

Discovery Science with the Large Hadron Collider

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APPEAL
University of Oxford
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The Standard Model of



Particle Physics = Cosmic DNA

The matter particles

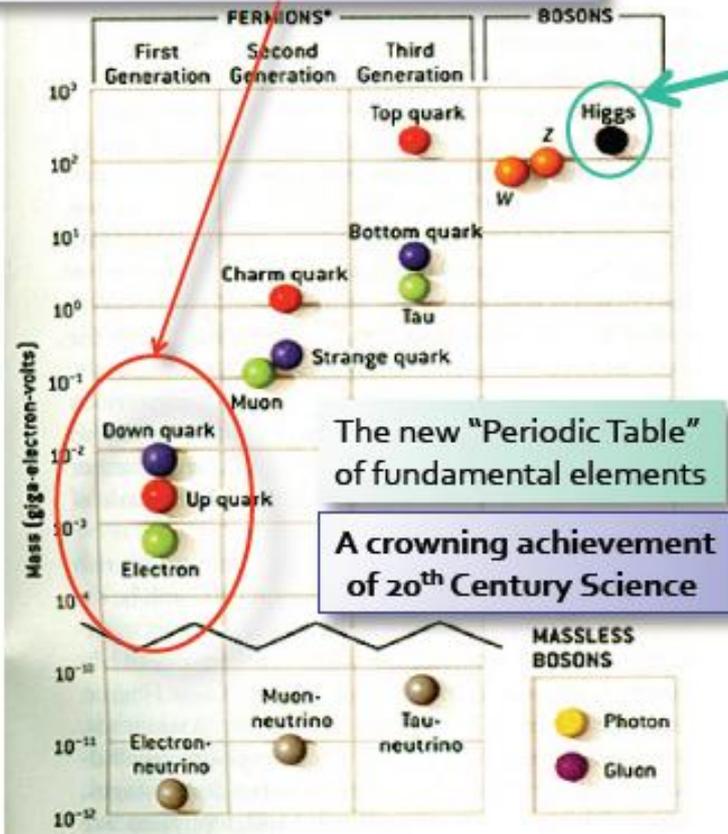


The fundamental interactions



The Standard Model of Particle Physics

These are all we normally "see" but the others are crucial to defining what we are.



The Standard Model

1 Missing piece: Higgs

	Measurement	Fit	$\frac{ O_{meas} - O_{fit} }{O_{meas}}$
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02766	0.00008
m_Z [GeV]	91.1875 ± 0.0021	91.1874	0.00001
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957	0.00020
σ_{had}^0 [nb]	41.540 ± 0.037	41.477	0.00150
R_b	20.767 ± 0.025	20.744	0.00110
$A_{fb}^{0,b}$	0.01714 ± 0.00095	0.01640	0.00450
$A_1(P_{\mu})$	0.1465 ± 0.0032	0.1479	0.00090
R_b	0.21629 ± 0.00066	0.21585	0.00020
R_c	0.1721 ± 0.0030	0.1722	0.00005
$A_{fb}^{0,b,c}$	0.0992 ± 0.0016	0.1037	0.00450
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0741	0.00480
A_b	0.923 ± 0.020	0.935	0.01300
A_c	0.670 ± 0.027	0.668	0.00030
$A_1(SLD)$	0.1513 ± 0.0021	0.1479	0.00230
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314	0.00040
m_W [GeV]	80.392 ± 0.029	80.371	0.00026
Γ_W [GeV]	2.147 ± 0.060	2.091	0.02600
m_t [GeV]	171.4 ± 2.1	171.7	0.00170

Summer, 2006

Confirmed at sub 1% level

$$\begin{aligned}
 L = & -\frac{1}{4}W_{\mu\nu}W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}G_{\mu\nu}G^{\mu\nu} \\
 & + \bar{\psi}_j \gamma^\mu (i\partial_\mu - g\boldsymbol{\tau}_j \cdot \mathbf{W}_\mu - g'Y_j B_\mu - g_s \mathbf{T}_j \cdot \mathbf{G}_\mu) \psi_j \\
 & + |D_\mu \phi|^2 + \mu^2 |\phi|^2 - \lambda |\phi|^4 \\
 & - (y_j \bar{\psi}_{jL} \phi \psi_{jR} + y'_j \bar{\psi}_{jL} \phi_c \psi_{jR} + \text{conjugate})
 \end{aligned}$$

