

Introduction to Particle Physics (Theory)

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CERN



Particle physics: structure of matter & fundamental forces

Experimental tools: Particle colliders at very high energies \Rightarrow

physical laws of nature at very short distances

- LEP2 (CERN): electron - positron collisions at 200 GeV * $\rightarrow 10^{-17}$ m
- TEVATRON (USA): protons - antiprotons at 2 TeV $\rightarrow 10^{-18}$ m
- LHC (CERN): proton - proton collisions at 14 TeV ** $\rightarrow 10^{-19}$ m

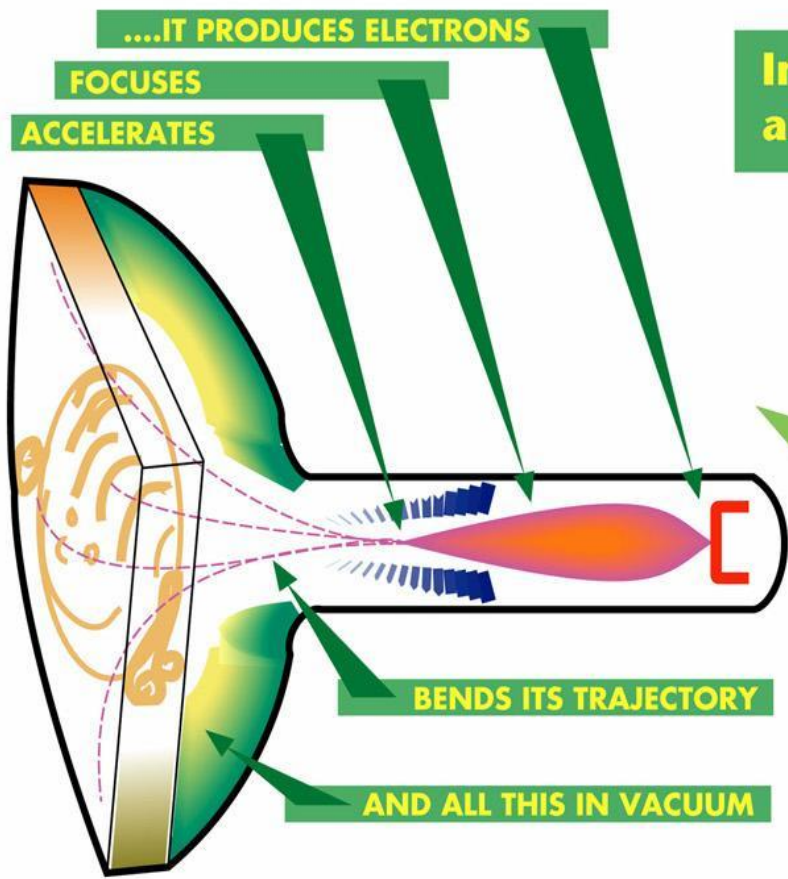
The description: simple mathematical theories with predictive power

encoding the symmetries of physical phenomena

* 1 GeV \simeq proton rest mass ($E = mc^2$) $\rightarrow 10^{-15}$ m

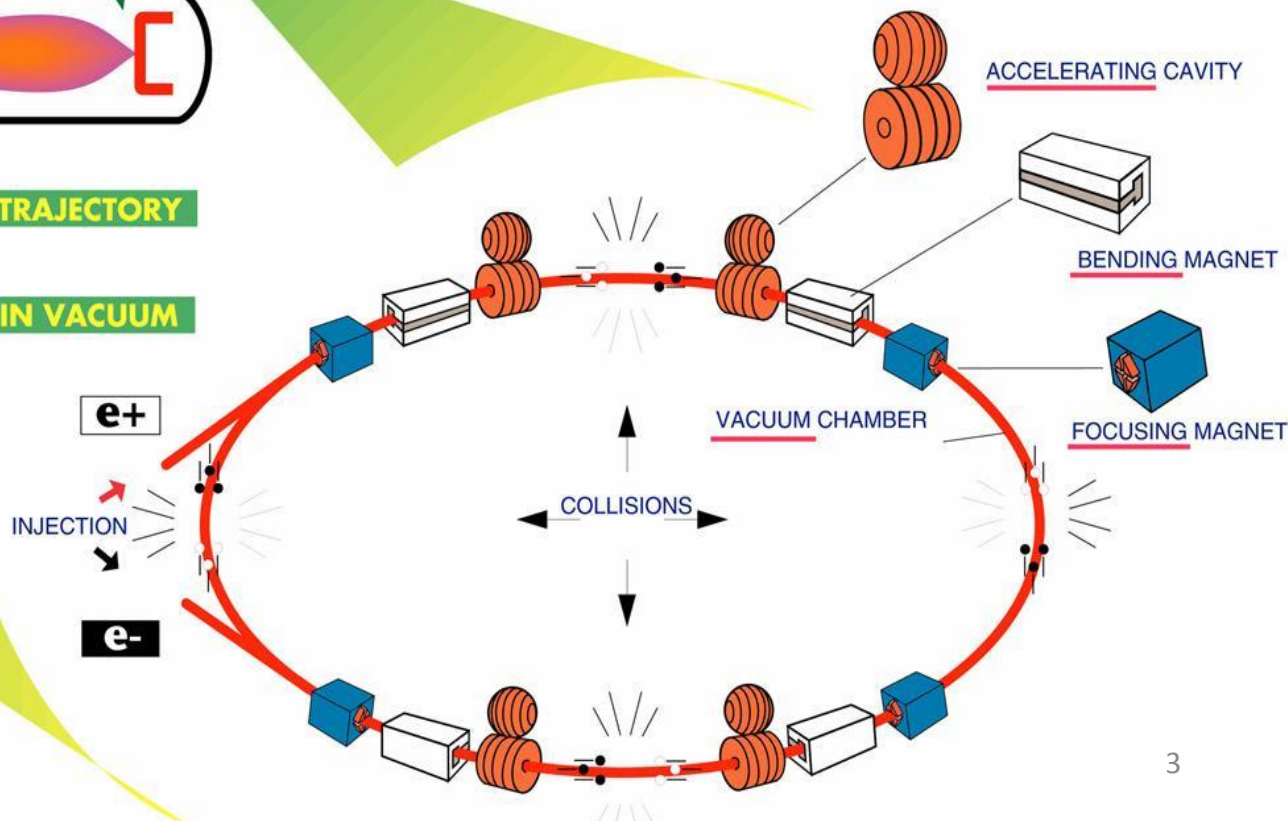
** for the moment 8 TeV 1 TeV = 1000 GeV

DID YOU KNOW YOUR TELEVISION SET IS AN ACCELERATOR ?



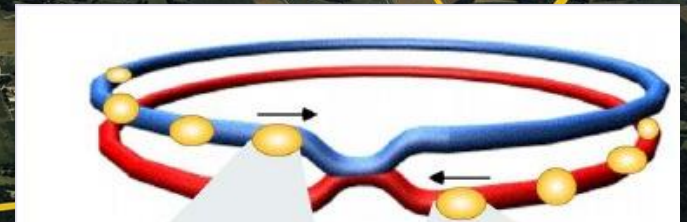
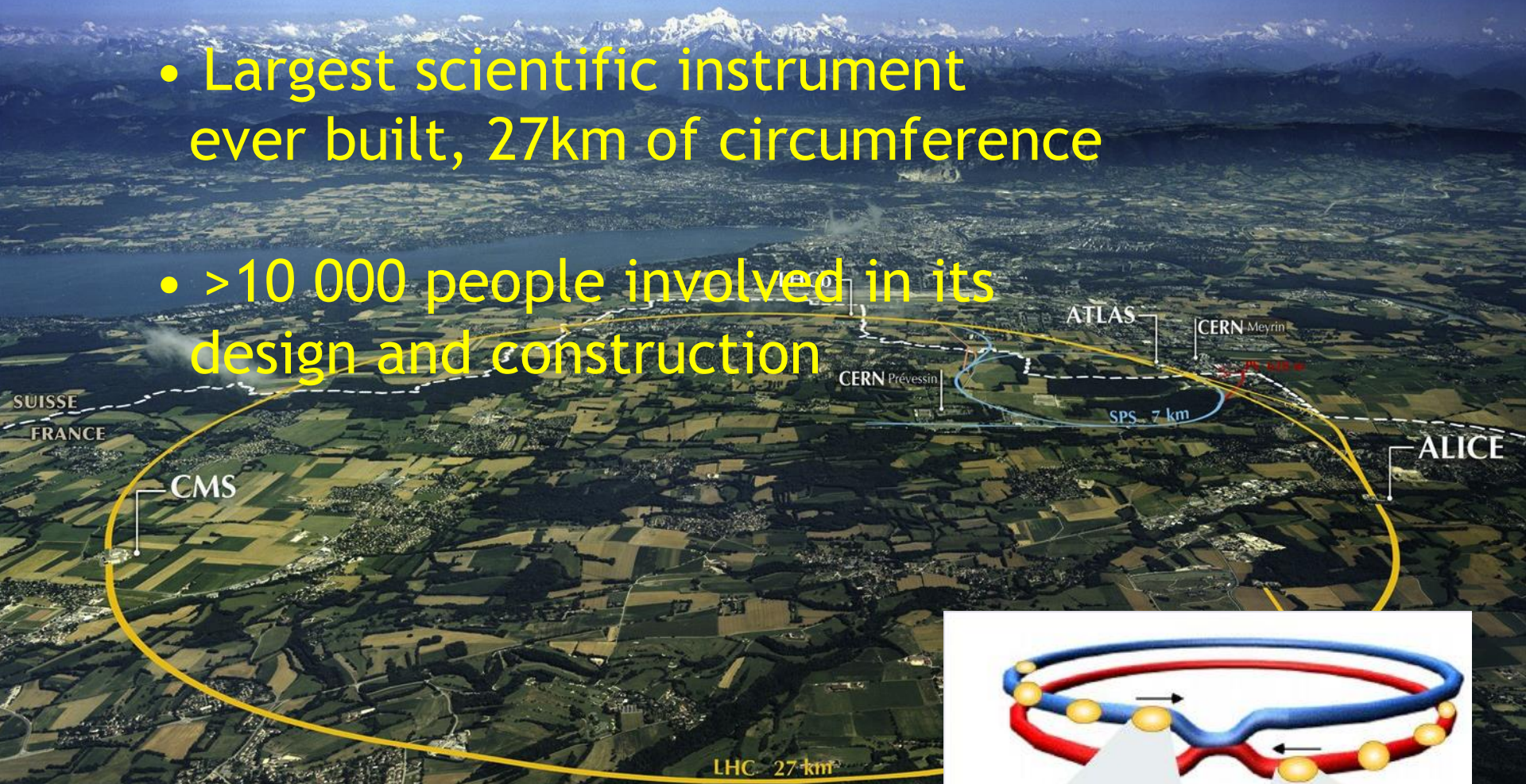
In your TV set, the electrons are accelerated to 20000 volts.

