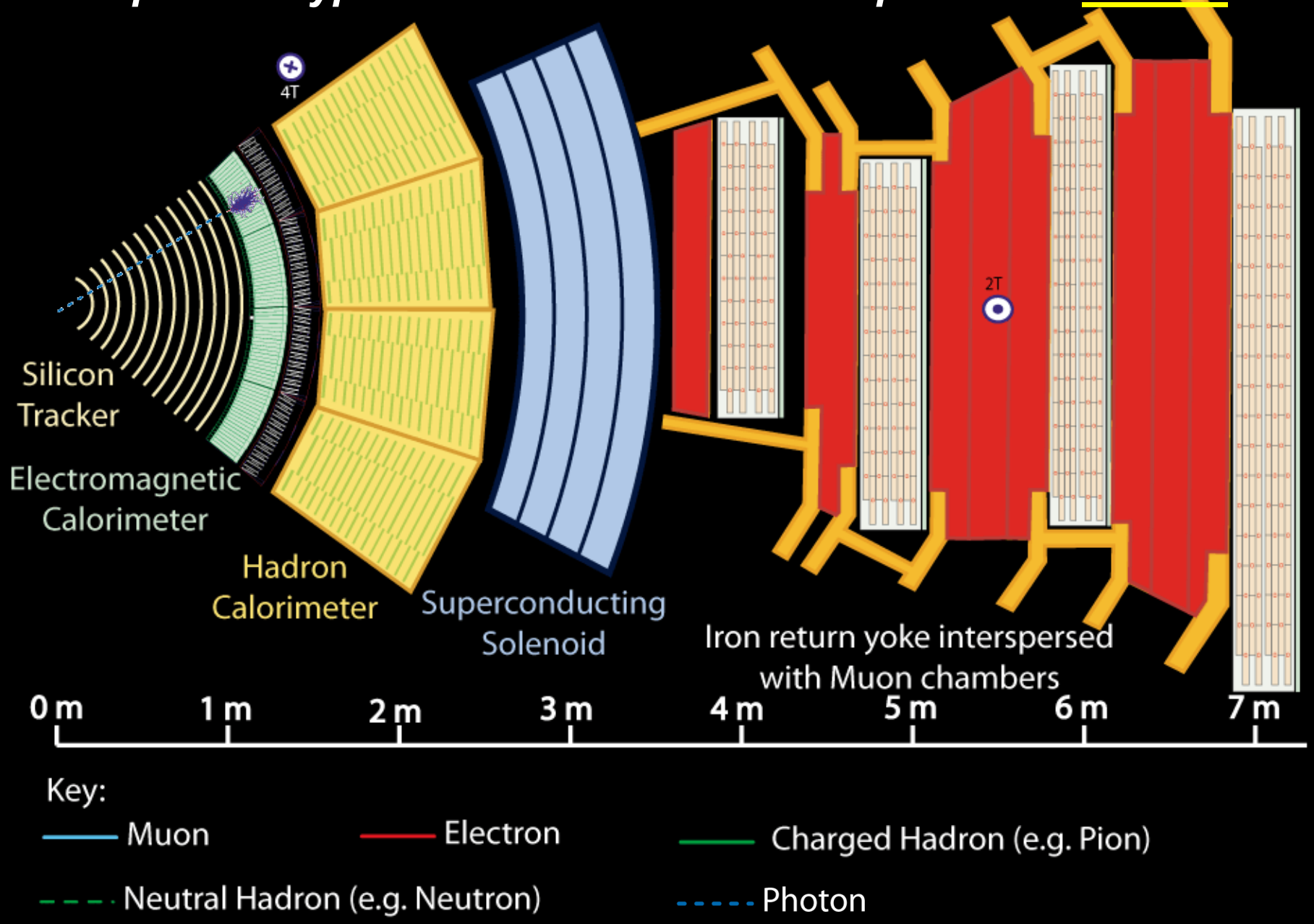
5 particle types detected in Collider Experiment: Muon



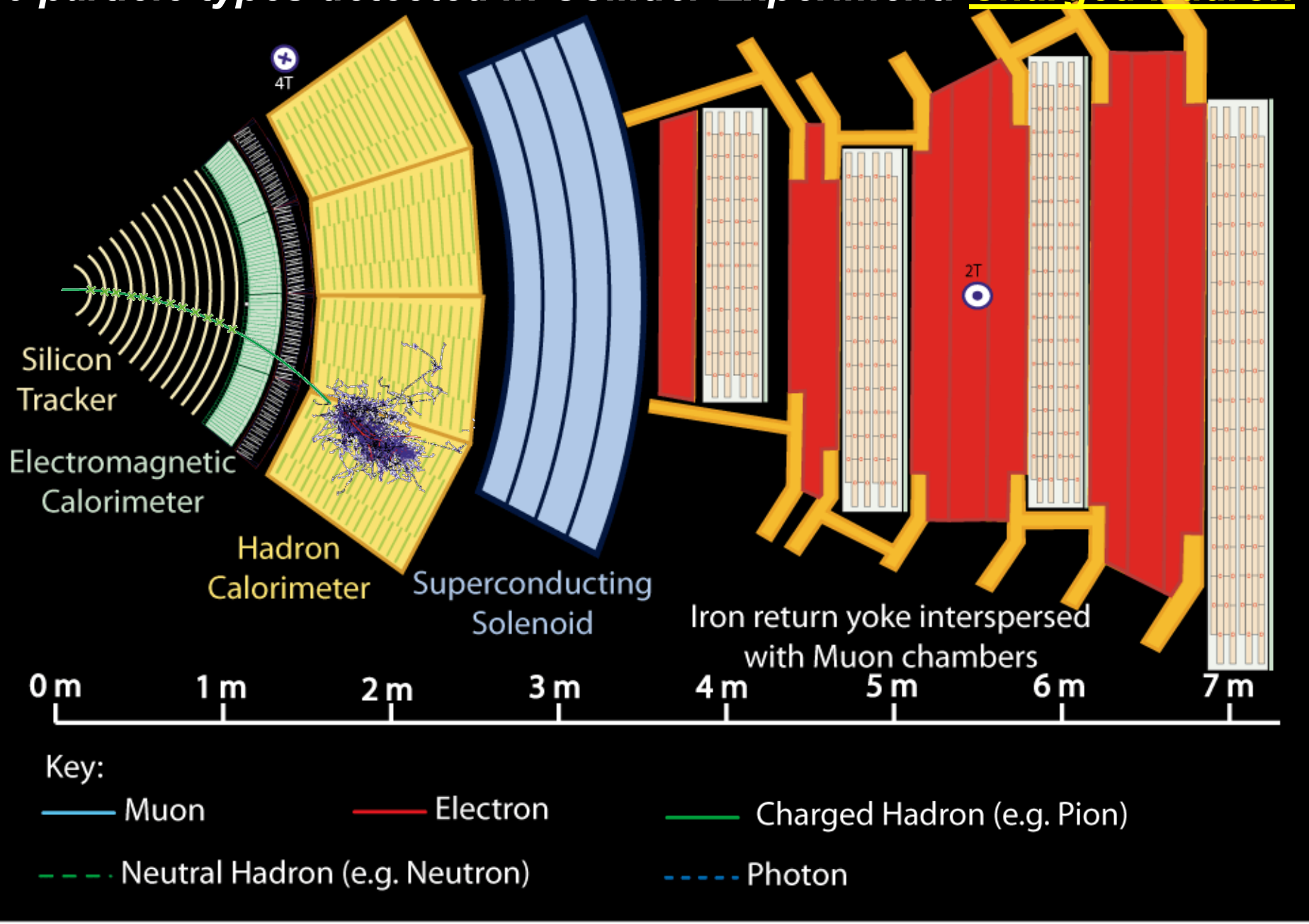
5 particle types detected in Collider Experiment: Electron



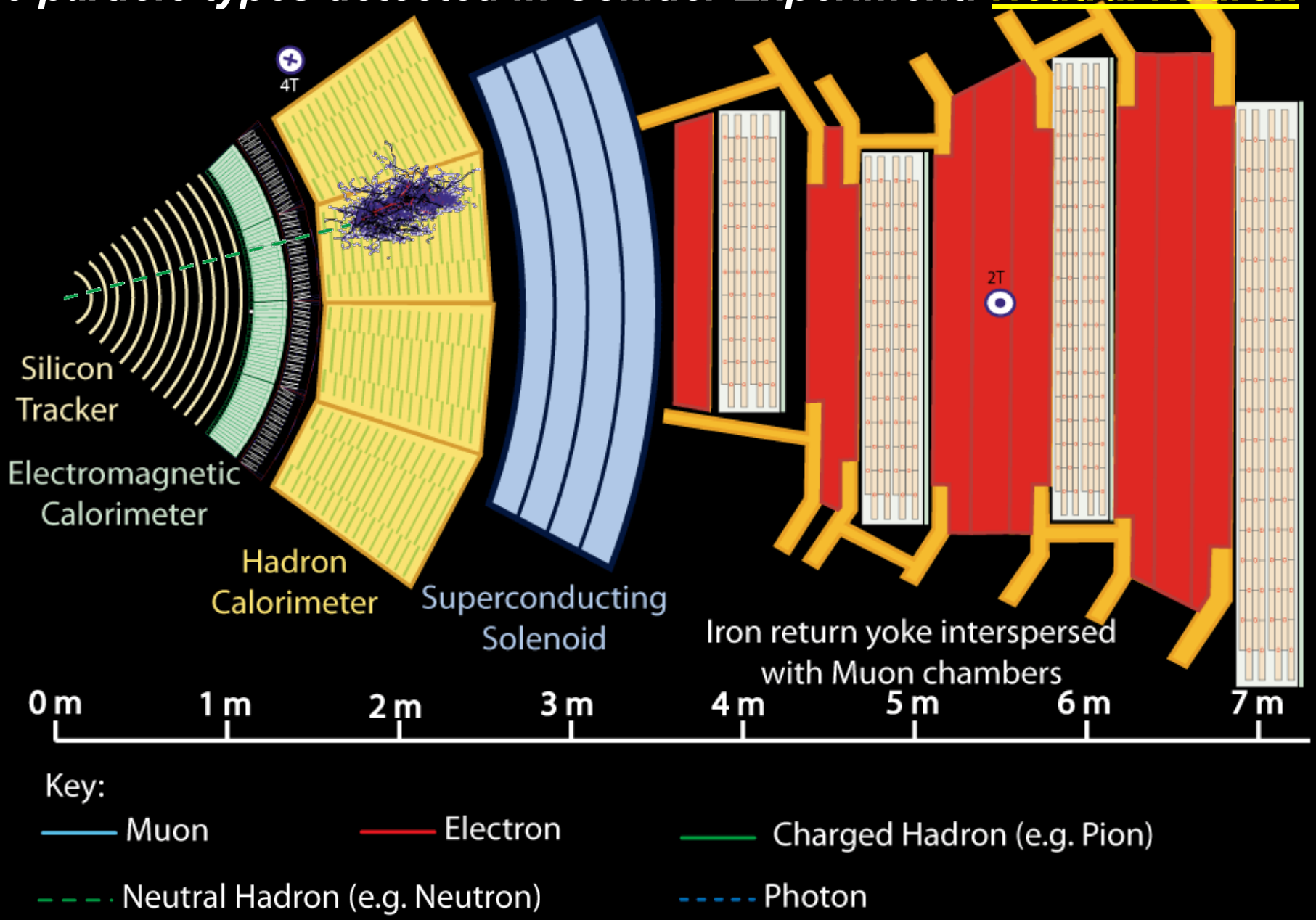
5 particle types detected in Collider Experiment: Photon



5 particle types detected in Collider Experiment: Charged Hadron



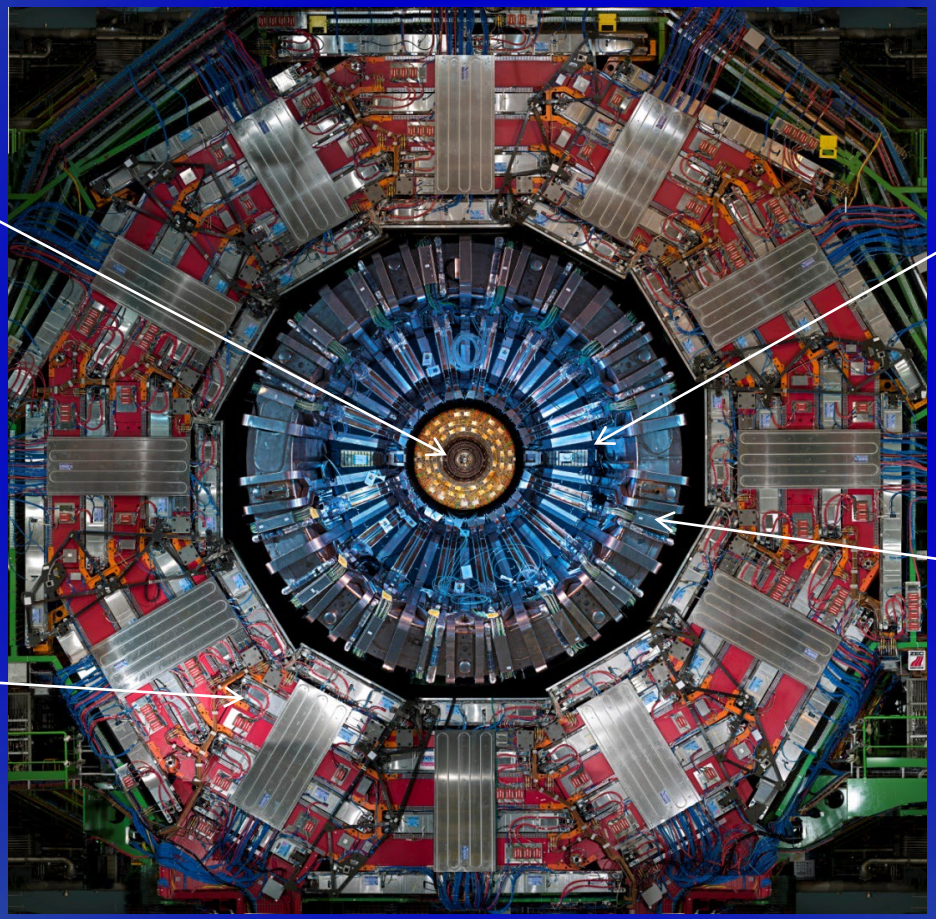
5 particle types detected in Collider Experiment: Neutral Hadron