In LEP, they are accelerated to 100 000 000 000 volts.



the Large Hadron Collider (LHC)

- Largest scientific instrument ever built, 27km of circumference
- >10 000 people involved in its design and construction



at



Accelerating Science and Innovation

The LHC is the world's most powerful microscope ...



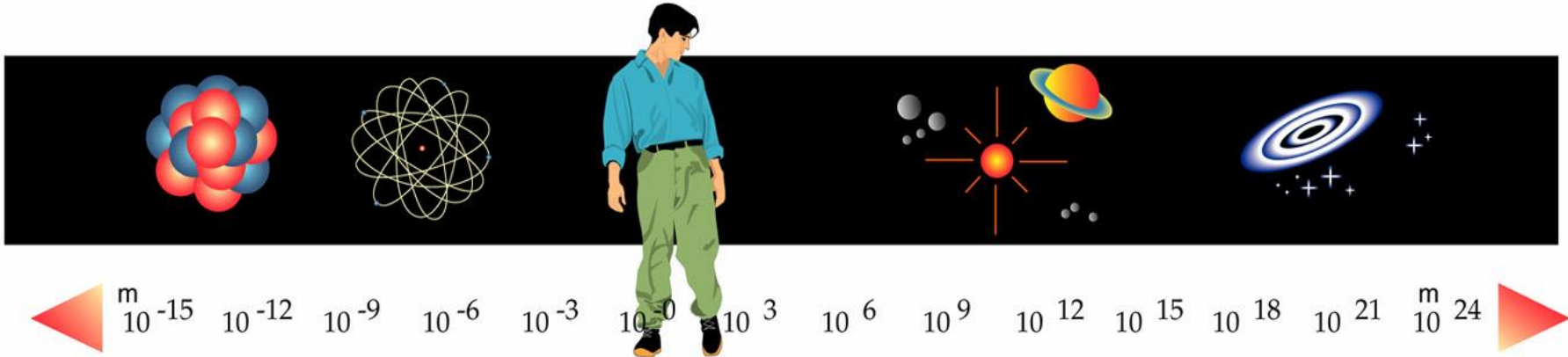
... and also a telescope

La physique des particules étudie la matière dans ses dimensions les plus petites.

Particle physics looks at matter in its smallest dimensions.

L'astrophysique étudie la matière dans ses dimensions les plus grandes.

Astrophysics looks at matter in its largest dimensions.



Microscopes
Microscopes

Jumelles
Binoculars

Telescopes optiques & radio
Optical & radio telescopes

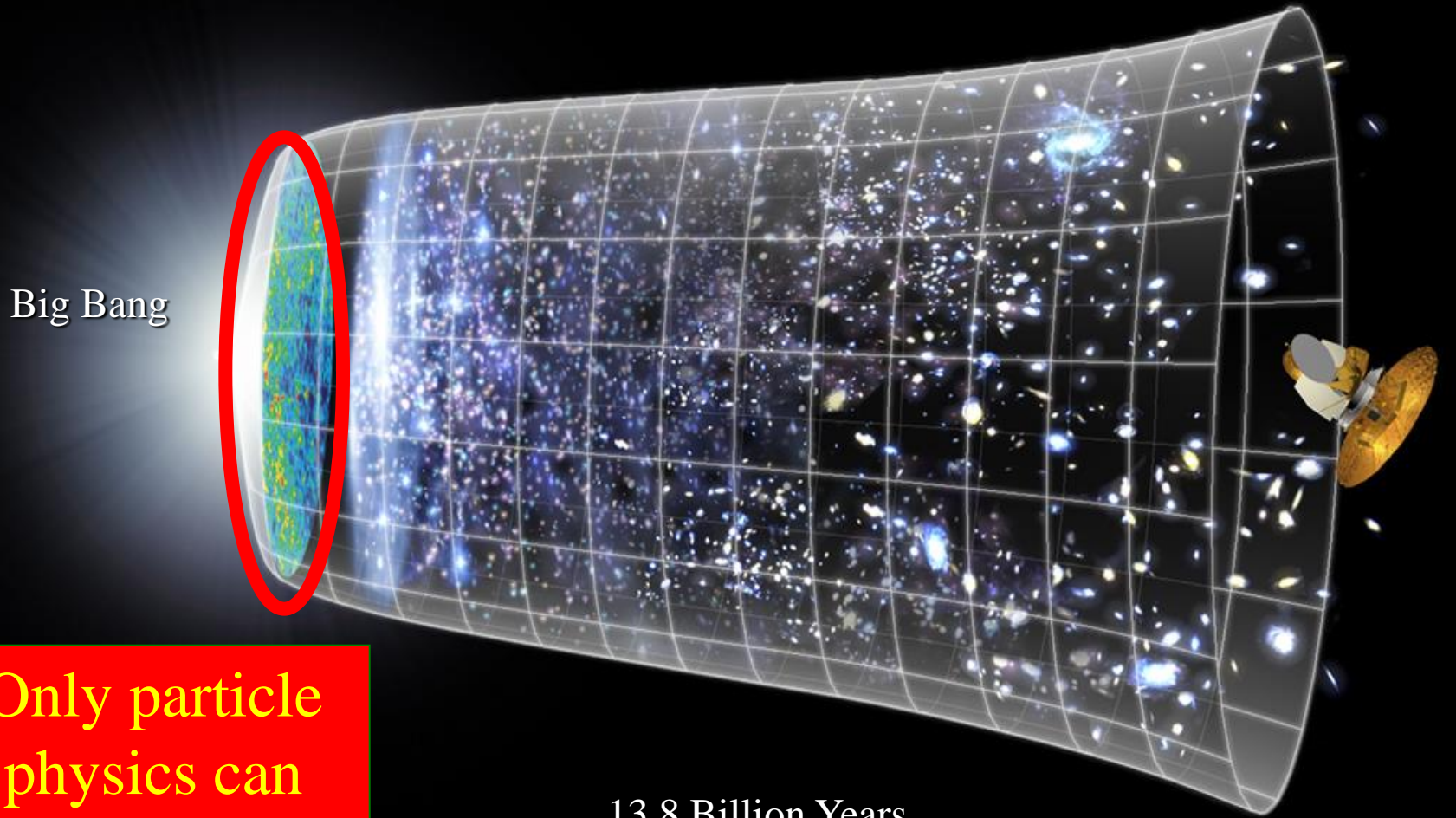
Accélérateurs
et détecteurs
Accelerators
and detectors

L'oeil nu.
Naked eye

THE TWO FRONTIERS OF PHYSICS

LES DEUX FRONTIÈRES DE LA PHYSIQUE

Evolution of the Universe



Big Bang

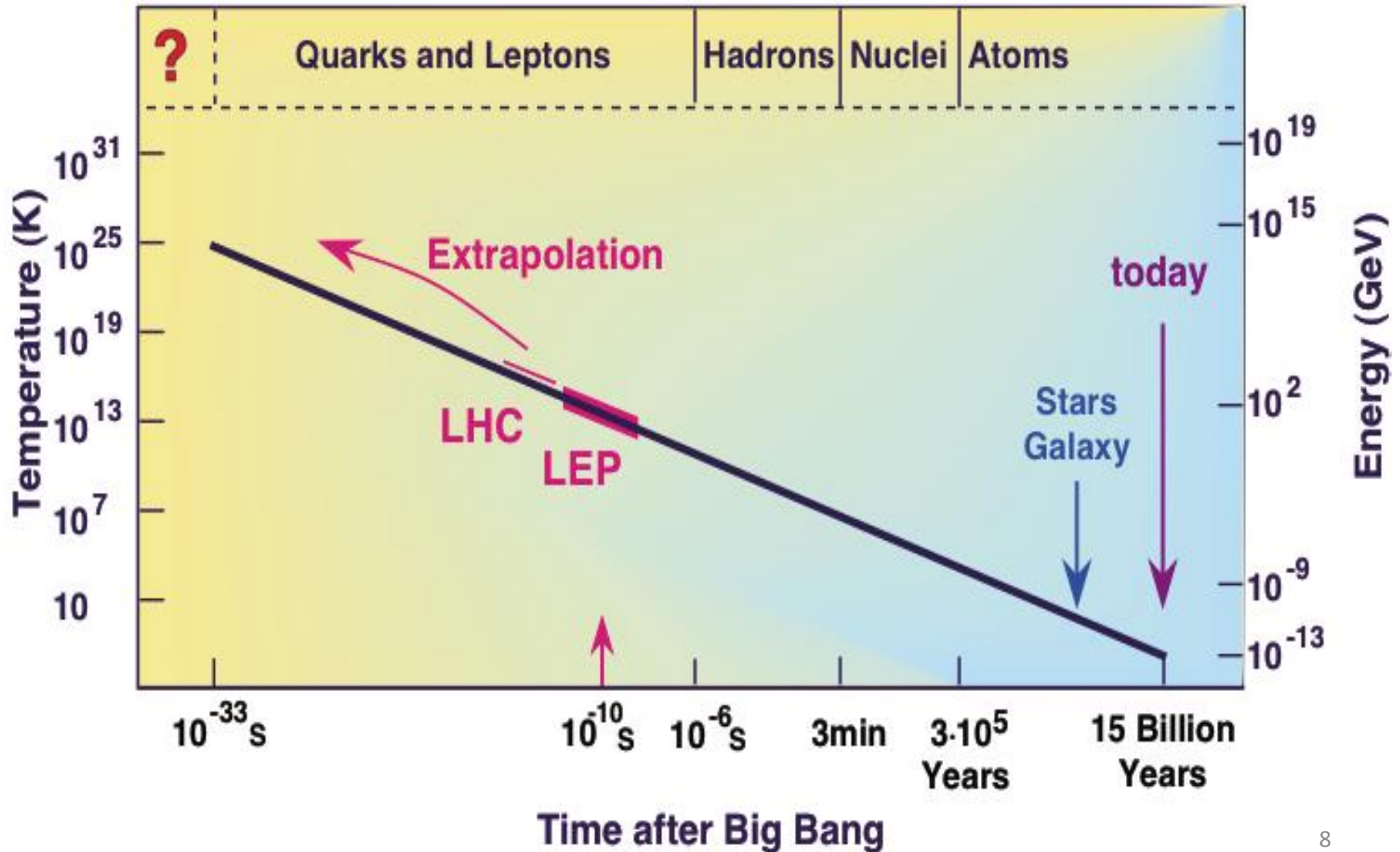
Today

13.8 Billion Years

10^{28} cm

Only particle physics can tell us what happened here

Evolution of the Universe



Major discoveries → fundamental constants

- Thermodynamics : $E = k_B T$

k_B = Boltzmann constant

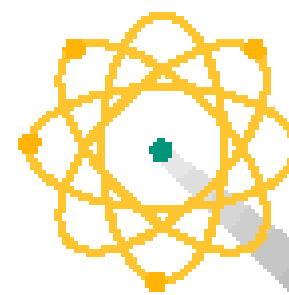
- Special relativity : $E = mc^2$

c = speed of light

- Quantum mechanics : $L \geq h/E$

h = Planck constant

Inside Matter



atoms have electrons ...



orbiting a nucleus ...

which is made of protons ...



... and neutrons

which are made of quarks, up-quarks and down-quarks ...



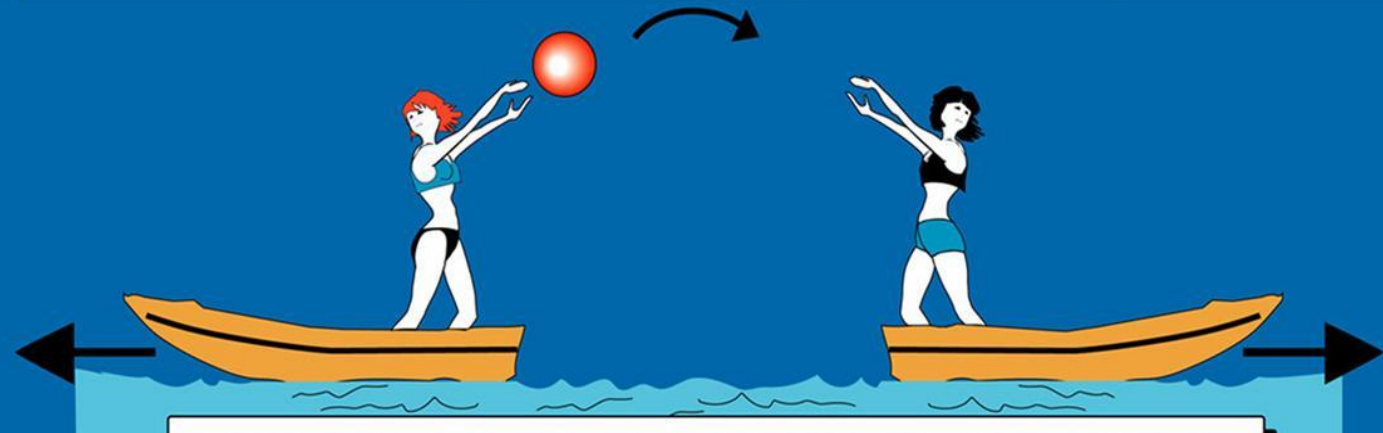
which are at the current limit of our knowledge

All matter is made of the same constituents

What are they?
What forces between them?

The forces in Nature

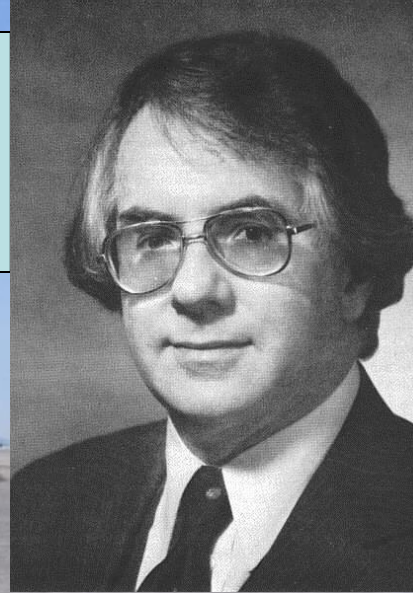
TYPE	INTENSITY OF FORCES (DECREASING ORDER)	BINDING PARTICLE (FIELD QUANTUM)	OCCURS IN :
STRONG NUCLEAR FORCE	~ 1	GLUONS (NO MASS)	ATOMIC NUCLEUS
ELECTRO -MAGNETIC FORCE	$\sim 10^{-3}$	PHOTONS (NO MASS)	ATOMIC SHELL ELECTROTECHNIQUE
WEAK NUCLEAR FORCE	$\sim 10^{-5}$	BOSONS Z^0, W^+, W^- (HEAVY)	RADIOACTIVE BETA DESINTEGRATION
GRAVITATION	$\sim 10^{-38}$	GRAVITONS (?)	HEAVENLY BODIES



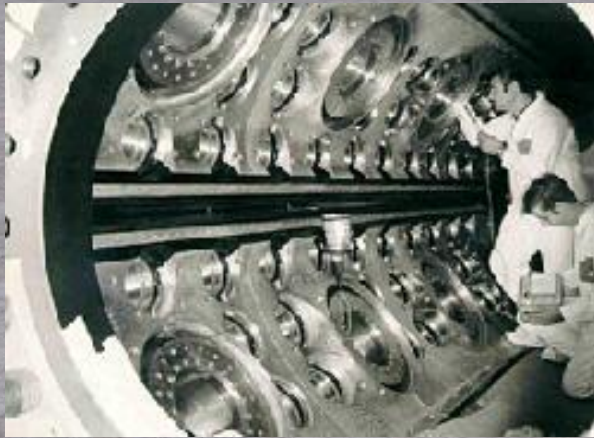
THE EXCHANGE OF PARTICLES IS RESPONSIBLE FOR THE FORCE

The 'Standard Model' of Particle Physics

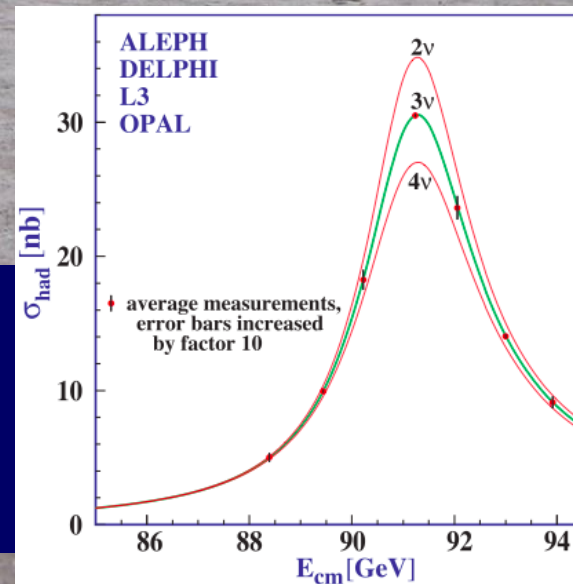
Proposed by Glashow,
Salam and Weinberg



Tested by experiments
at CERN



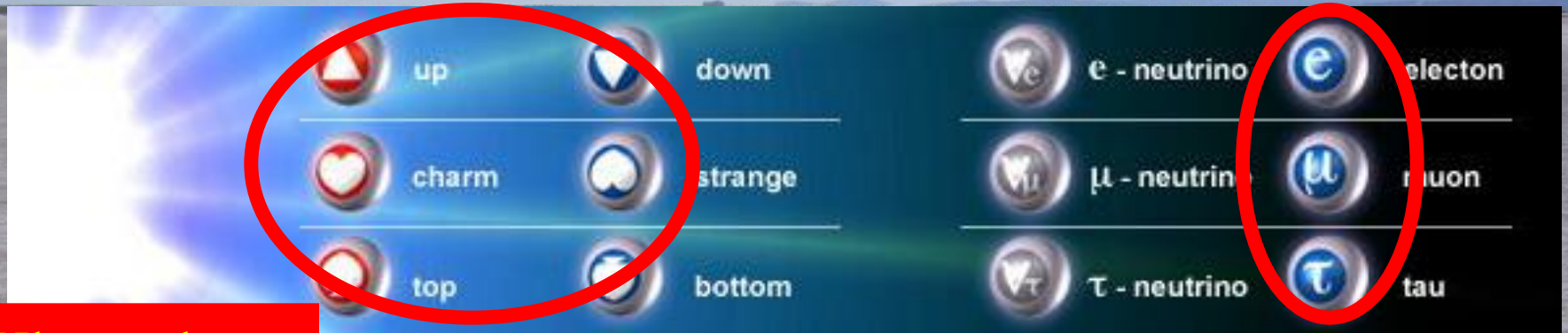
Perfect agreement between
theory and experiments
in all laboratories



The 'Standard Model'

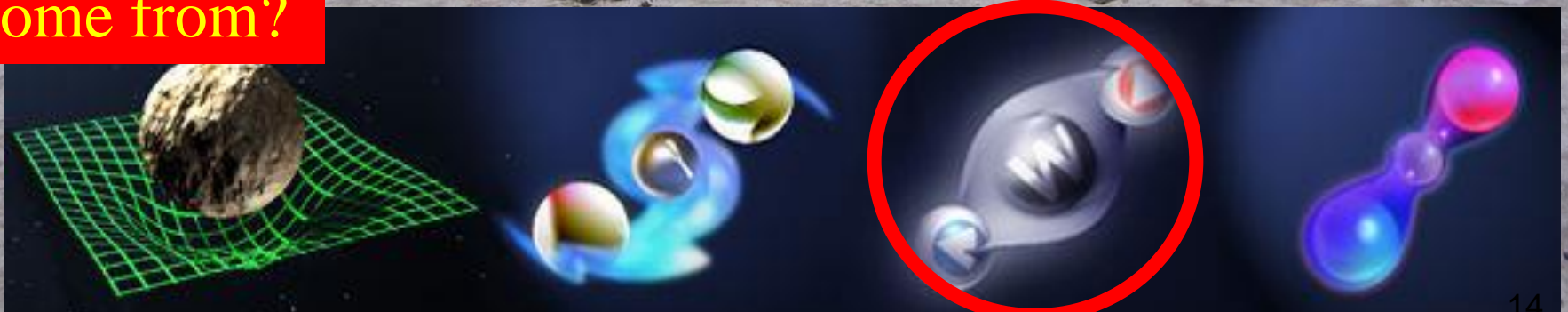
= Cosmic DNA

The matter particles : quarks and leptons



Where does mass come from?

The fundamental interactions



Gravitation

electromagnetism

weak nuclear force

strong nuclear force

The Standard Model of Particle Physics :

electro-weak + strong forces

- Quantum Field Theory : Quantum Mechanics + Special Relativity
- Symmetry principle : gauge invariance

Very accurate description of physics at present energies

17 parameters

Several Nobel Prizes :

- Theory Glashow, Salam, Weinberg 79
- Discovery of W^\pm , Z at CERN Rubbia, Van Der Meer 84
- Theoretical consistency t'Hooft, Veltman 99
- Asymptotic freedom of strong force Gross, Politzer, Wilczek 04

Electroweak Symmetry

Leptons

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}$$

$$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$$

Quarks

$$\begin{pmatrix} u \\ d \end{pmatrix}$$

s

particles in pairs

Electroweak Symmetry

Leptons

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}$$

$$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$$

Quarks

$$\begin{pmatrix} u \\ d \end{pmatrix}$$

$$\begin{pmatrix} c \\ s \end{pmatrix}$$

particles in pairs

discovery of the 4th quark

Glashow-Iliopoulos-Miani 1974

Richter-Ting Nobel Prize 1976

also Quantum Chromodynamics \Rightarrow quarks in three 'colors'

$$\text{e.g.: } u \rightarrow (u, u, u)$$

Open Questions within & beyond the Standard Model

- What is the origin of particle masses?
due to a Higgs boson? LHC
- Why so many types of matter particles? LHC
- What is the dark matter in the Universe? LHC
- Unification of fundamental forces? LHC
- Quantum theory of gravity? LHC

To answer these questions:

The Large Hadron Collider (LHC)