The CMS Detector: Concept to Data Taking – Took 18 Years

3000 scientists from 40 countries
CMS Letter of Intent (Oct. 1992)

Silicon Tracker



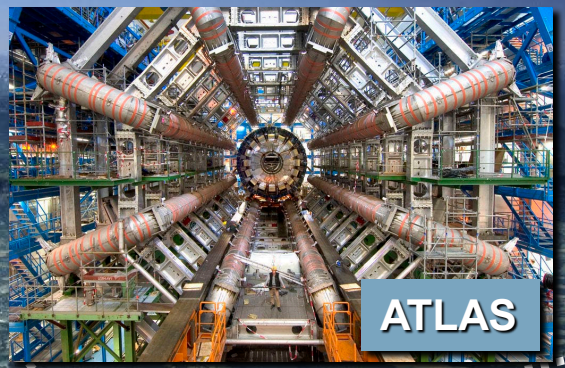
Scintillating Crystals

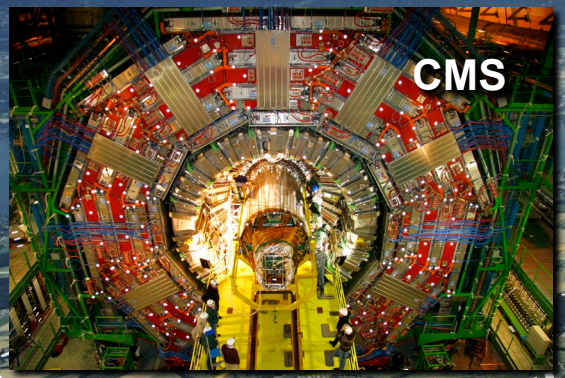
Gaseous detectors

Brass plastic scintillator

Need to make very advanced systems:
Forefront of: Engineering, Imaging Sensors, Electronics, Computing

> 2010: a New Era in Fundamental Science

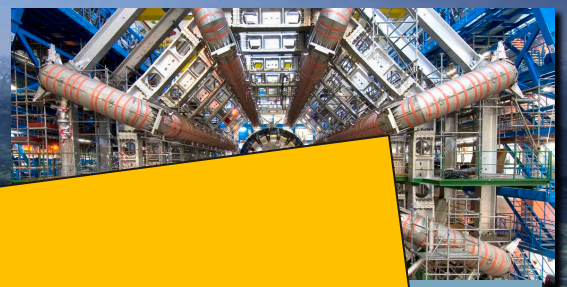




LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
ALICE

Exploration of a New Energy Frontier
Large Hadron Collider (LHC)

> 2010: a New Era in Fundamental Science



- Largest scientific instrument ever built, 27 km of circumference
- >10 000 people involved in its design, construction, exploitation
- ATLAS / CMS collaborations: > 3000 people contributed to the construction of the experiments for the Higgs discovery

  → can you imagine, 500 full professors. 3000 PhD Students from > 200 institutes worldwide working together towards common goal **– it is possible !**

- Collides protons to reproduce conditions at the birth of the Universe …
  40 million times a second

LHC- Marvel of Technology – World's Fastest Racetrack

Protons are accelerated around circular orbits by electric fields (superconducting RF cavities) → 1232 superconducting magnets, each 15 m long, operating at 8.3 T (200'000 x Earth's magnetic field) and 1.9K (-271°C) in superfluid helium.

Energy stored in LHC magnets:

1 dipole magnet E_{stored} = 7 MJ
All magnets E_{stored} = 10.4 GJ

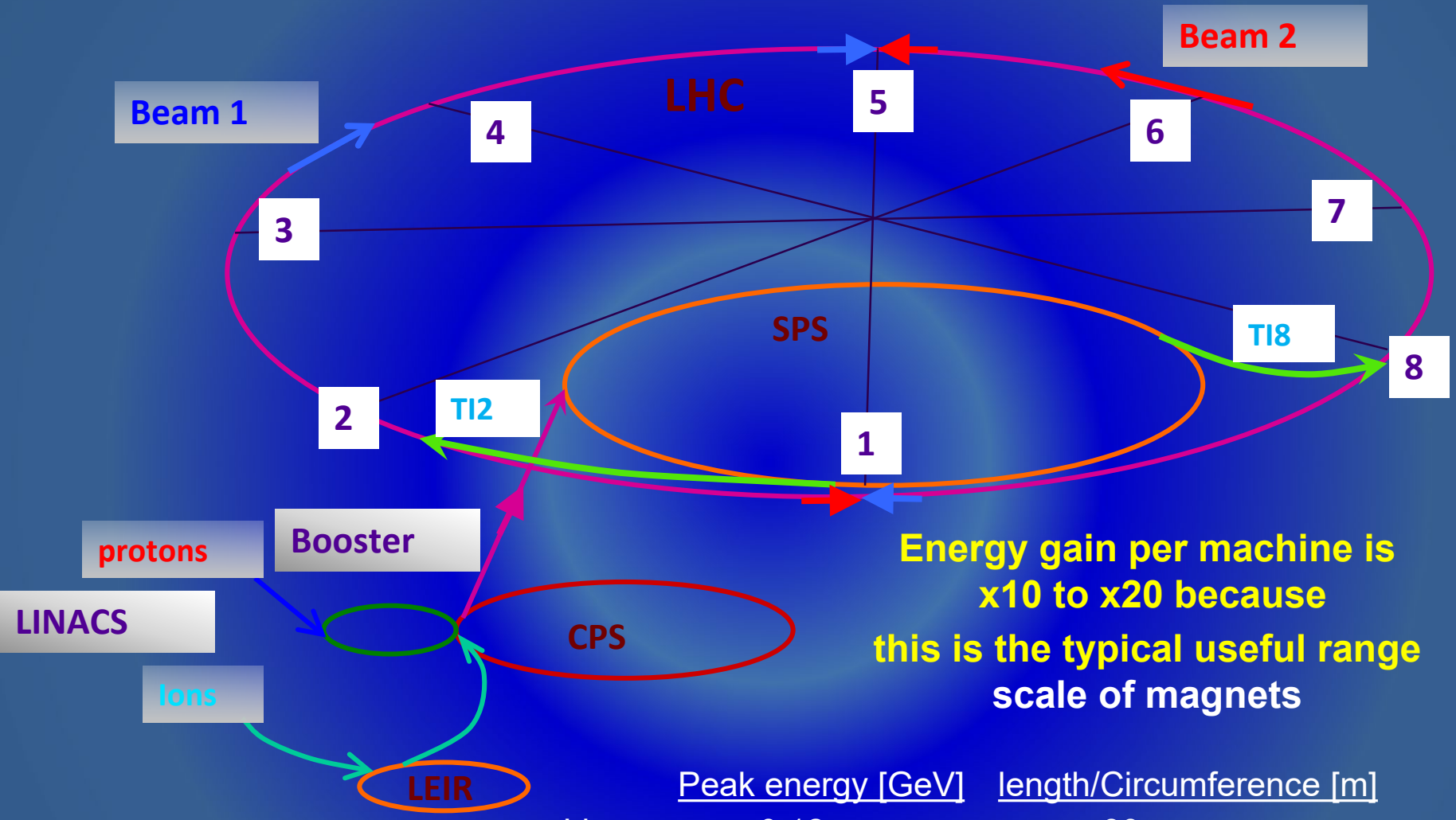
The kinetic energy of an A380 at 700 km/hour

Energy stored in LHC beams

- Kinetic energy of 1 proton bunch:
  - E_1 = (1.15 x 10^{11} protons) x 7 TeV = 129 kJ
- Kinetic energy of beam = 2808 bunches:
  - E_{beam} = k x E_1 = 2808 x E_1 = 362 MJ

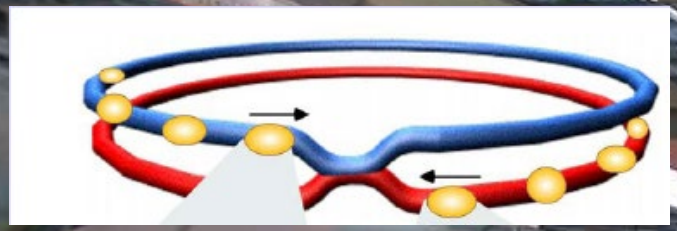
Enough to melt 5.6 tons of gold

CERN / LHC ACCELERATOR COMPLEX



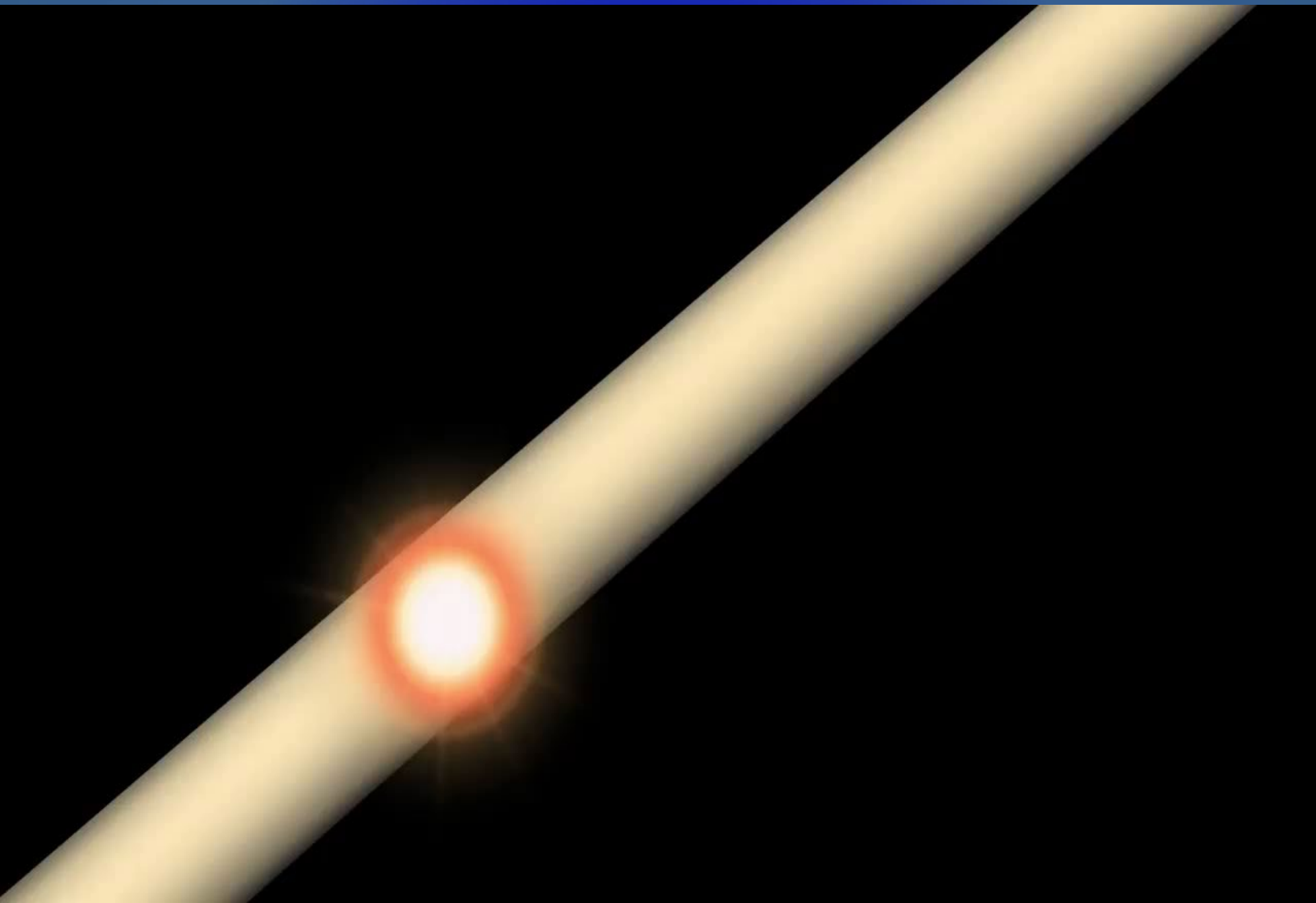
Energy gain per machine is x10 to x20 because this is the typical useful range scale of magnets

	Peak energy [GeV]	length/Circumference [m]
Linac	0.12	30
PSB	1.4	157
CPS	26	628 = 4 PSB
SPS	450	6'911 = 11 x PS
LHC	7000	26'657 = 27/7 x SPS