Several thousand billion protons
Each with the energy of a fly
99.9999991% of light speed
Orbit 27km ring 11 000 times/second
A billion collisions a second

Primary targets:

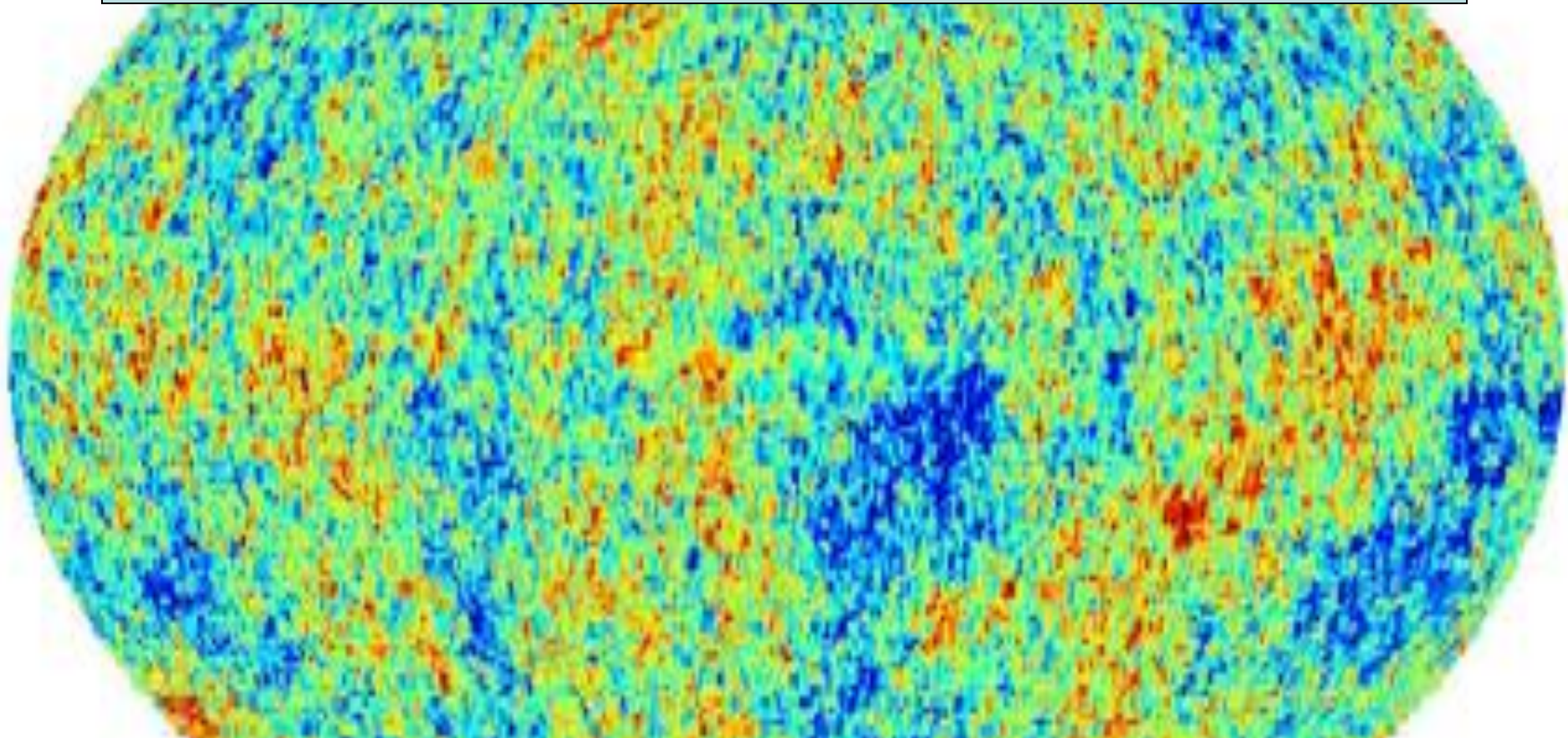
- Origin of mass
- Nature of Dark Matter
- Primordial Plasma
- Matter vs Antimatter

The Emptiest Space in the Solar System

A photograph of a long, brightly lit tunnel, likely a particle accelerator. The tunnel is filled with various pipes, machinery, and structural elements. The lighting is warm and focused, highlighting the metallic surfaces and the complex arrangement of equipment. The perspective is from the end of the tunnel, looking down its length.

Vacuum similar to interplanetary space:
the pressure in the beam-pipes are ten
times lower than on the Moon.


Cooler than Outer space



LHC 1.9 degrees above absolute zero = - 271 C

Outer space 2.7 degrees above zero = - 270 C

The Hottest Place in the Galaxy



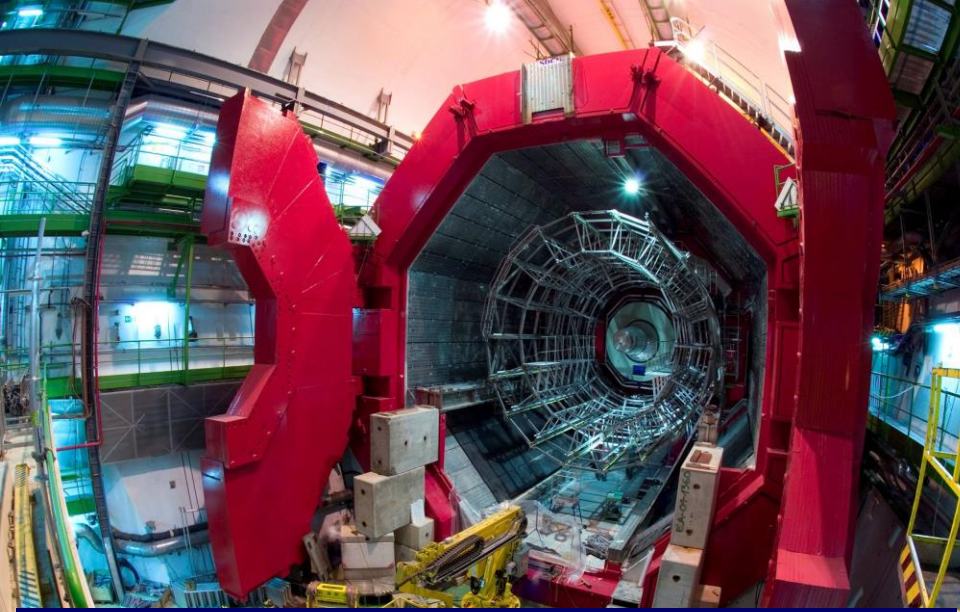
Particle collisions create
(within a tiny volume)
temperatures a billion times higher than in
the heart of the Sun

Enter a New Era in Fundamental Science

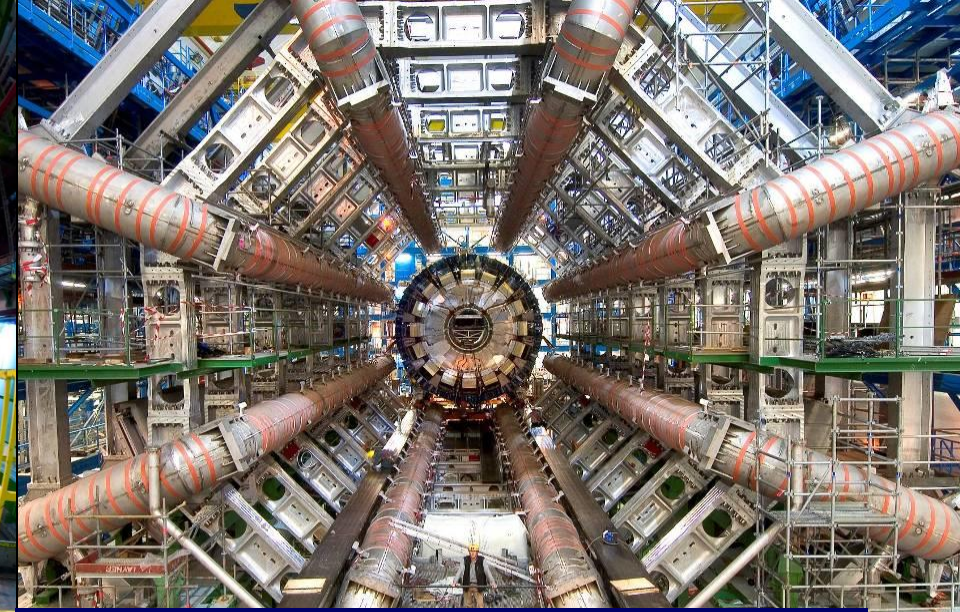


Exploration of a new energy frontier
in p-p and Pb-Pb collisions

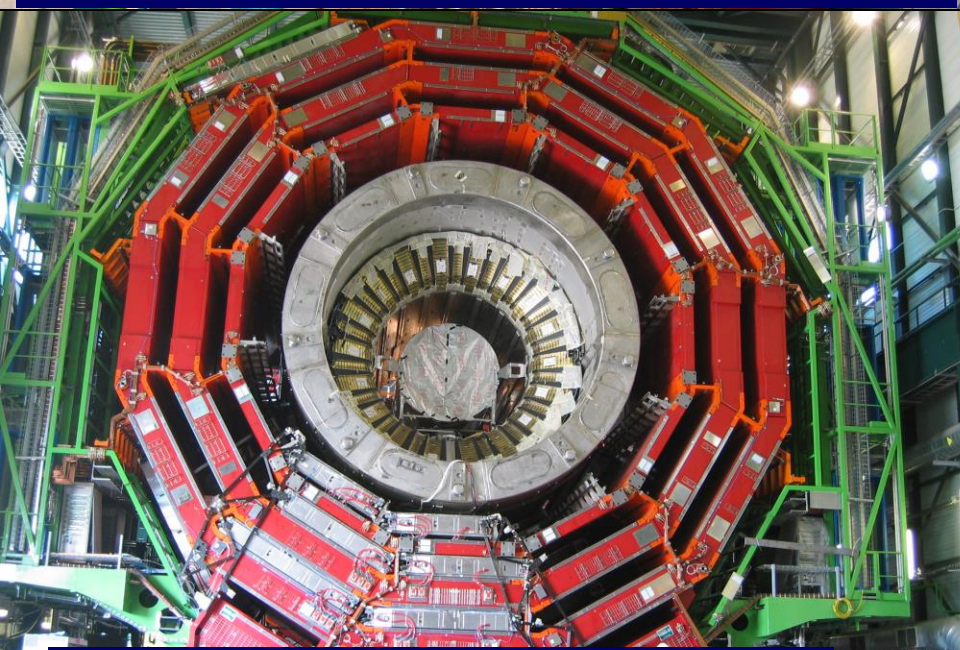




ALICE: Primordial cosmic plasma



ATLAS: Higgs and dark matter



CMS: Higgs and dark matter



LHCb: Matter-antimatter difference

Why do Things Weigh?

Newton:

Weight **proportional to** Mass

Einstein:

Energy **related to** Mass

Neither explained origin of Mass

Where do the masses
come from?

Are masses due to Higgs boson?

Brout-Englert Higgs mechanism 1964



Think of a Snowfield



Skier moves fast:

Like particle without mass

e.g., photon = particle of light

Snowshoer sinks into snow,
moves slower:

Like particle with mass

e.g., electron



Hiker sinks deep,
moves very slowly:

Particle with large mass



**The LHC looks for
the snowflake:
The Higgs Boson**

Without Higgs ...

... there would be no atoms

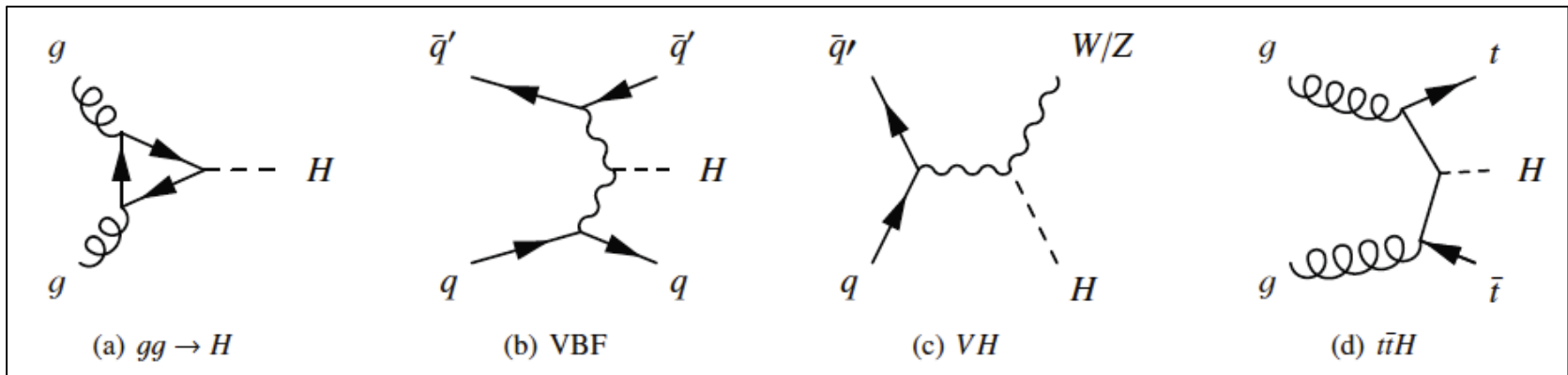
- Electrons would escape at the speed of light

... weak interactions would not be weak

- Life would be impossible: everything would be radioactive

Its existence is a big deal!

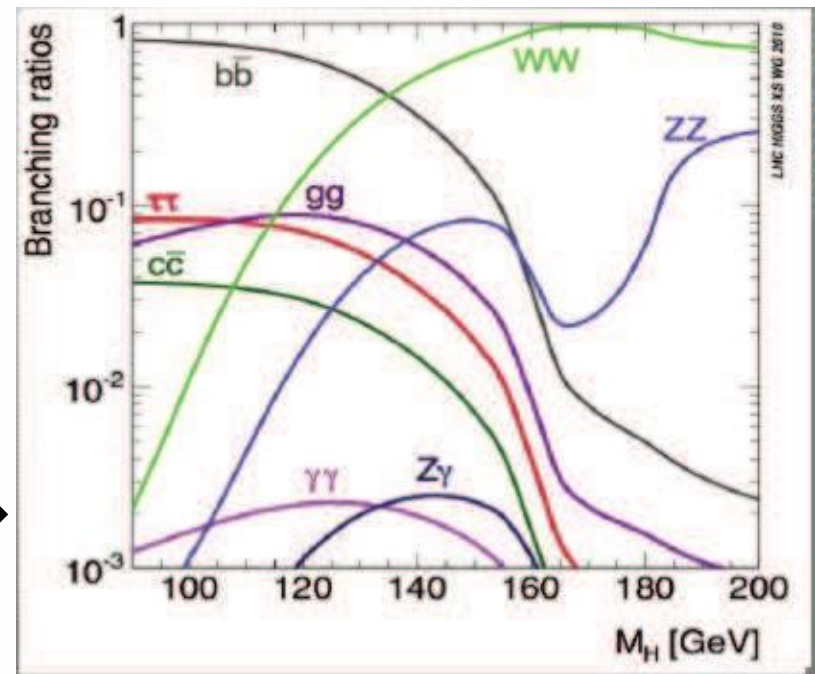
Search for the Higgs-Boson at the LHC



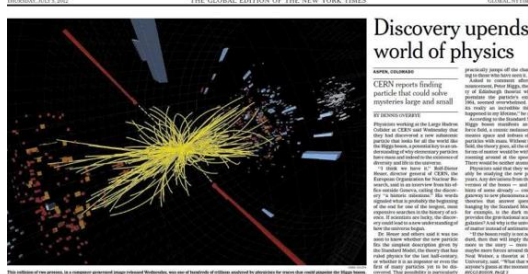
- Gluon fusion
- Vector Boson fusion
- Associated



Analyze : (production modes)
x (decay possibilities) →



July 4th 2012
The discovery of a new particle



Discovery upends world of physics

CERN reports finding particle that could solve mysteries large and small



ヒッグス粒子発見か
新素粒子検出 年内に結論
日米欧2チーム

Le Monde newspaper snippet: Science: la matière dévoilée. Le boson de Higgs, particule manquante pour expliquer l'Univers, vient d'être découvert.

Frankfurter Allgemeine newspaper snippet: Masse macht's. Die Teilchenphysiker haben die Existenz eines neuen Teilchens bestätigt.

The Gazette newspaper snippet: The particle discovery has scientists giddy. Page A2.

MK newspaper snippet: ПОСЛЕДНИЙ КИРПИЧ В СТЕНУ МИРОЗДАНИЯ. «КРЕМЛЕВСКИЕ» САМОЛЕТЫ ПРИШЛОСЬ МЕНЯТЬ НА ПЕРЕГРABE.

AD ALGEMEEN DAGBLAD newspaper snippet: Eindelijk belijk na 48 jaar. Zieke Kaj en zijn moeder toch samen in de VS.

Frankfurter Allgemeine newspaper snippet: Große Mehrheit im Bundestag. Die Bundestag hat sich für die Einführung der Ehe für alle entschieden.

CHINA DAILY newspaper snippet: Fallada la partícula clave para a comprensión del universo. Iron Man film company looks to China for screen success.

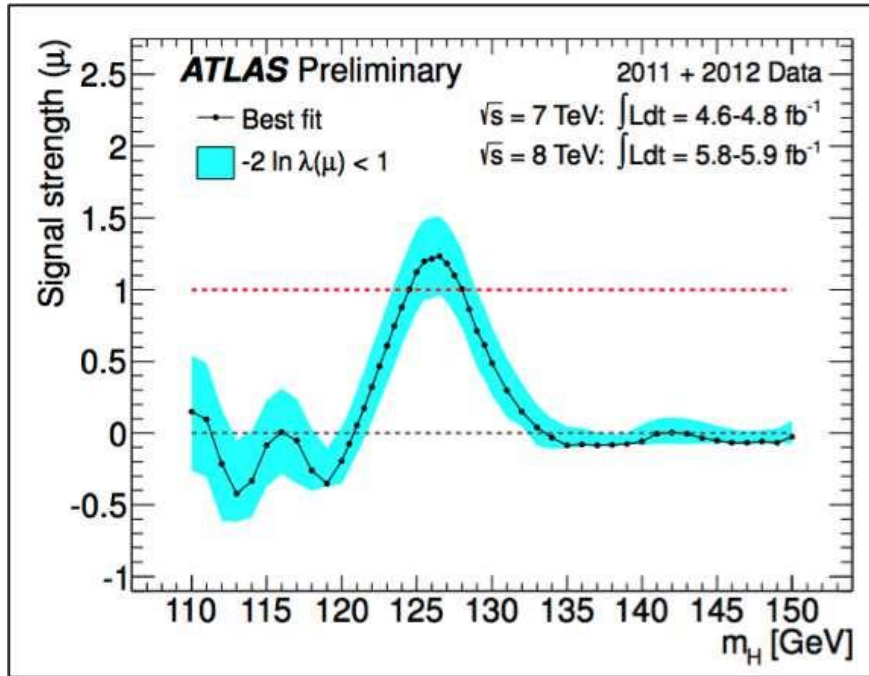
THE HINDU newspaper snippet: Elusive particle found, looks like Higgs boson. CERN physicists hail evidence of game-changing discovery of subatomic particle.

CORRIERE DELLA SERA newspaper snippet: La particella che può svelare i segreti dell'universo. Scoperto al Cern di Ginevra il bosone di Higgs, in attesa di prove che ne parli di 40 anni fa.

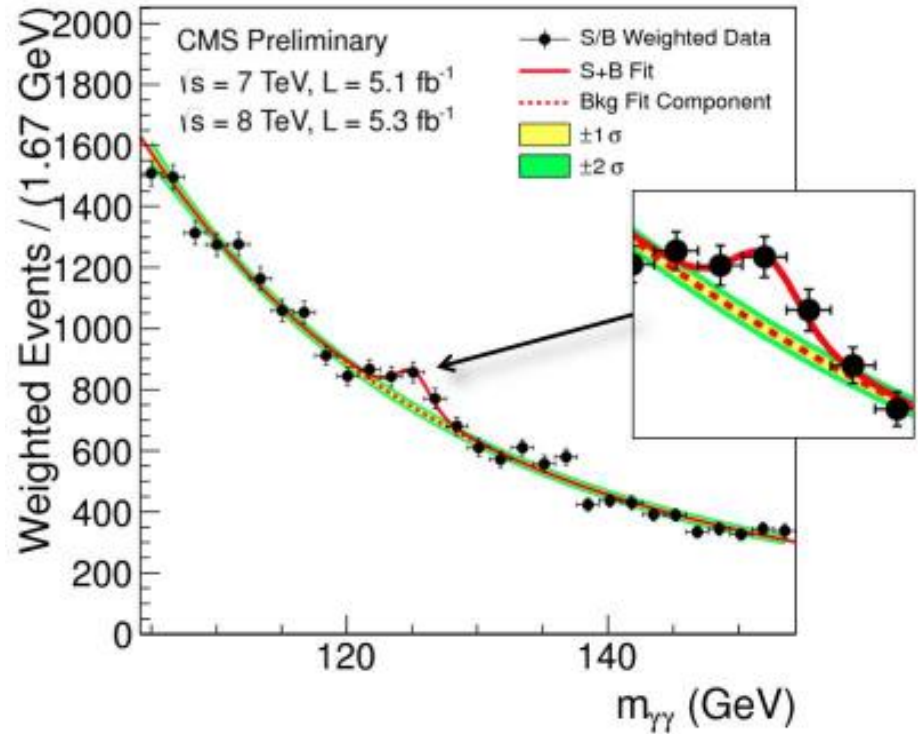
gazeta newspaper snippet: Cząstke Higgsa fizycy najpierw wymyślił, potem szukali 40 lat. Boska masa. Pytanie odżyło iważ jut nigdy nie będzie tańd same.