The LHC tunnel – with bending magnets as far as the eye can see

CERN / LHC ACCELERATOR COMPLEX




and its all done within view of spectacular Mont Blanc!
40
40
MAIN ENTRANCE

ATLAS and CMS Detectors: Two Giants (Size & Weight)

Building of 5 floor

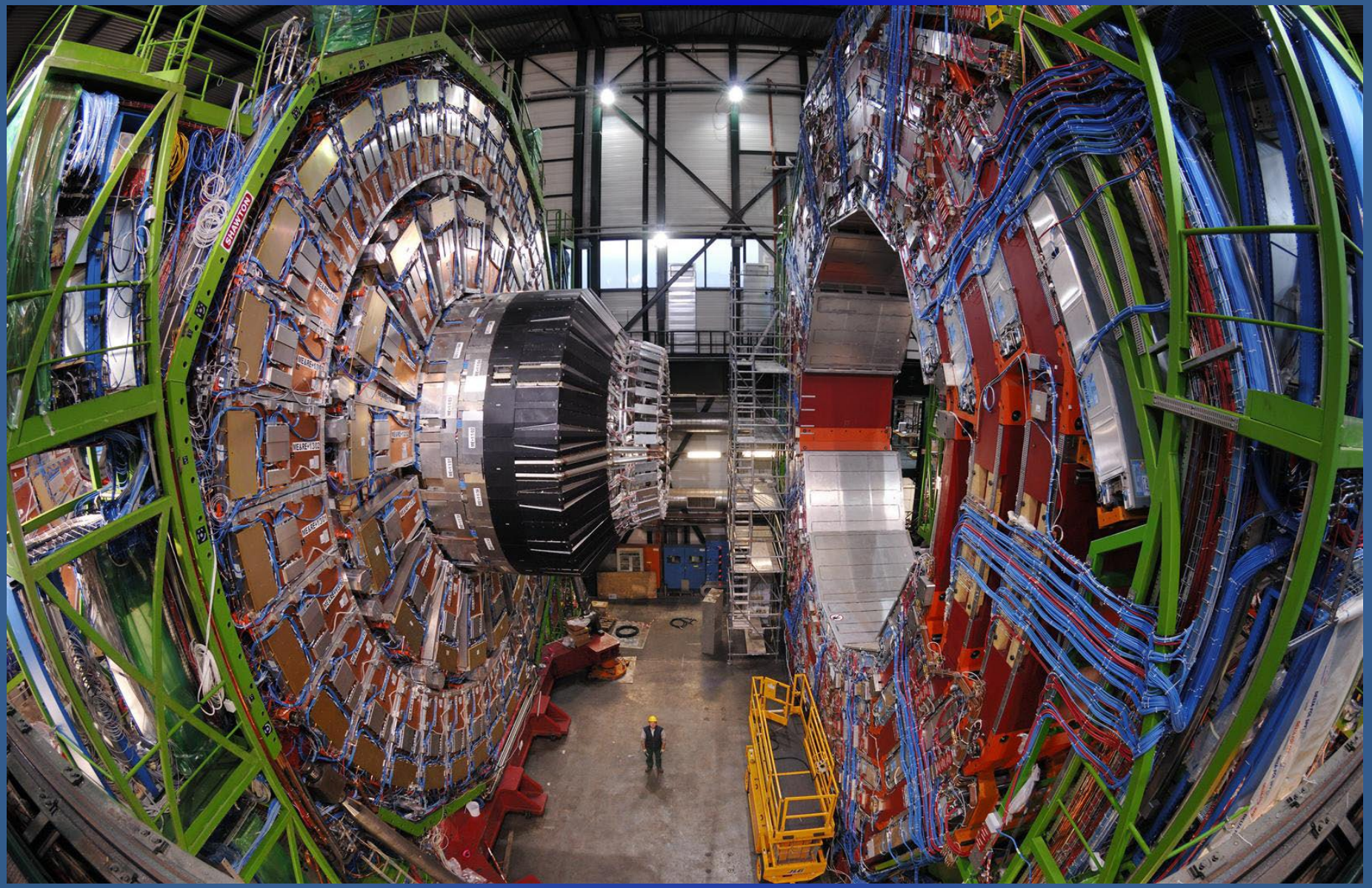
ATLAS

CMS

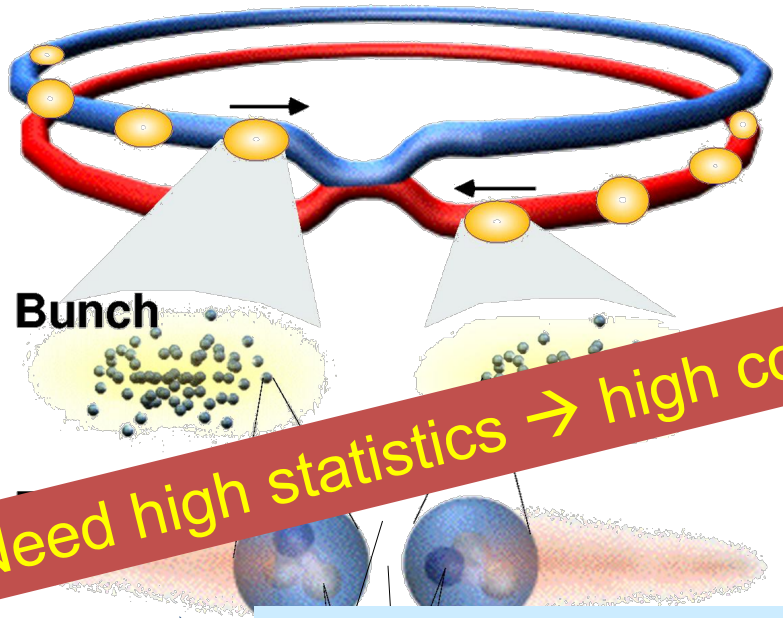
CMS is 30% heavier than the Eiffel tower

LHC Detectors: Events Watched by the “Most Complex Eyes”

CMS detector have 140 million data channels observing at 40 million times a second.

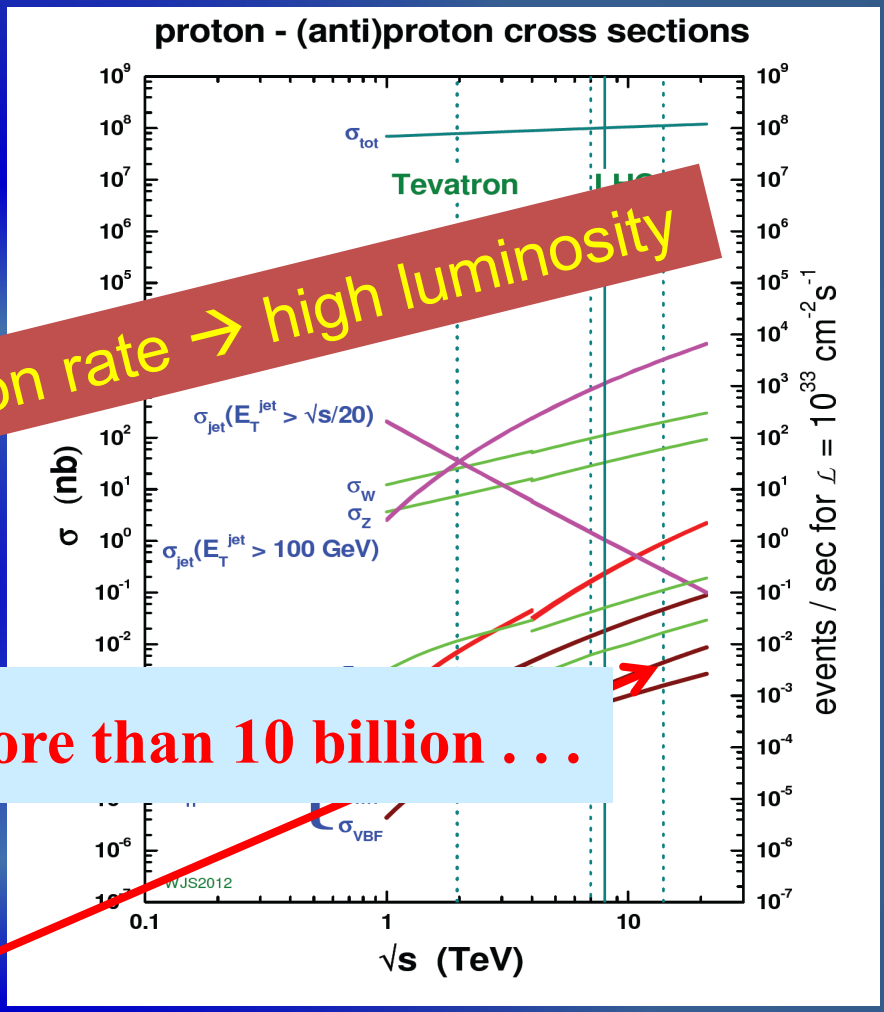


LHC Versatility: What is in this Data ?



Need high statistics → high collision rate → high luminosity

select 1 out of much more than 10 billion . . .

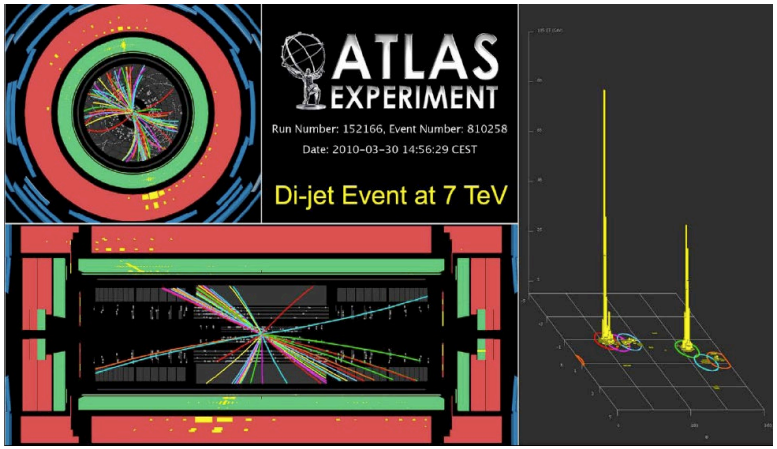


Both ATLAS and CMS have seen already:

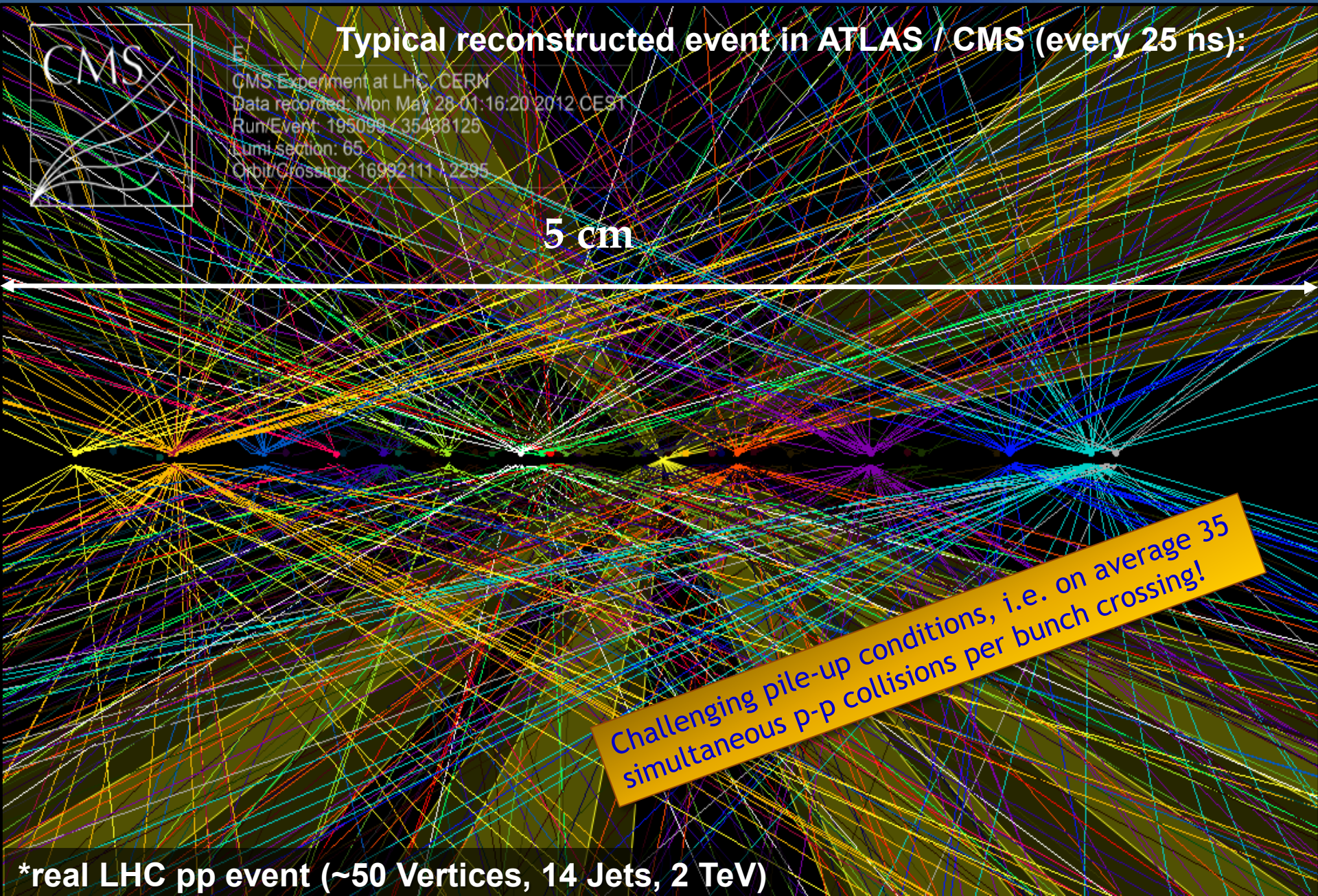
Particle	# produced
H boson	≈ 8 million
t quark	≈ 280million
Z boson	≈ 8 billion
W boson	≈ 26 billion
b quark	≈ 160 trillion