বিশ্বনাের 'স্বশ্বর' দর্শন. আনন্দবাজার পত্রিকা. সত্যেন্দ্রনাথকে বিনস প্রণাম.

Higgs Boson discovery at the LHC

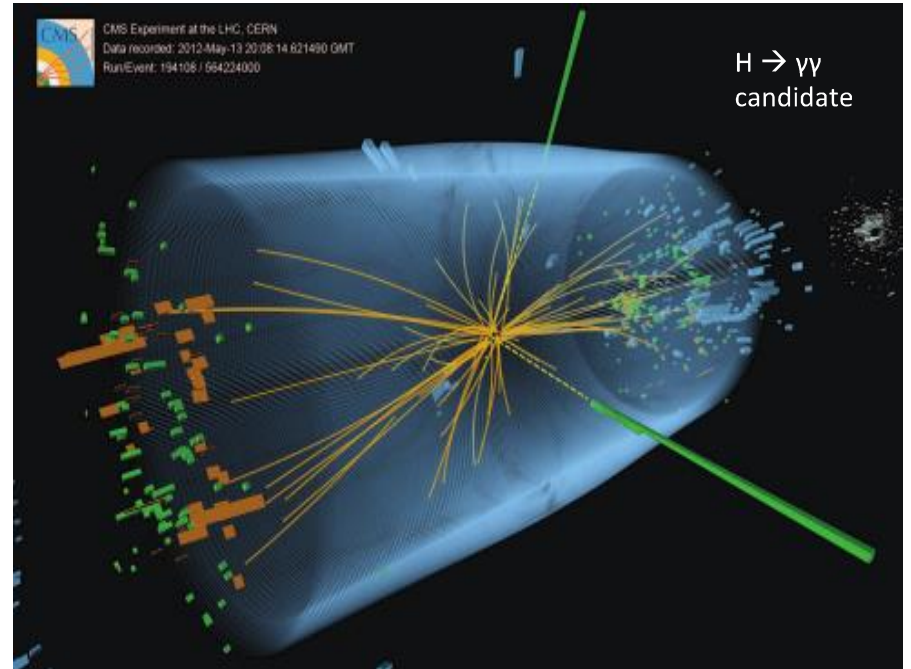
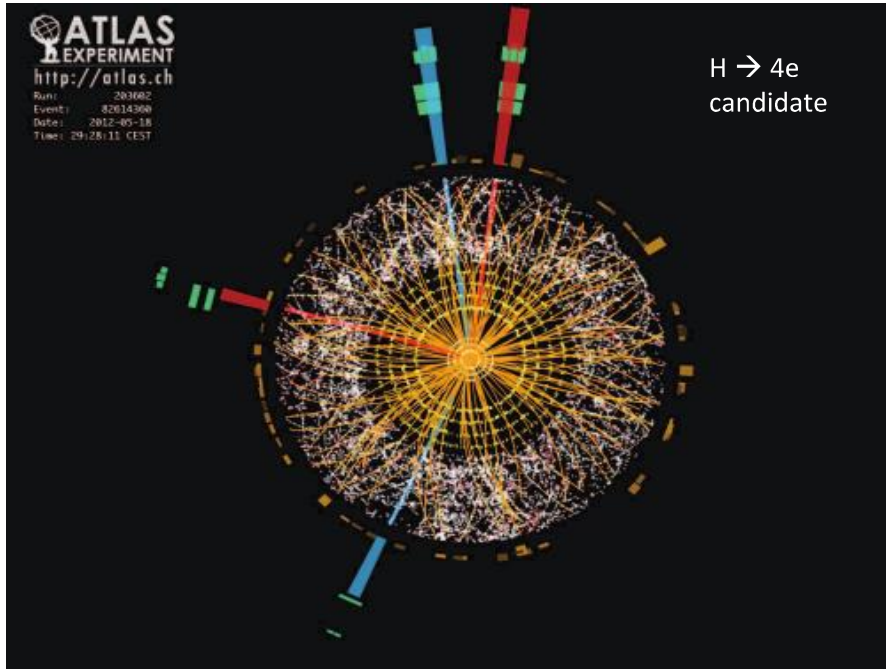


$$m_H = 125.5 \pm 0.2 \text{ (stat.)} \pm 0.5 \text{ (syst.)}$$



$$m_H = 125.7 \pm 0.3 \pm 0.3 \text{ GeV}$$

Possible Higgs boson events



The Particle Higgsaw Puzzle

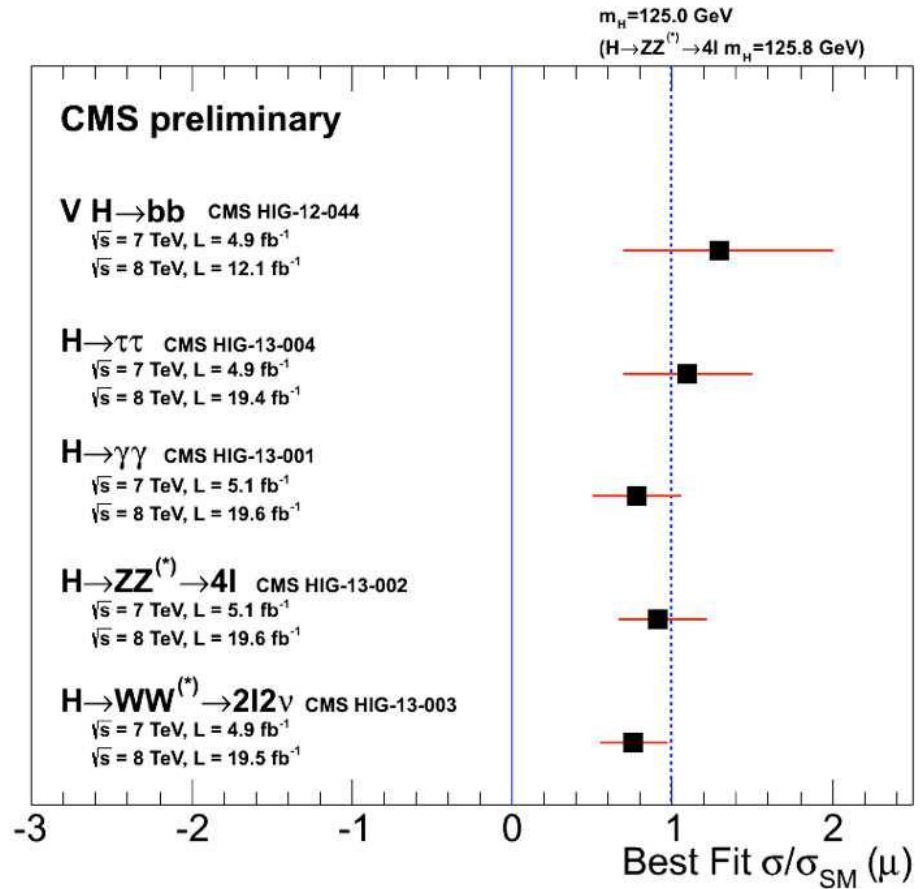
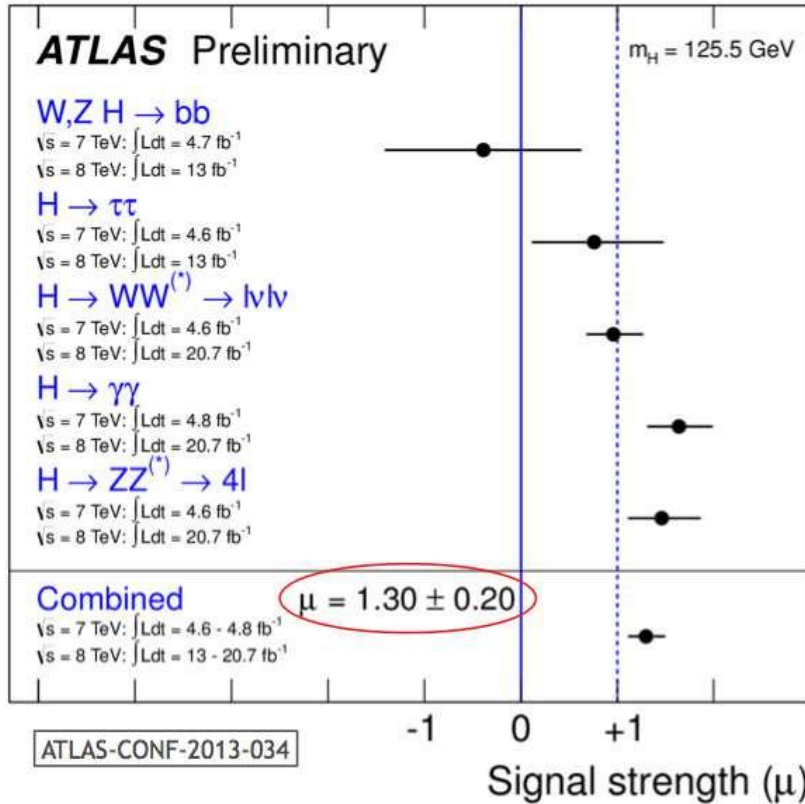
A 3D rendering of a puzzle with one piece missing, set against a background of a blue grid with wavy lines. The missing piece is a light blue color, while the surrounding pieces are a darker blue. The puzzle is centered in the image.

Is LHC finding the missing piece?

Is it the right shape?

Is it the right size?

Couplings of the new boson vs SM Higgs



- Agreement with Standard Model Higgs expectation at 1.5σ
- Measurement of its properties and decay rates currently under way

François Englert

Peter Higgs



Open Questions within & beyond the Standard Model

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- What is the dark matter in the Universe? LHC
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How do Matter and Antimatter Differ?

Dirac predicted the existence of antimatter:

same mass

opposite internal properties:

electric charge, ...

Discovered in cosmic rays

Studied using accelerators



Matter and antimatter not quite equal and opposite: WHY?