The LHC is an "EVERYTHING" factory (with additional background collisions)

Basic (Di-Jet Production) Processes at the LHC

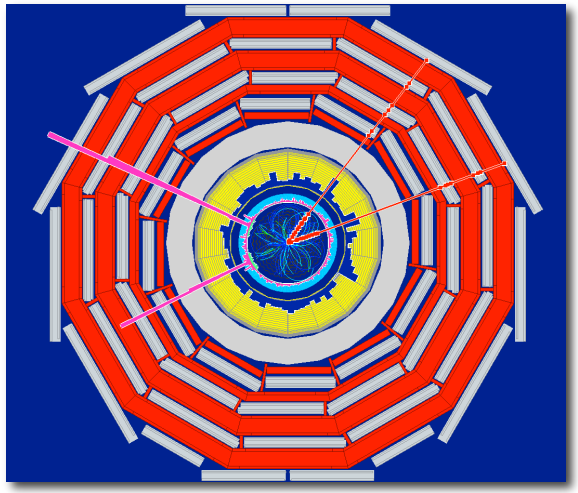


What do We See in Reality – The Challenge of Pileup



*real LHC pp event (~50 Vertices, 14 Jets, 2 TeV)

Higgs Production at the LHC



Higgs Discovery by Bump Hunting (Resonances)

Focus on high mass resolution & most sensitive channels

To start look for:

$$pp \to Higgs \to \gamma\gamma$$
$$pp \to Higgs \to ZZ \to e^+e^-\mu^+\mu^-$$

$p + p \to H\,X \to Z^0\,Z^{0*}\,X \to e^+\,e^-\;\mu^+\,\mu^-\,X$

Compute (from the measured kinematics) :

$$m_H^2 = (E_{Z^0} + E_{Z^{0*}})^2 - (\vec{p}_{Z^0} + \vec{p}_{Z^{0*}})^2$$

Also for each Z^0 compute (e.g. for $Z^0 \to \mu^+\mu^-$) :

$$m_{Z^0}^2 = (E_{\mu+} + E_{\mu-})^2 - (\vec{p}_{\mu+} + \vec{p}_{\mu-})^2$$

The same for the other Higgs decay mode : $H \to \gamma\gamma$
In all cases we have to reconstruct tracks (EM clusters for photons) and measure momenta, energies and idetify particles (charge and mass hypothesis).

The Standard Model of Particle Physics

= COSMIC DNA OF THE UNIVERSE

Some background and history

What is everything made of ? What holds it all together ?

Matter particles

Quarks

u up | c charm | t top

d down | s strange | b bottom

Leptons

e electron | μ muon | τ tau

ν_e electron neutrino | ν_μ muon neutrino | ν_τ tau neutrino

Universal Forces

Z Z boson | γ photon

W W boson | g gluon

Gravitational interaction

Strong

Gluons (8)

Quarks

Mesons
Baryons

Nuclei

Electromagnetic

Photon

Atoms
Light
Chemistry
Electronics

Gravitational

Graviton ?

Solar system
Galaxies
Black holes

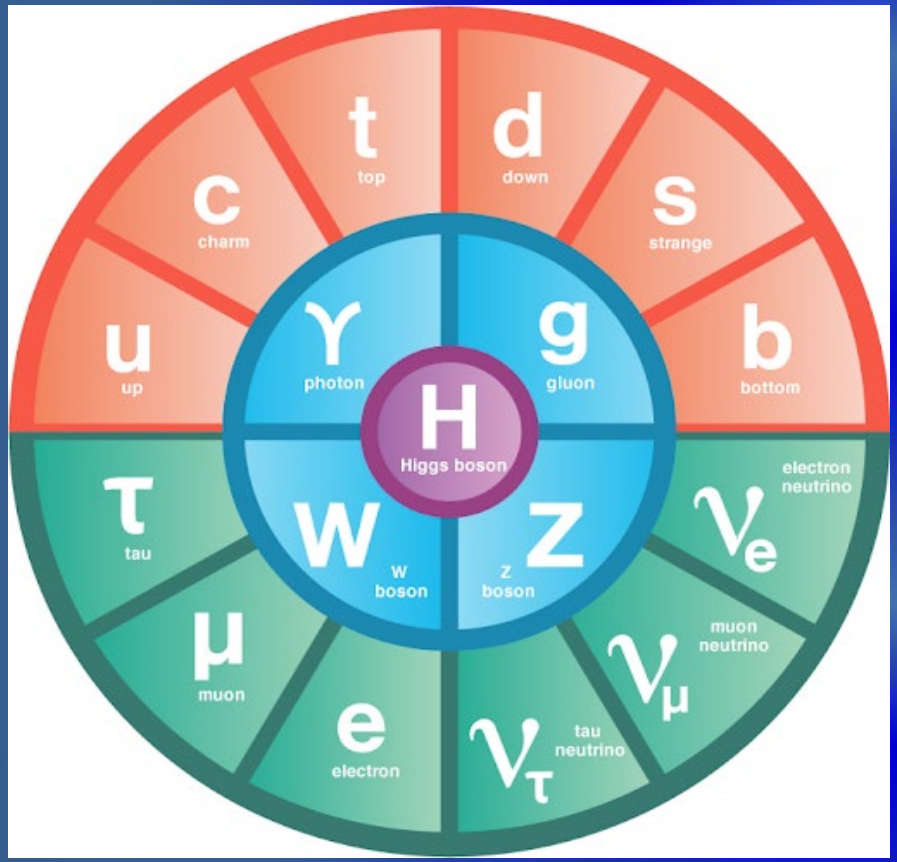
Weak

Bosons
(W,Z)

Neutron decay
Beta radioactivity
Neutrino interactions
Burning of the sun

A Crowning Achievement of 20th Century Science

All our knowledge is today «codified» in **the Standard Model** :
Matter, Interaction, Unification Interaction, Unification



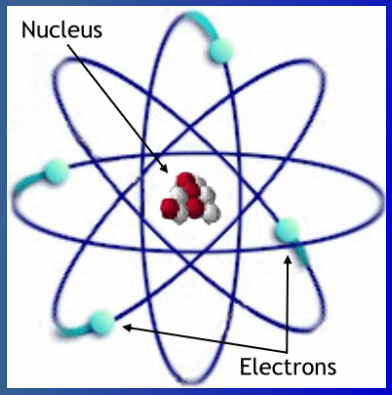
The new (final?) “Periodic Table” of fundamental elements

The Standard Model :

- ✓ **A quantum field theory: SU(3) x SU(2) x U(1)**
- ✓ Classify the matter particles in family (fermions)
- ✓ Explain the interactions through local gauge principle symmetry (bosons)
- ✓ Allow the particle to acquire masses through the Higgs mechanism
- ✓ **Without the Higgs, all particles are massless**
- ✓ **Without the Higgs, quantum corrections are infinite**
- ✓ **Has been tested with high precision at collider experiments**

If there were no Higgs Boson

- Higgs boson explains why electron has mass
- Radius of nuclei depend on electron mass



… there would be **no atoms**
→ massless electrons would escape at the speed of light

… there would be **no heavy nuclei**
… weak interactions would not be weak
→ Life would be impossible: everything would be radioactive

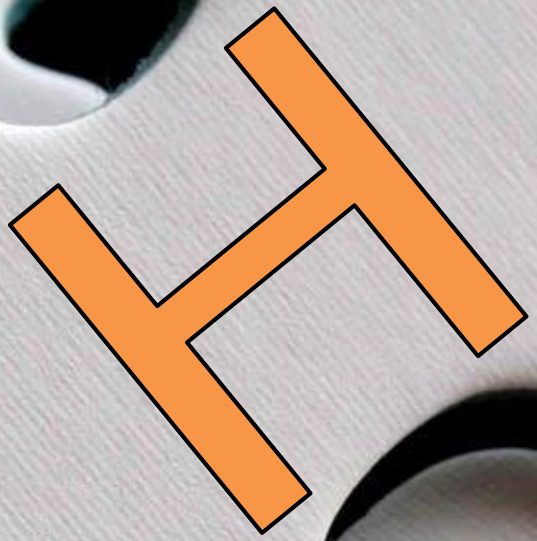
It's existence is a big deal!

THE HIGGS MECHANISM … IN ACTION …

- **H** boson is an excitation of the H field.
- **H** field - not **H** boson - creates particle masses.

- **H** field is responsible for masses of all elementary particles, atoms, chemistry - and life.
- **H** field is not responsible for most of our mass (proton mass comes from gluon interactions) & mass in universe
- **H** is not gravity!

The quantum theory predicts that the field has an associated quantum / particle:



The Higgs Boson!

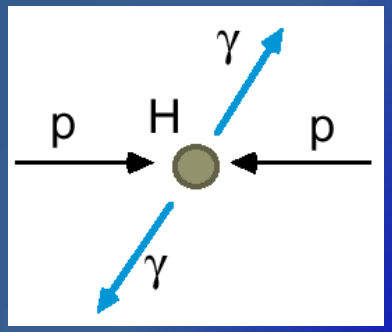
We can create the Higgs boson in LHC experiments !
Finding the Higgs Boson would establish the existence of this field!

Higgs Hunting Over the Years

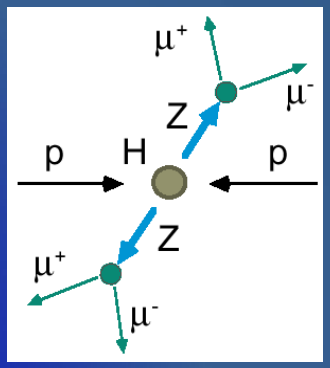
30 Years of Experiments:

Accelerator	type, laboratory	energy $\sqrt{s}$	years of operation
LEP-I	e^+e^- collider, CERN	91 GeV	1989 - 1994
LEP-II	e^+e^- collider, CERN	209 GeV	1995 - 2000
HERA-I	ep collider, DESY	27 + 800 GeV	1992 - 2000
HERA-II	ep collider, DESY	27 + 920 GeV	2002 - 2007
TeVatron Run I	ppbar collider, Fermilab	1.8 TeV	1987 - 1996
TeVatron Run II	ppbar collider, Fermilab	1.96 TeV	2002 - 2011
LHC, phase I	pp collider, CERN	7 TeV	2010- 2012
LHC, phase II	pp collider, CERN	14 TeV	2014- .....

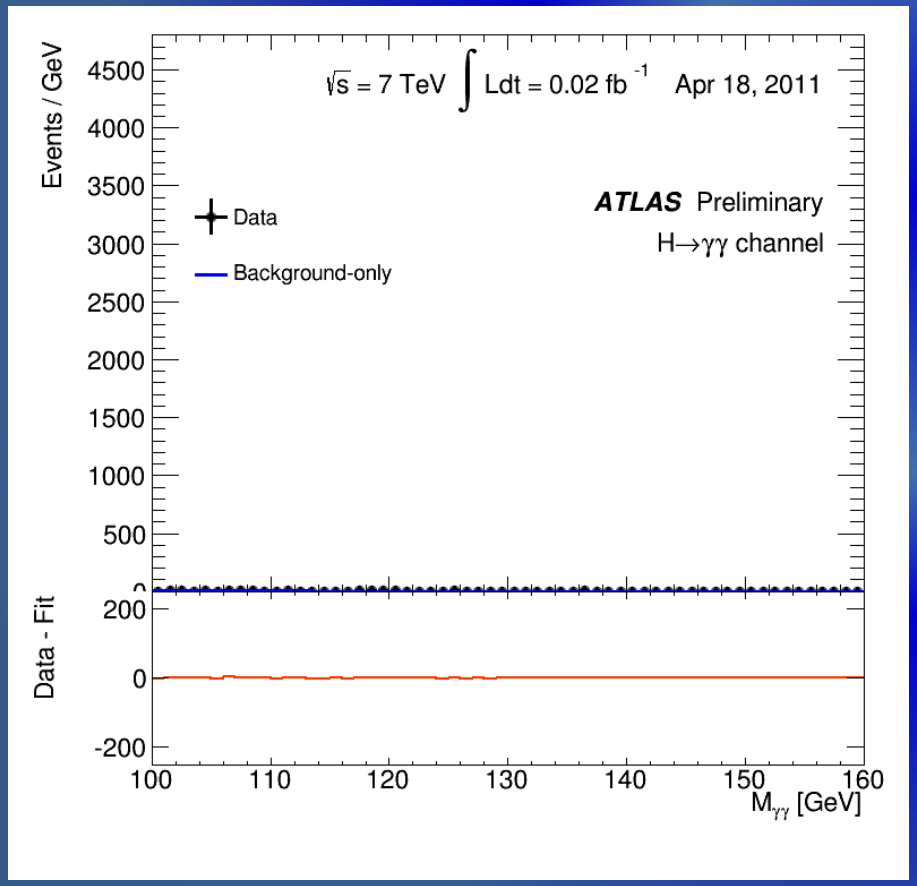
The Birth of a Higgs Particle – Evolution in Time