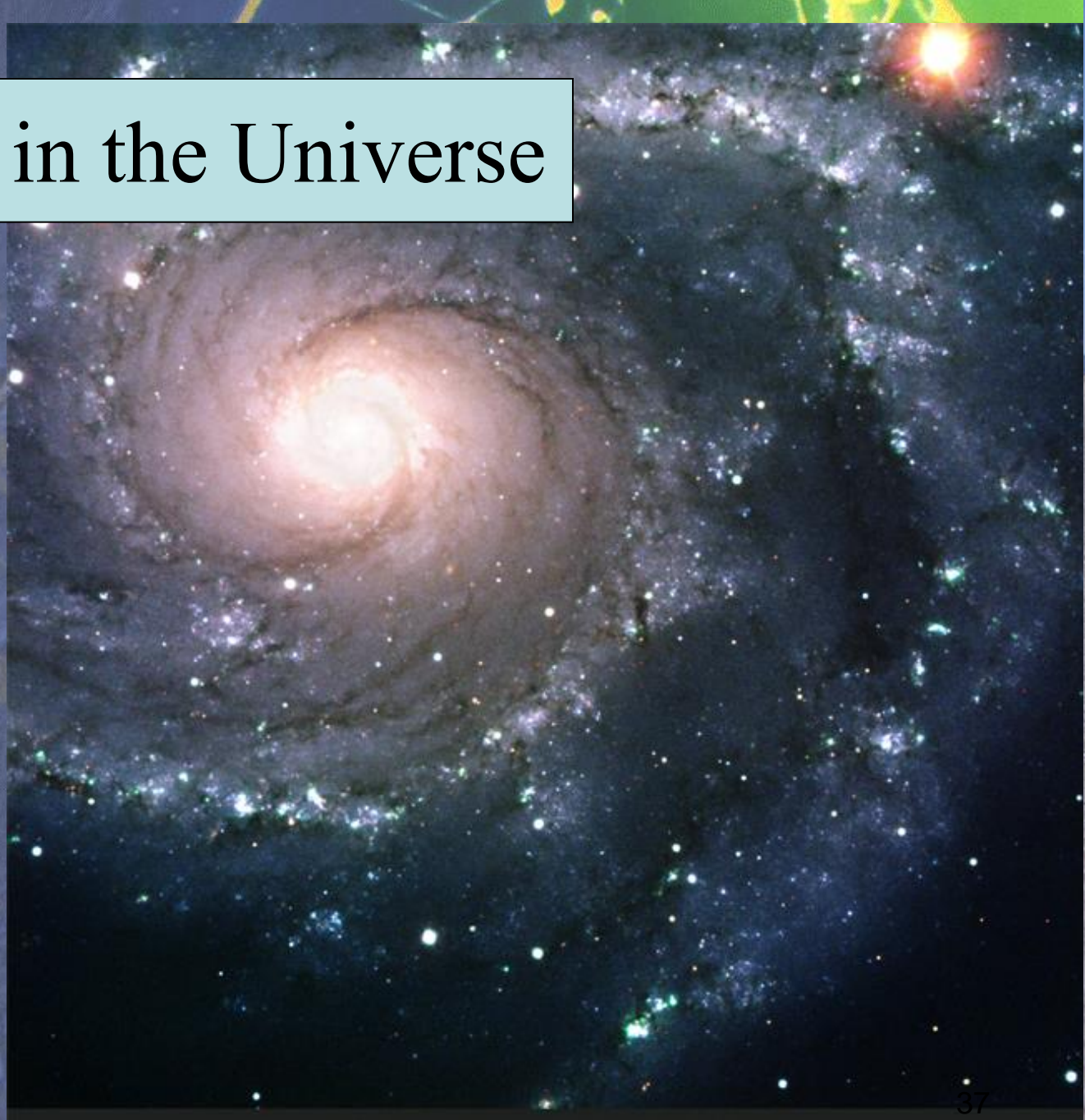
Why does the Universe mainly contain matter, not antimatter?

Experiments at LHC and elsewhere looking for answers

Dark Matter in the Universe

Astronomers say
that most of the
matter in the
Universe is
invisible
Dark Matter

**We will look for it
with the LHC**

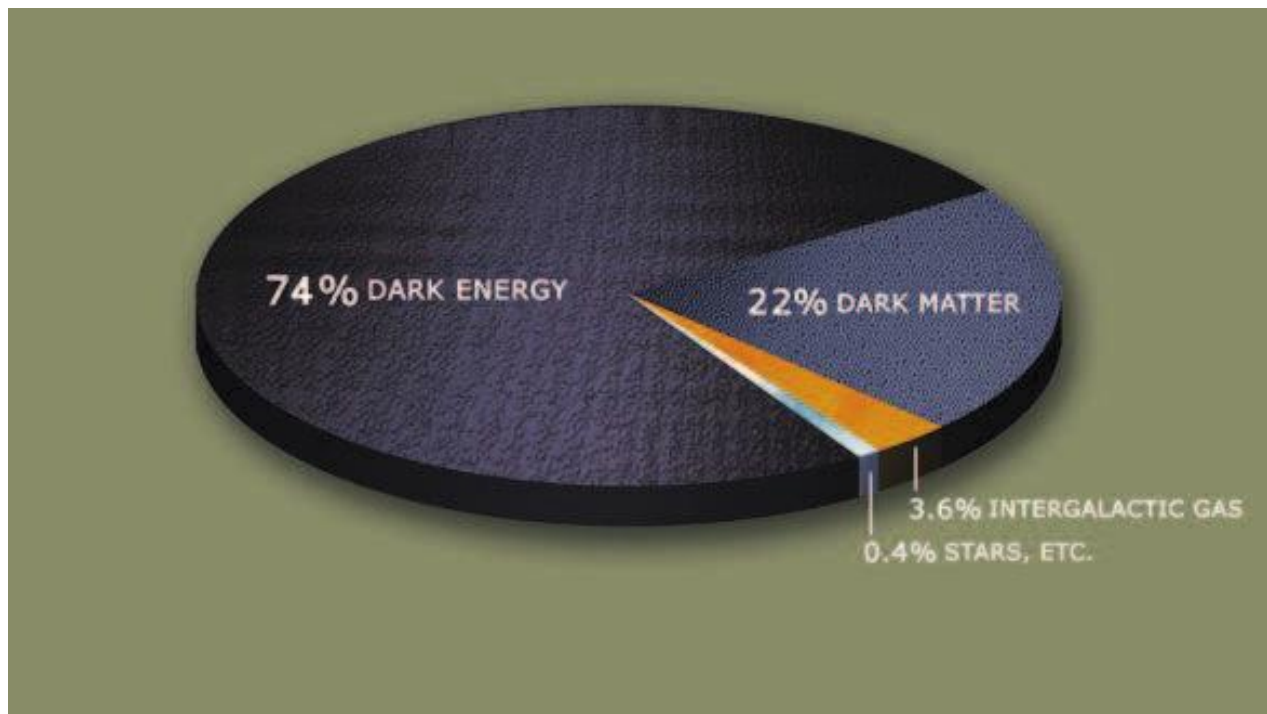


What our Universe is made of ?

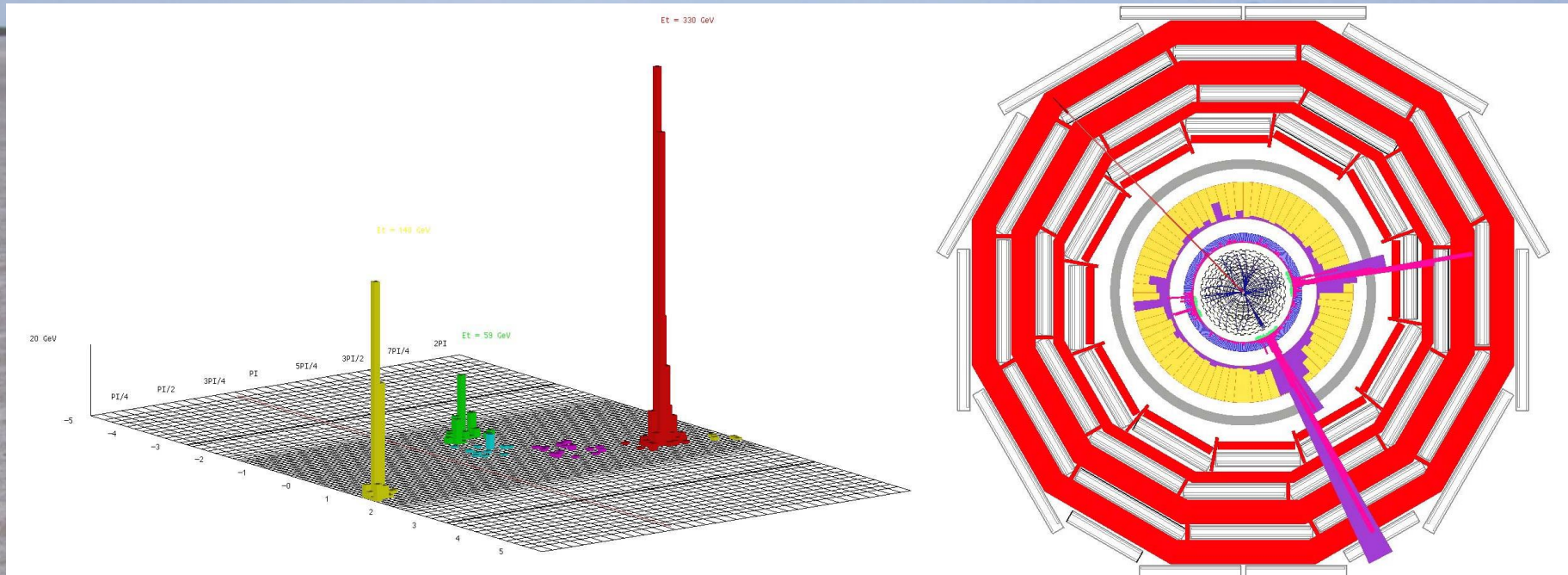
- Ordinary matter: only a tiny fraction
- Non-luminous (dark) matter: $\sim 25\%$

Natural explanation: new stable Weakly Interacting Massive Particle
in the LHC energy region

- Unknown relativistic dark energy: $\sim 70\%$

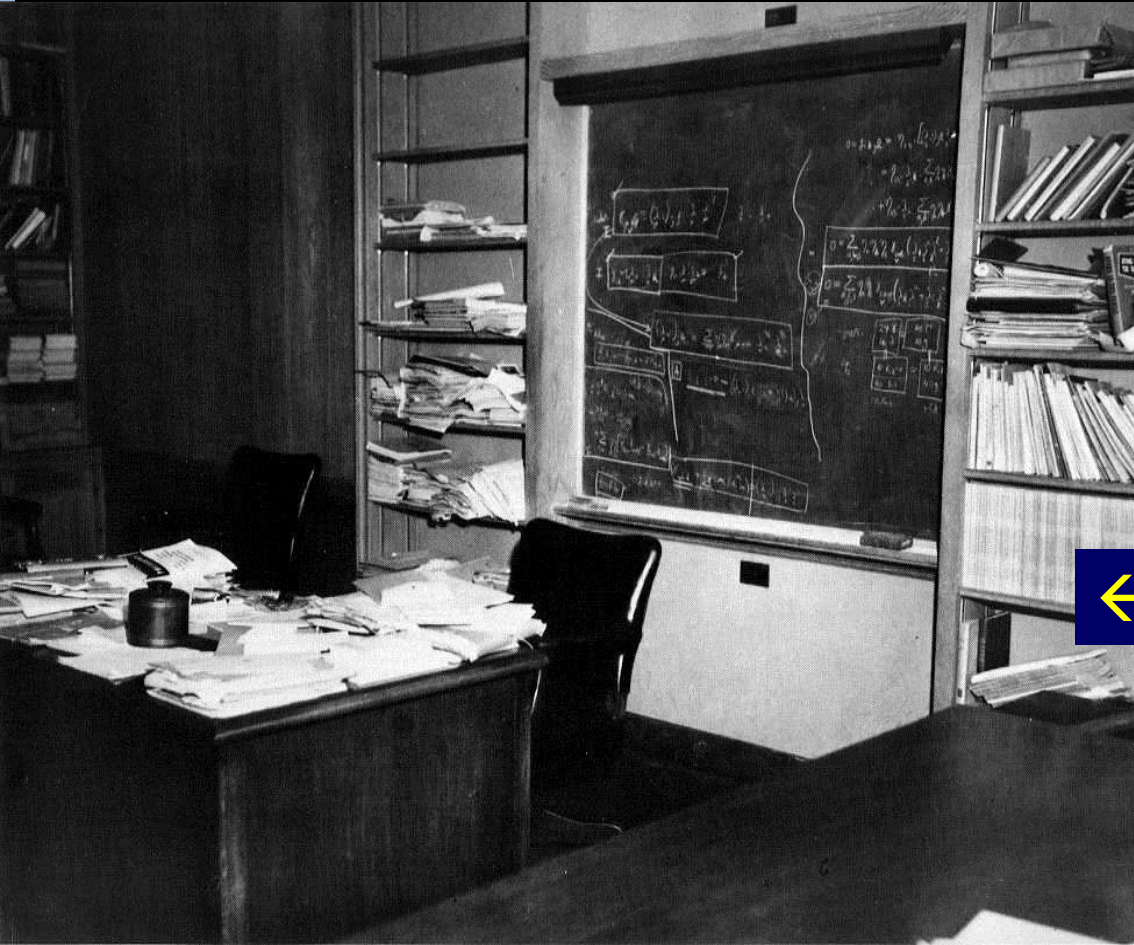


Classic Dark Matter Signature



Missing transverse energy
carried away by dark matter particles

Unify the Fundamental Interactions: Einstein's Dream ...