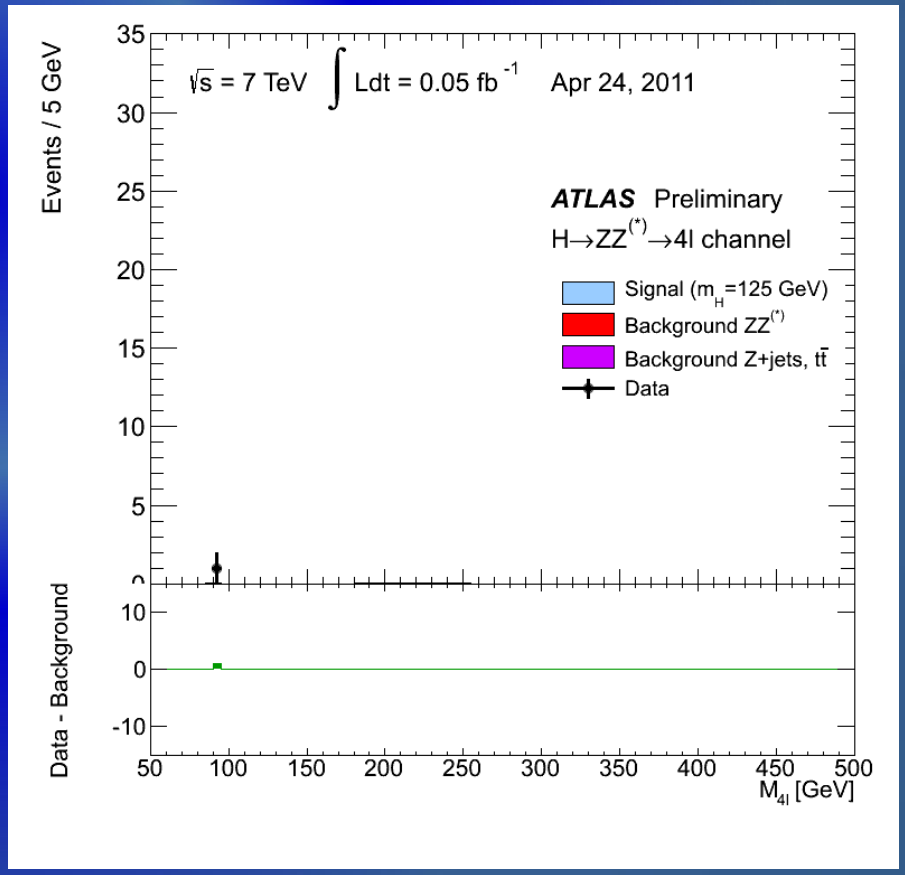
"History" of the data accumulation in 2011-2012: bumps in the invariant mass signify a new particle, found in two different ways (decay channels), at the same mass – about 125 GeV/c²



H → γγ



H → ZZ



Higgs Discovery at Large Hadron Collider @ CERN (2012)

"As a layman I would now say… I think we have it – It is a Discovery" (Rolf-Dieter Heuer, CERN DG)

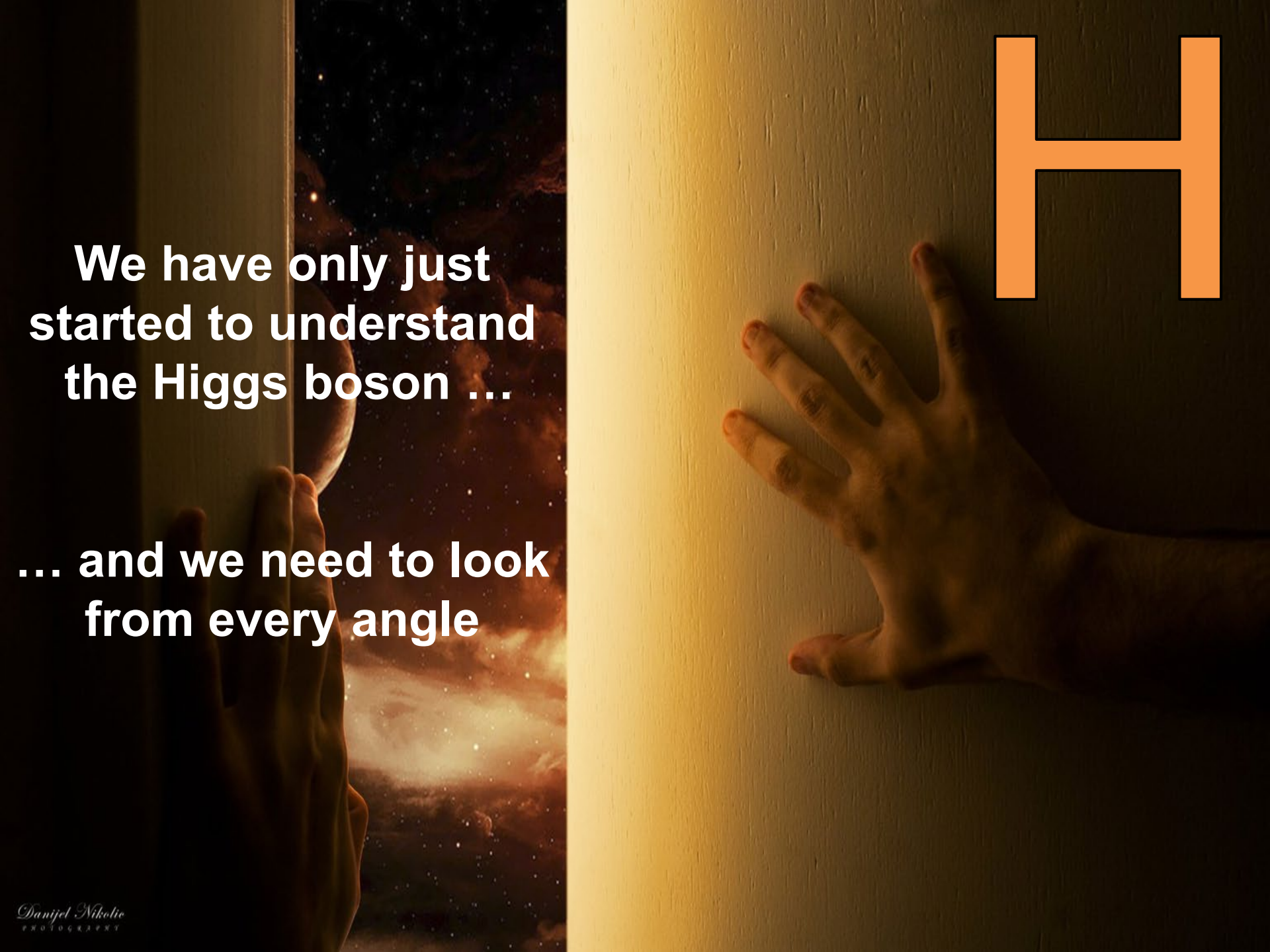
Both ATLAS and CMS Collaborations have reported observation of a narrow resonance ~ 125 GeV consistent with long-sought Higgs boson

The HIGGS BOSON is part of our "origin".

We did not know on that day and still have to establish if it is – "THE HIGGS BOSON" of the SM or comes from one of the SM extensions

2013: Nobel Prize in Physics for Higgs Boson Discovery

'The Large Hadron Collider at CERN is the largest most complex machine in the world, possibly the universe. By smashing particles together at enormous energies, it recreates the conditions of the Big Bang. The recent discovery of what looks like the "Higgs particle" is a triumph of human endeavour and international collaboration. It will change our perception of the world and has the potential to offer insights into a complete theory of everything.' ***Stephen Hawking***

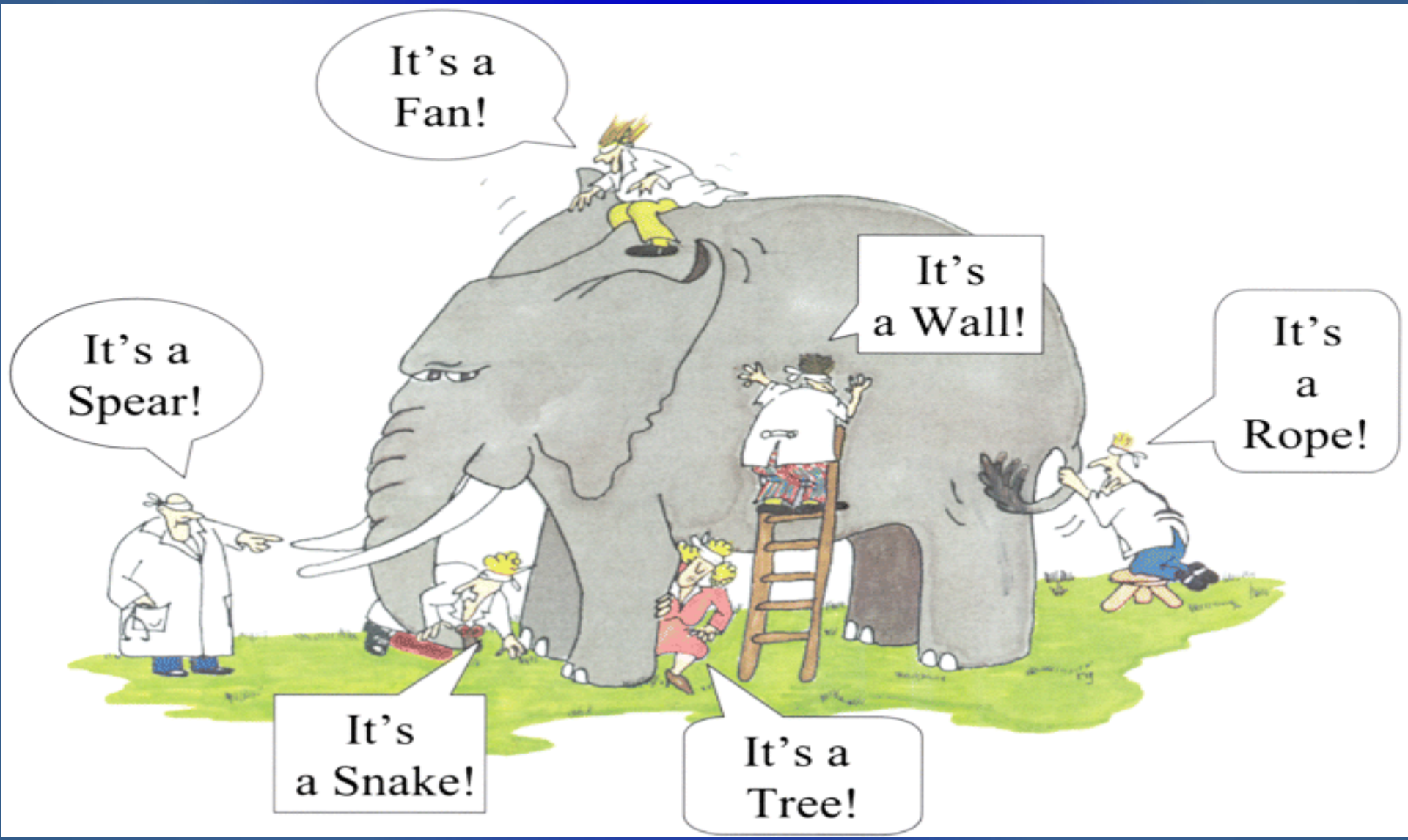

We have only just started to understand the Higgs boson …
… and we need to look from every angle
H
Danijel Nikolic
PHOTOGRAPHY


It's
a
Rope!

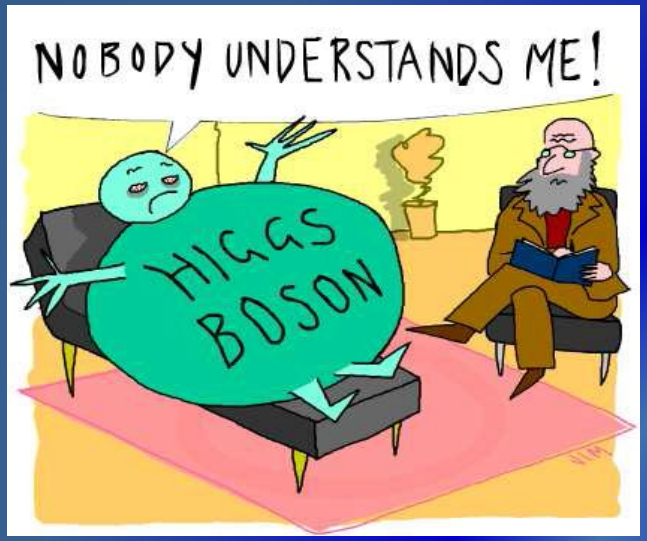

It’s a
Spear!


It's
a Wall!

We have only started to understand the Higgs boson …
… and we need to look from every angle

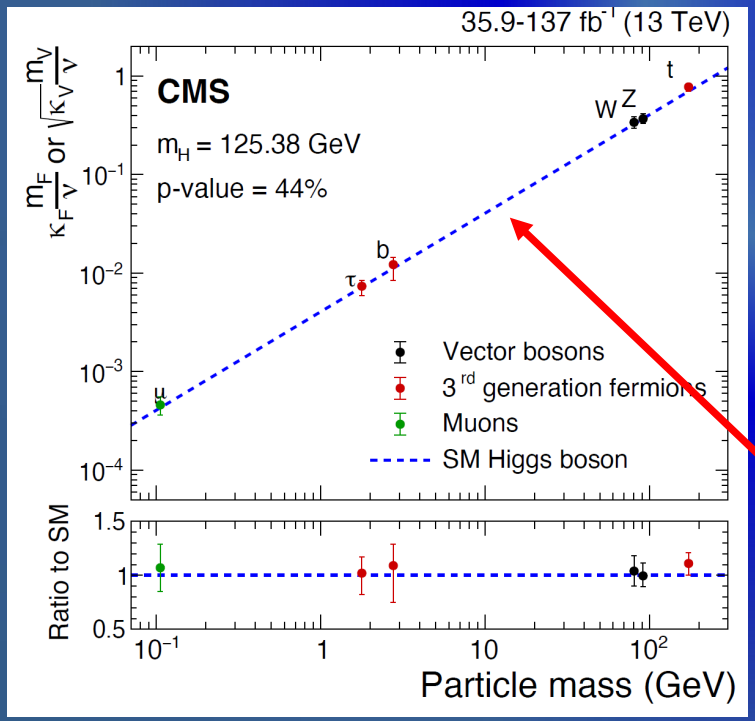


Historic Milestone: the Higgs is just Different



All the matter particles are spin-1/2 fermions.
All the force carriers are spin-1 bosons

- ✓ Higgs particle is the only spin-0 (scalar) particle in the SM: Higgs field does the most important job in the SM (gives masses)
- ✓ Higgs is a totally new form of matter (neither matter nor force): "FACELESS"



FROM DISCOVERY TO PRECISION MEASUREMENTS

- ✓ Higgs couplings to fermions and gauge bosons *fixed in SM*
- ✓ Do coulings scale with mass ?
  → *A deviation from this pattern signals new physics!*

The Higgs boson
final piece in the puzzle?

...but there must be a deeper relationship
between Higgs / mass / gravity / dark energy

Determine Higgs properties as precisely as possible to address fundamentl questions:

… is it "THE Higgs Boson" (of the Standard Model) ? or one of several ?

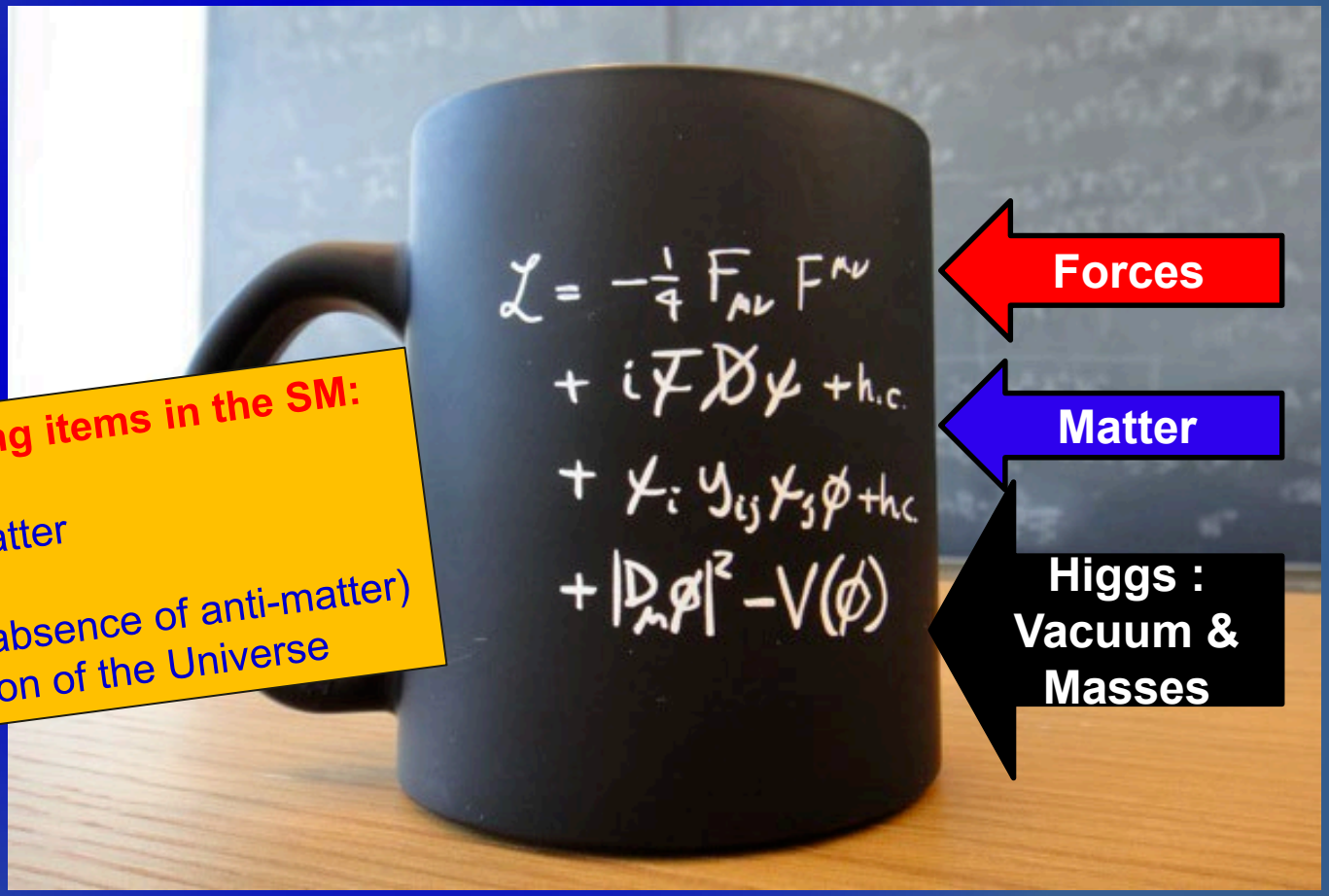
… its properties could give information on Dark Matter

… its properties could give first hints on Dark Energy

We Know There Must be New Physics: Puzzle is Sharpened

No evidence of New Physics (YET) in the LHC data, beyond the SM
→ it may remain valid up to very high energies

Lagrangians & coffee mugs



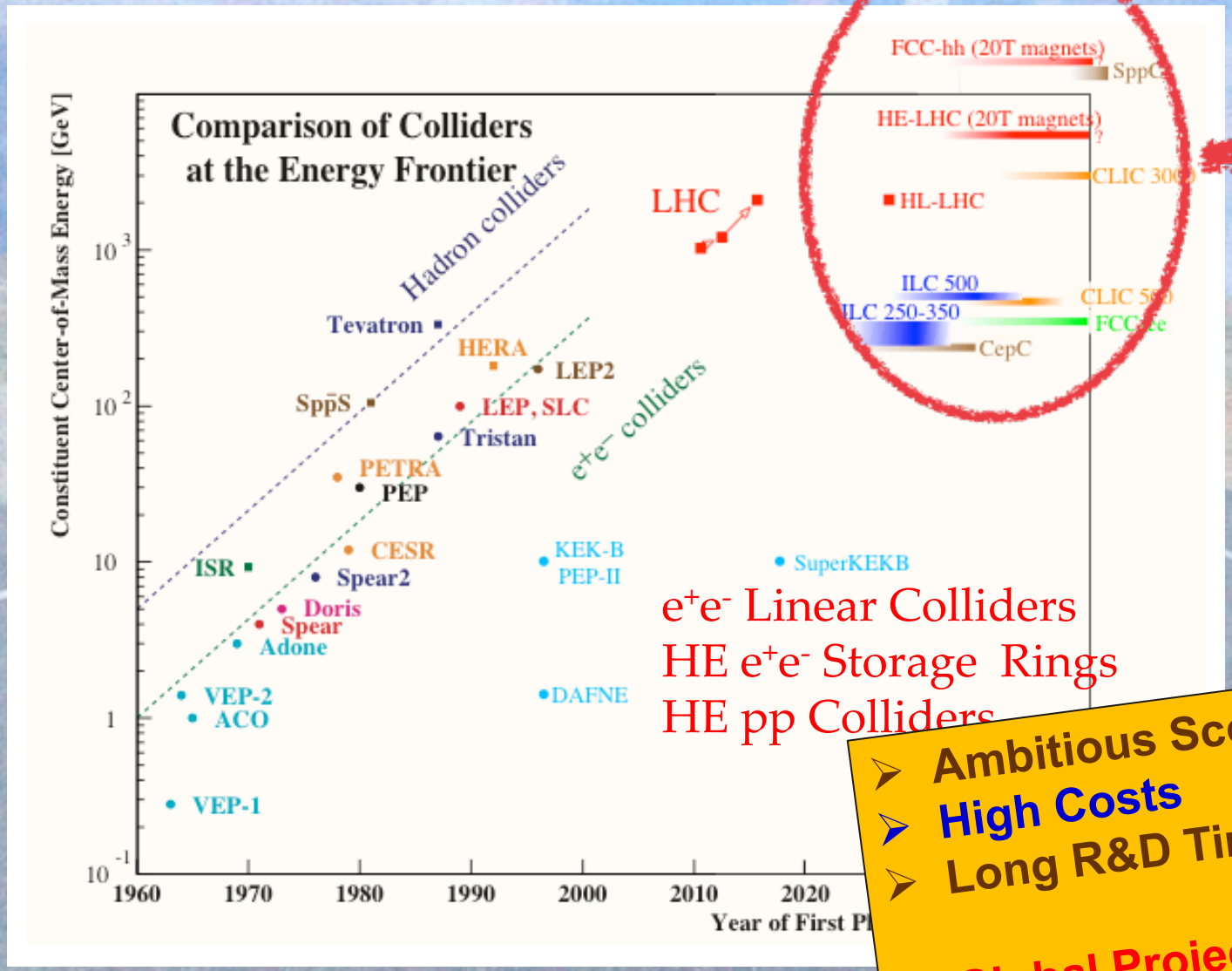
There are several missing items in the SM:

- non-baryonic dark matter
- neutrino mass
- baryon asymmetry (absence of anti-matter)
- accelerated expansion of the Universe

REALLY NEW IDEAS NEEDED

Beyond Paradigms of Spacetime + Internal Symmetries

Energy Frontier Colliders: Past, Present, Future



- Ambitious Scope
- High Costs
- Long R&D Times

→ Global Projects (Politics!)

N. Walker, 2014 ICHEP

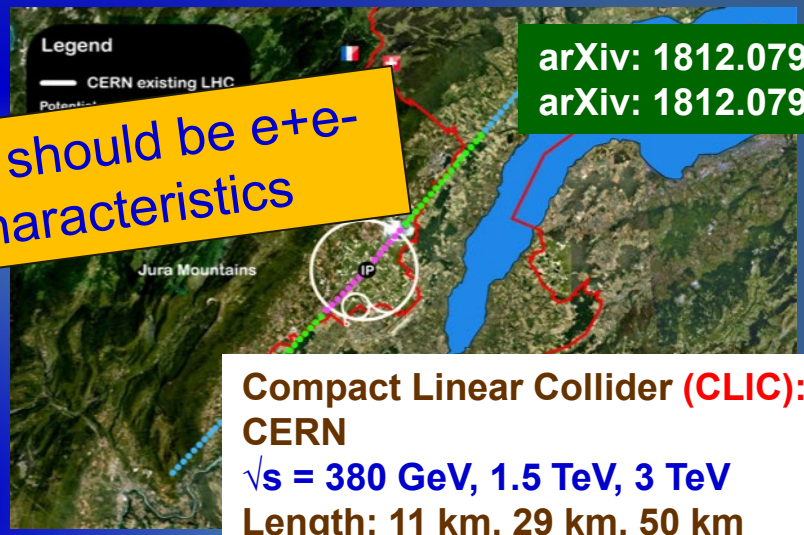
Future Electron-Positron Colliders: " Higgs Factory"

Linear colliders: *ILC, CLIC* (technical extendability to TeV regime)

arXiv: 1901.09829
arXiv: 1901.09825

General consensus: next "big machine" should be e+e- collider to scrutinize Higgs boson characteristics

International Linear Collider (ILC):
Japan (Kitakami)
√s = 250 - 500 GeV, 1 TeV
Length: 21 km - 31 km (50 km)



arXiv: 1812.07987
arXiv: 1812.07986

Compact Linear Collider (CLIC):
CERN
√s = 380 GeV, 1.5 TeV, 3 TeV
Length: 11 km, 29 km, 50 km