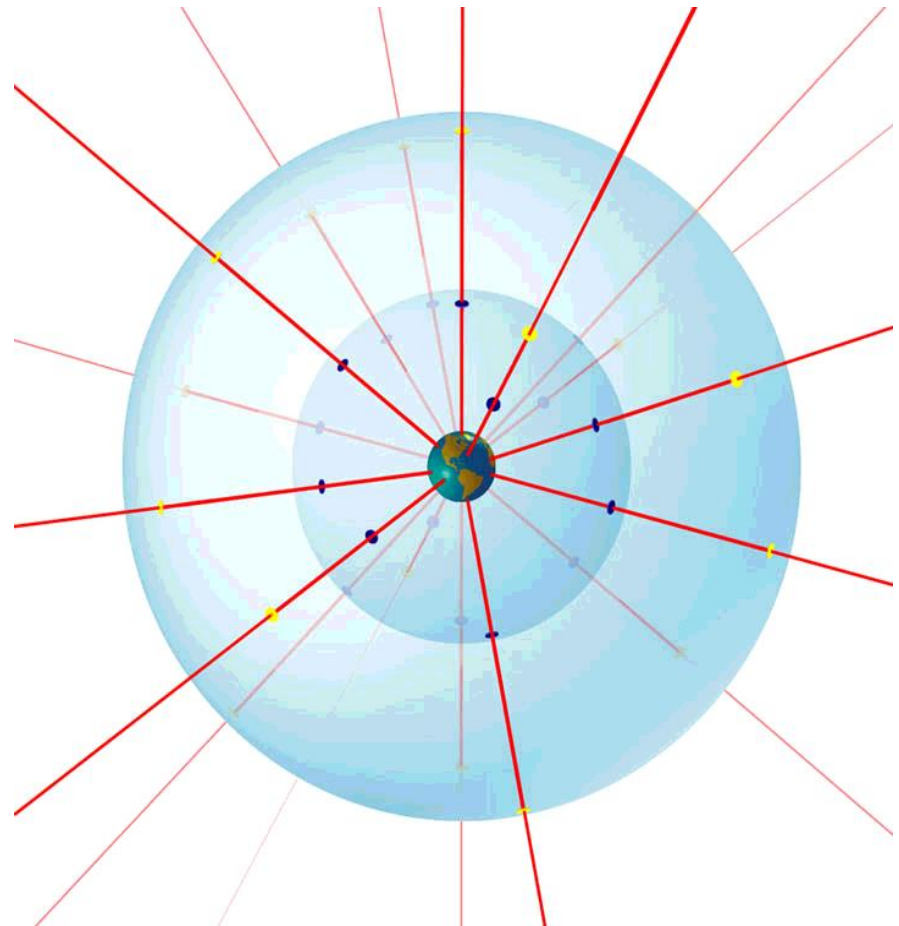
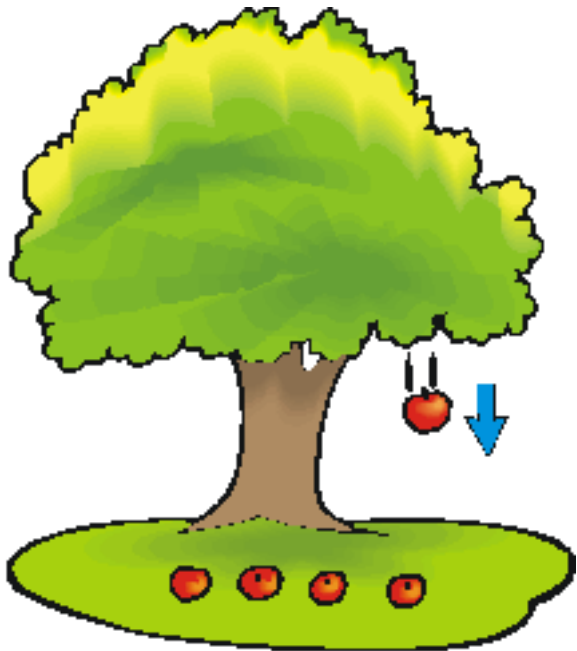
← ... but he never succeeded



Unification via extra dimensions of space?

Gravity force

Newton's law: force decreases with the area



Gravity : dominant force in astrophysics but irrelevant in particle physics

$$m \bullet \longleftarrow r \longrightarrow \bullet m \quad F_{\text{grav}} = G_N \frac{m^2}{r^2} \quad G_N^{-1/2} = M_{\text{Planck}} = 10^{19} \text{ GeV}$$

Compare with electric force: $F_{\text{el}} = \frac{e^2}{r^2} \Rightarrow$

effective gravitational 'charge' $G_N m^2$ or in general $G_N E^2$ at energies E

$$E = m_{\text{proton}} \Rightarrow \frac{F_{\text{grav}}}{F_{\text{el}}} = \frac{G_N m_{\text{proton}}^2}{e^2} \simeq 10^{-40}$$

\Rightarrow Gravity is very weak !

However theories with extra dimensions modify Newton's law

and predict strong gravity effects at high energies

Main Beyond the Standard Model proposals

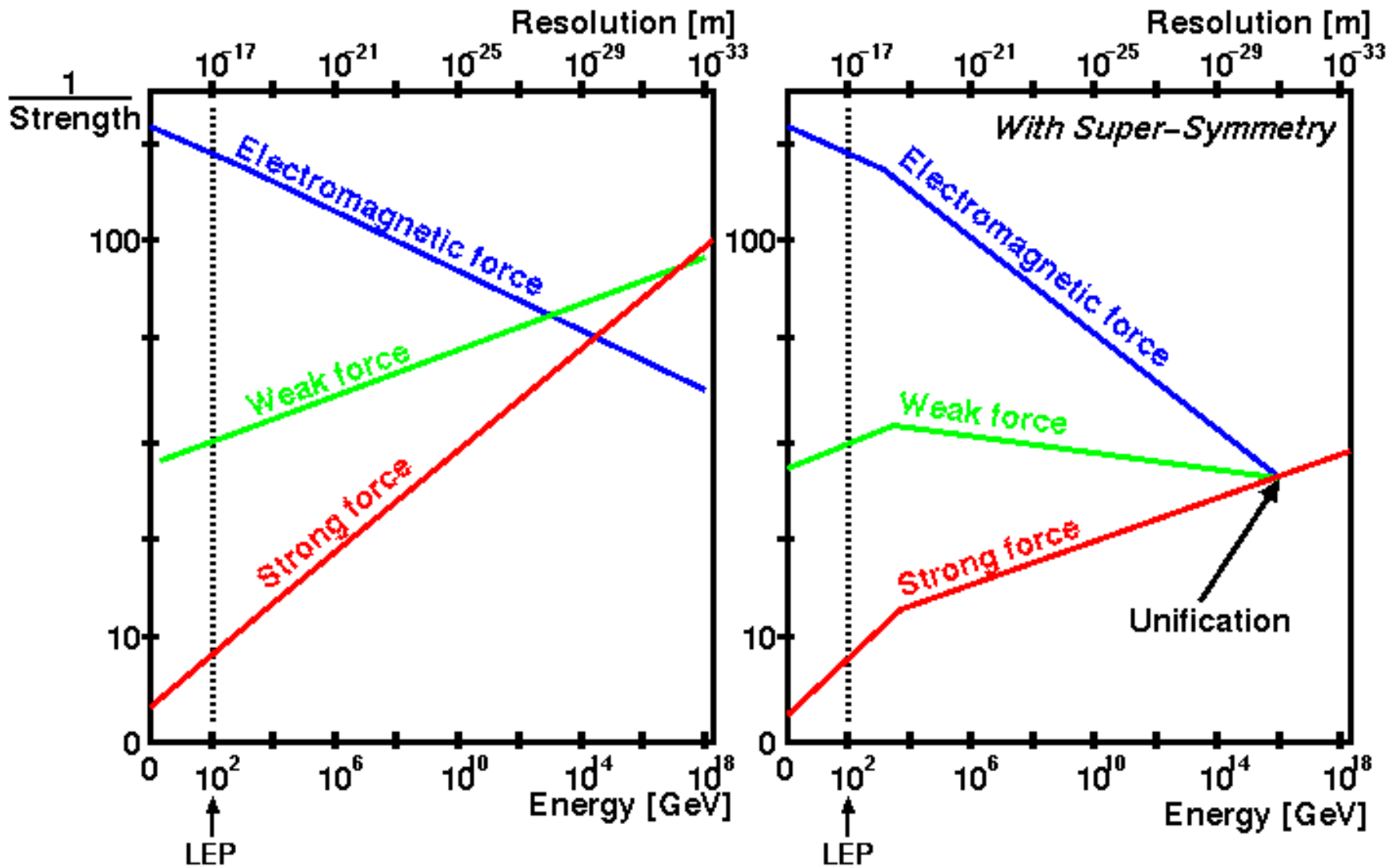
Supersymmetry: every particle has a superpartner

- realize unification of Standard Model forces
- natural dark matter candidate (lightest supersymmetric particle)
- prediction of light Higgs
- rich spectrum of new particles within LHC reach

String Theory: replaces point particles by strings

- quantum gravity
- framework for unification of all interactions
- prediction of new dimensions of space
- spectacular new phenomena if string scale in the TeV region

Energy evolution of the three force inverse-intensities



Supersymmetry \rightarrow unification of forces at around 10^{16} GeV

Conclusions

Confirmation of the Higgs scalar discovery at the LHC :

important milestone of the LHC research program

LHC and Particle physics enters a new era with possible new discoveries

unveiling the fundamental laws of Nature