Circular colliders: *CEPC, FCC-ee*

arXiv: 1901.03169
arXiv: 1901.03170

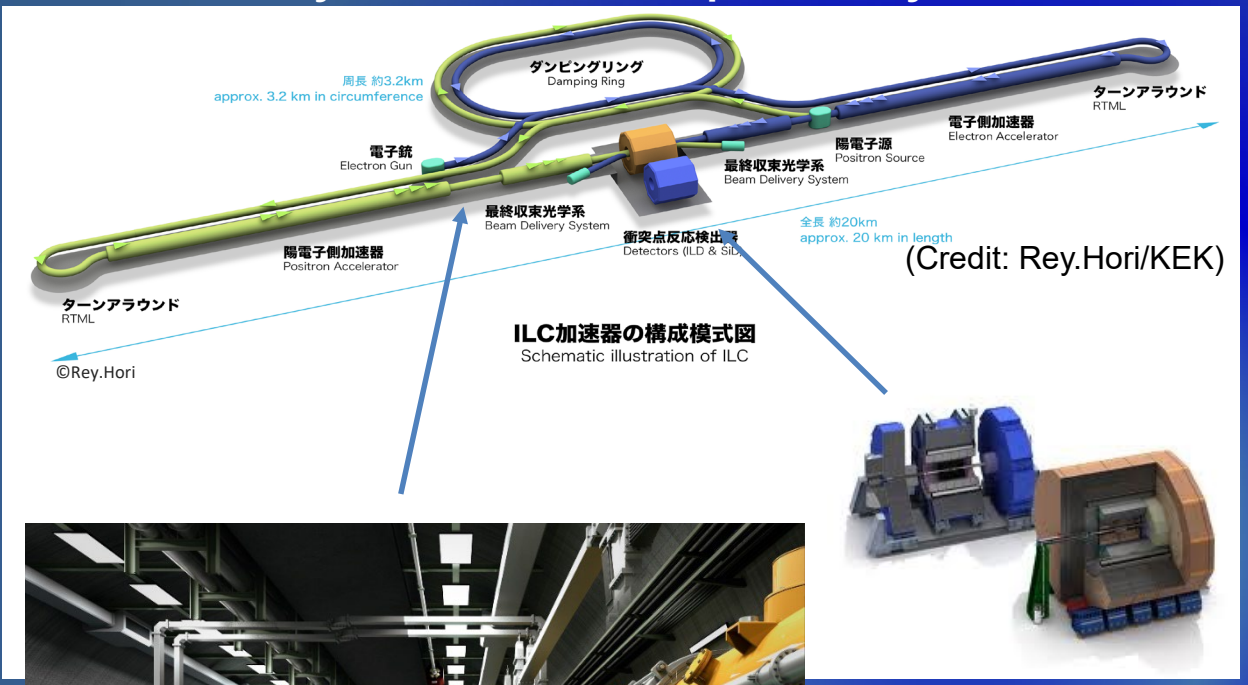
Circular Electron-Positron Collider (CEPC):
China
√s = 90 - 240 GeV
Circumference: 100 km

http://fcc-cdr.web.cern.ch/

Future Circular Collider (FCC-ee):
CERN
√s = 90 - 350 GeV
Circumference: ~100 km

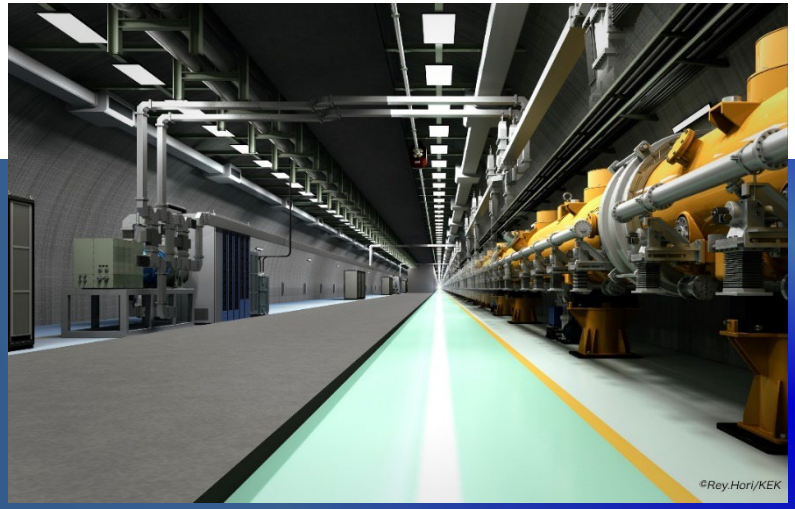
International e+e- Linear Collider in Japan

The ILC vidyo in 2 minutes: https://www.youtube.com/watch?v=40Ap98o-4tU&t=45s



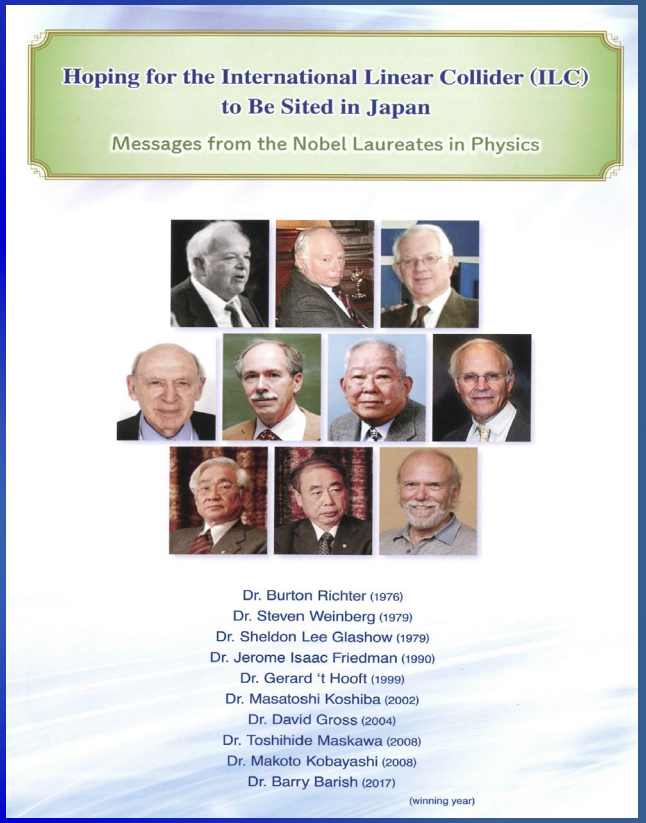
(Credit: Rey.Hori/KEK)

State-of-the-art
Detectors: SiD, ILD



21km underground tunnel (250 GeV)

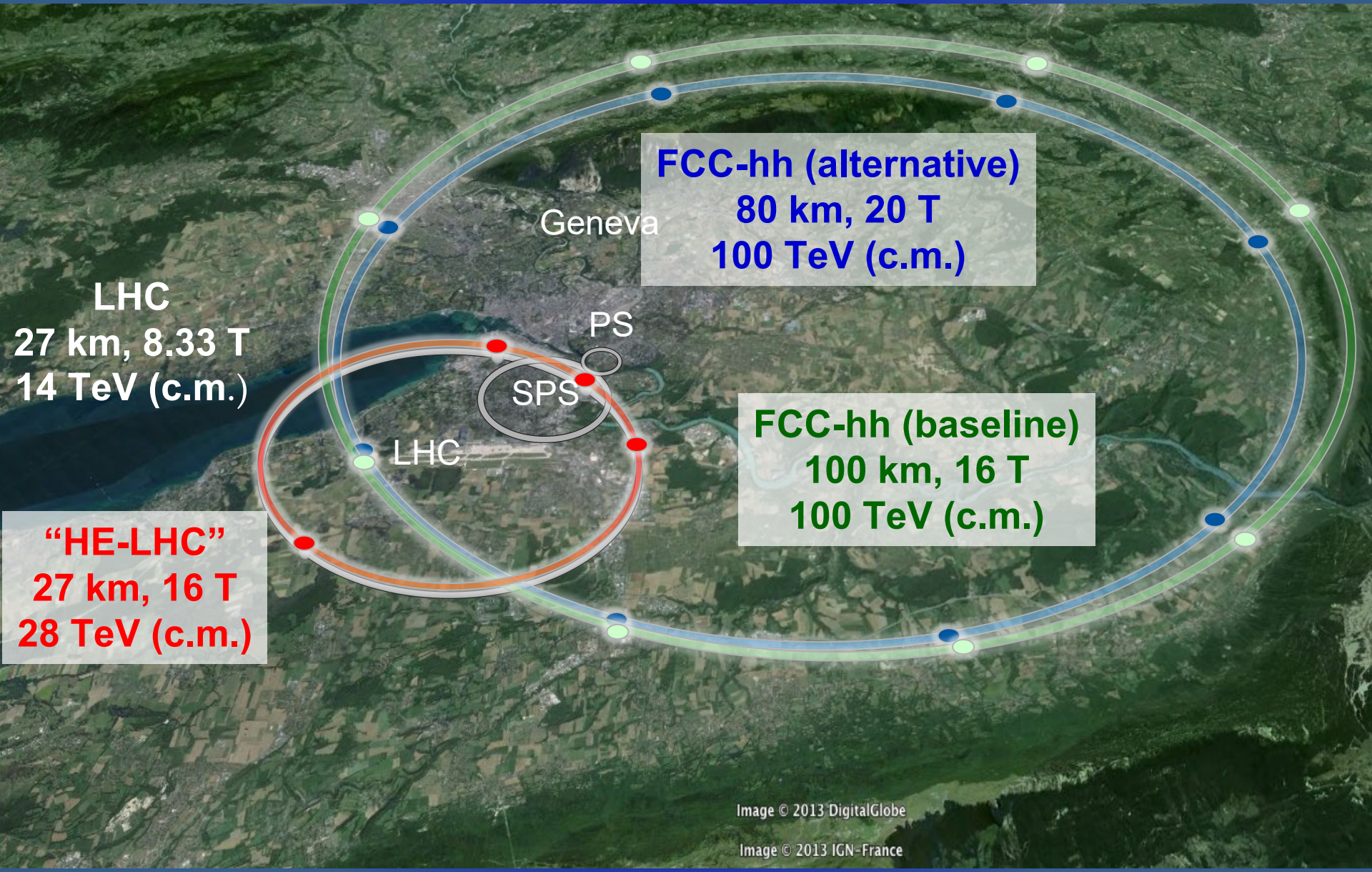
Superconducting RF acceleration technology: gradient 31.5 MV/m



Energy Extendibility:

e+e- collisions for many decades to come
(also upgrades using other acc. technologies – e.g. PWA)

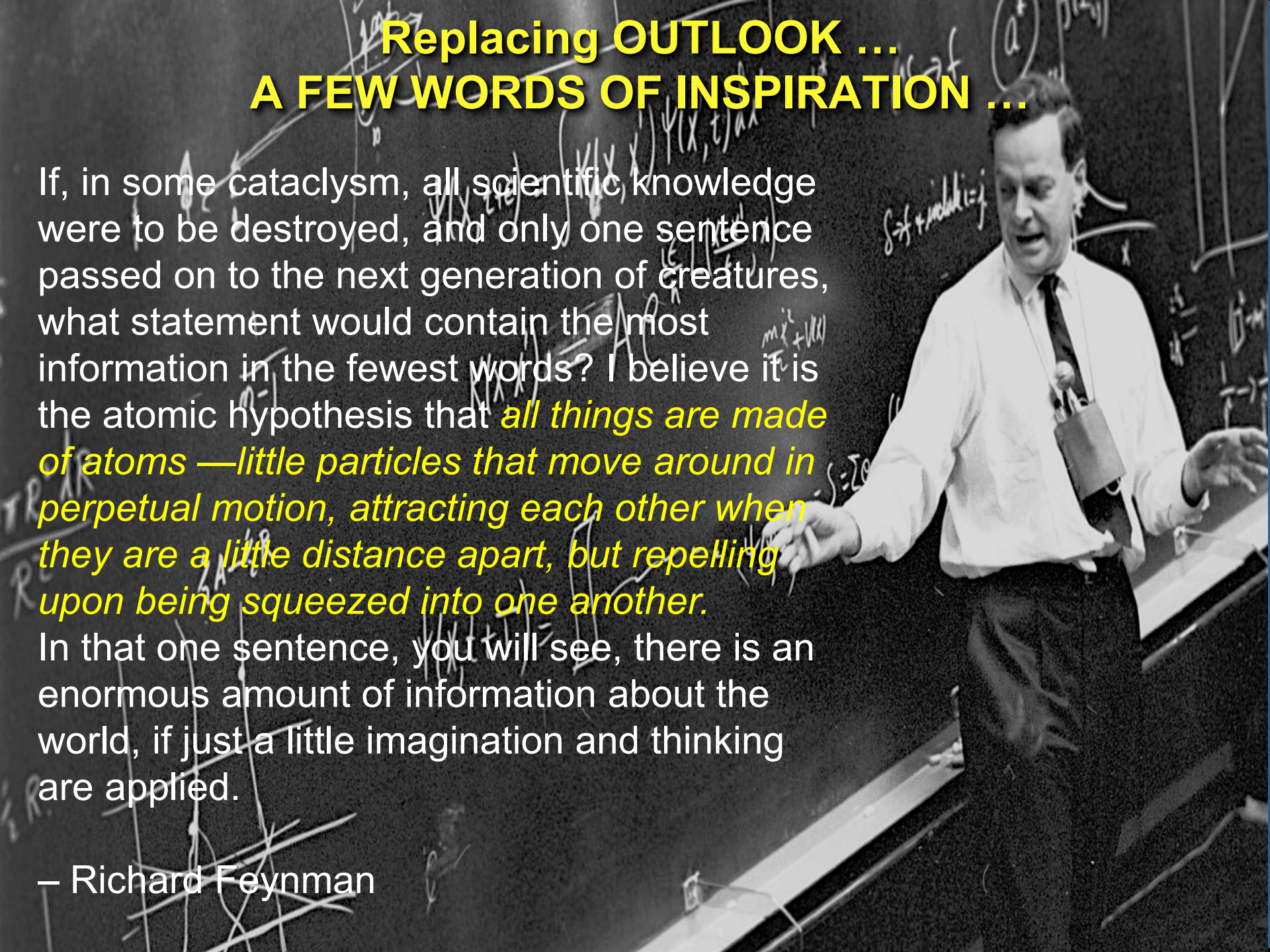
Future (Long –Term) Energy Frontier Hadron Colliders



Linear Collider Upgrade → Main Driver for Plasma WakeField Accelerator (PWA)

DREAM: with acceleration gradient of 1 GeV/m → ILC length would be O (20-50 m)

Replacing OUTLOOK …
A FEW WORDS OF INSPIRATION …



If, in some cataclysm, all scientific knowledge were to be destroyed, and only one sentence passed on to the next generation of creatures, what statement would contain the most information in the fewest words? I believe it is the atomic hypothesis that *all things are made of atoms —little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another.*
In that one sentence, you will see, there is an enormous amount of information about the world, if just a little imagination and thinking are applied.

– Richard Feynman

5* Scientific Discoveries of the Last Decade In Fundamental Physics

- ✓ *Higgs Boson*
- ✓ *Gravitational Waves*
- ✓ *Black Hole Event Horizon*

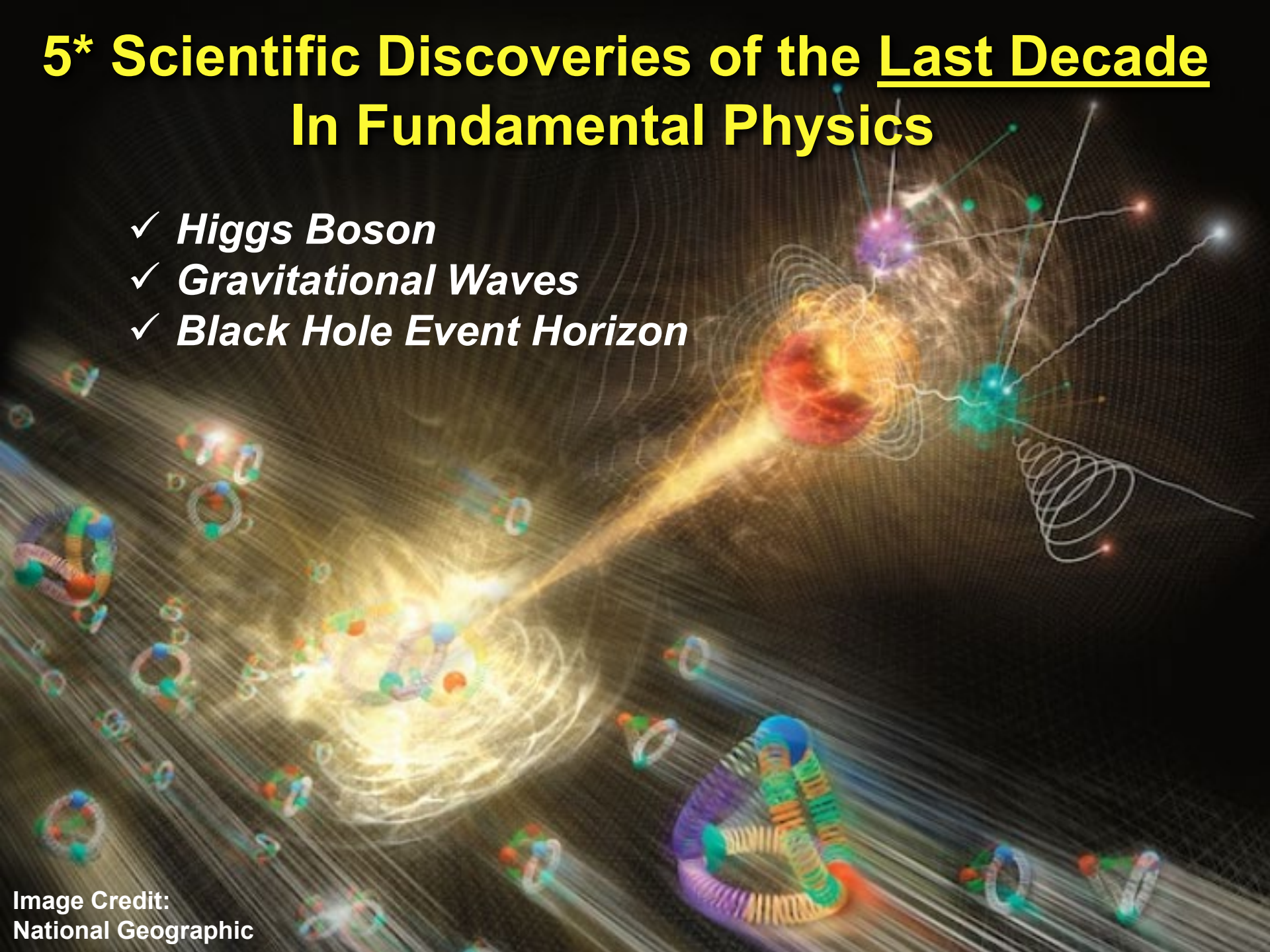


Image Credit:
National Geographic

Gravitational Waves – LIGO Observatory (2016)

M87 Black Hole – Event Horizon Telescope (2019)

What Are We Seeing in This image ?

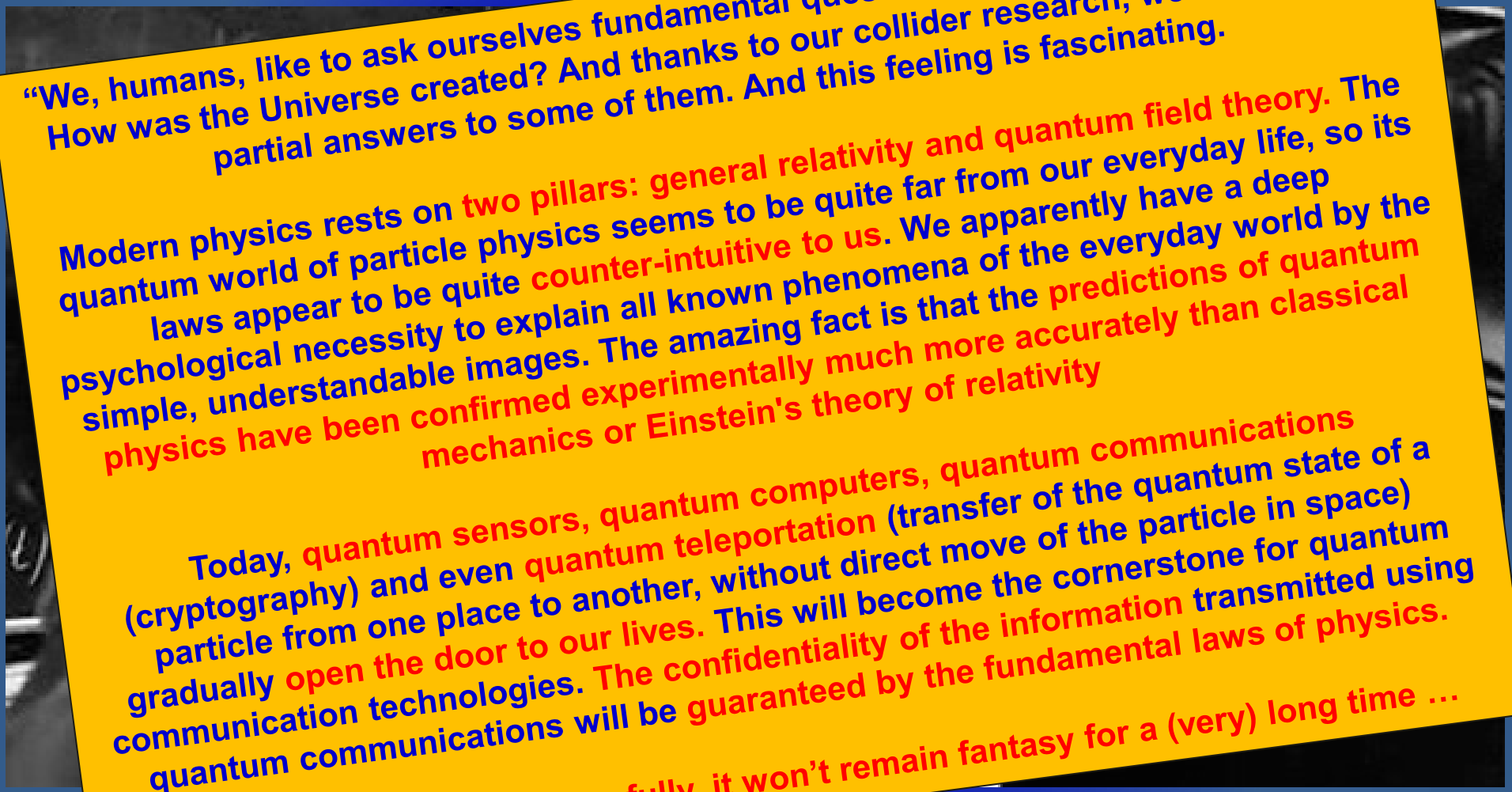
Black Holes are "Where God Divided by Zero!"

- The first **DIRECT** evidence for black holes !!!
- Black holes are **REALLY BLACK**, consistent with GR predictions
- The bright ring comes from emission of the accretion materials

Richard Feymann – The Quantum World of Particle Physics - There's Plenty of Room at the Bottom(1959)

"The principles of quantum physics do not speak against the possibility of maneuvering things atom by atom."

Richard Feymann – The Quantum World of Particle Physics - There's Plenty of Room at th… 59)



"We, humans, like to ask ourselves fundamental questions. Where did we come from? How was the Universe created? And thanks to our collider research, we can provide partial answers to some of them. And this feeling is fascinating.

Modern physics rests on two pillars: general relativity and quantum field theory. The quantum world of particle physics seems to be quite far from our everyday life, so its laws appear to be quite counter-intuitive to us. We apparently have a deep psychological necessity to explain all known phenomena of the everyday world by the simple, understandable images. The amazing fact is that the predictions of quantum physics have been confirmed experimentally much more accurately than classical mechanics or Einstein's theory of relativity

Today, quantum sensors, quantum computers, quantum communications (cryptography) and even quantum teleportation (transfer of the quantum state of a particle from one place to another, without direct move of the particle in space) gradually open the door to our lives. This will become the cornerstone for quantum communication technologies. The confidentiality of the information transmitted using quantum communications will be guaranteed by the fundamental laws of physics.

For now, it's a fantasy... Hopefully, it won't remain fantasy for a (very) long time …

… of quantum physics do not speak against the possibility of maneuvering things atom by atom."

One Day at CERN in 2050 …

THE DAILY TELEGRAPH Monday

The Daily Telegraph

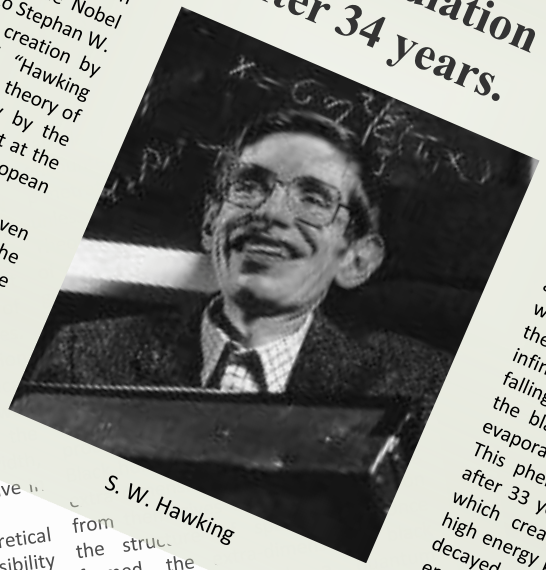
News

Hawking's "luminous" victory!

Stephen Hawking's black hole radiation theory is proven experimentally at CERN after 34 years.

CAMBRIDGE, 17 November: The Sweedish Royal Academy has announced that the Nobel Price in Physics for this year will go to Stephan W. Hawking for his theory of particle creation by black holes, which is also named "Hawking radiation" after its founder. Hawking's theory of black hole decay was proved recently by the famous black hole production experiment at the LArge Hadron Collider (LHC) of CERN (European Center for Nuclear REsearch.

Black holes are such objects from which even light cannot escape. Since lightspeed is the ultimate speed in universe, black holes are objects from which no escape is possible. However this idea was completely changed by a revolutionary paper by Hawking published in 1975 which suggested that black holes could emit radiation via a



S. W. Hawking

complicated quantum mechanical process. Briefly this idea states that spacetime near a black hole is not a classical vacuum. Energy fluctuations near a black hole creates particle-antiparticle pairs among which the antiparticle with negative energy enters the black hole while the particle with positive energy flies off to infinity. Negative energy of the antiparticle falling into the black hole reduces the mass of the black hole, therefore black hole seems to evaporate and emit particles.

This phenomena was finaly observed in CERN after 33 years of its proposal in an experiment which created miniature black holes through high energy proton collisions. These black holes decayed immediately after their production, emitting a spectrum of high multiplicity of particle species.

Who Knows …

The Role of Big High Energy Physics Laboratories, like CERN – innovate, discover, publish, share

… in order to bring the world (a little bit) closer together