$$M_W = gv/2$$

$$M_Z = \frac{v}{2} \sqrt{g^2 + g'^2}$$

$$m_Z = 91.1875 \pm 0.0021 \text{ GeV}$$

$$\Gamma_Z = 2.4952 \pm 0.0023 \text{ GeV}$$

CERN-PH-EP/2005-041
 SLAC-R-774
 hep-ex/0509008
 7 September 2005

$$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$$

Prediction (1981) $M_W \sim 79 \text{ GeV}$, $M_Z \sim 89 \text{ GeV}$

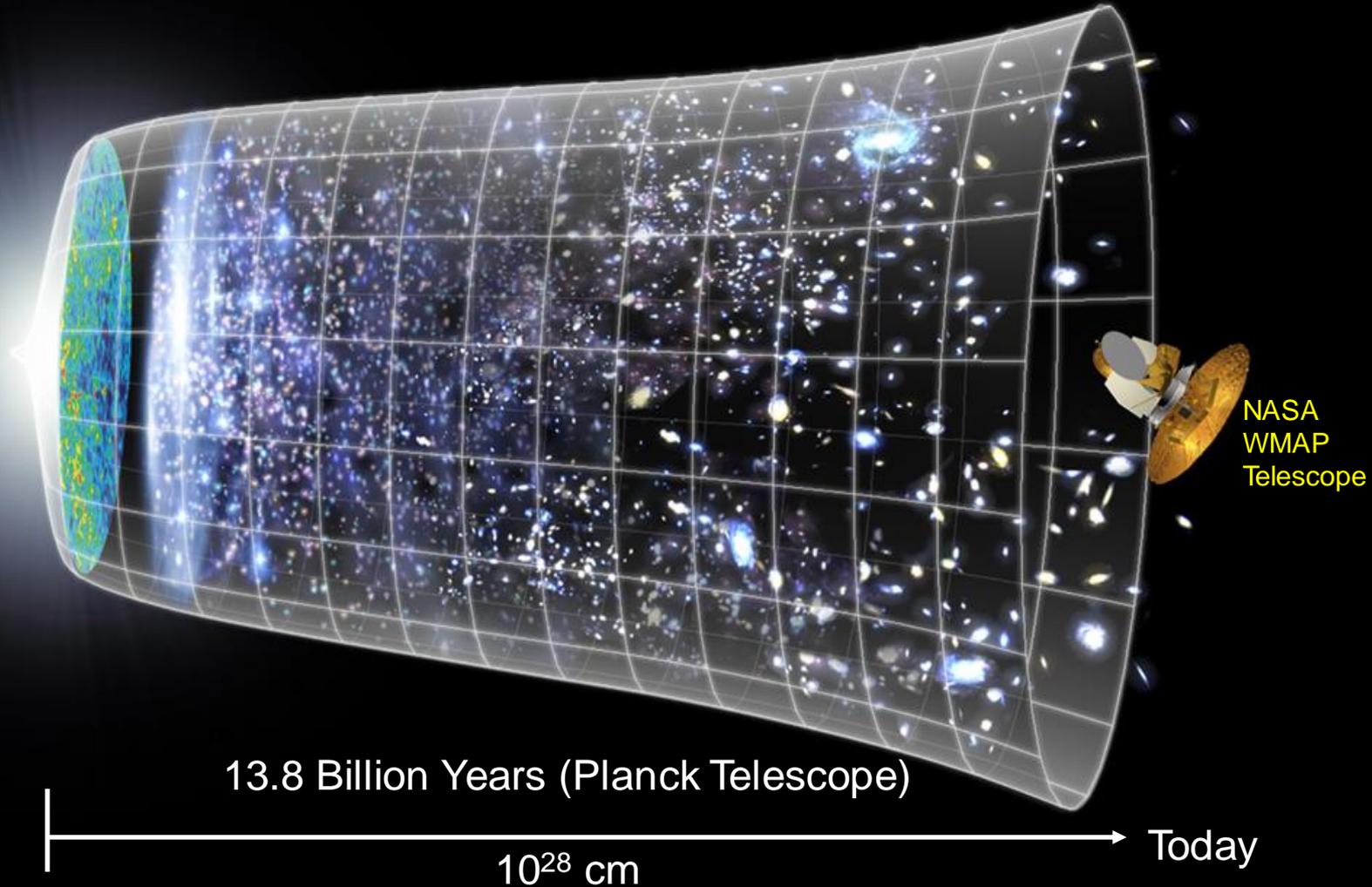
$$M_W = 80.390 \pm 0.016 \text{ GeV}$$

$$M_H < 145 \text{ GeV}$$

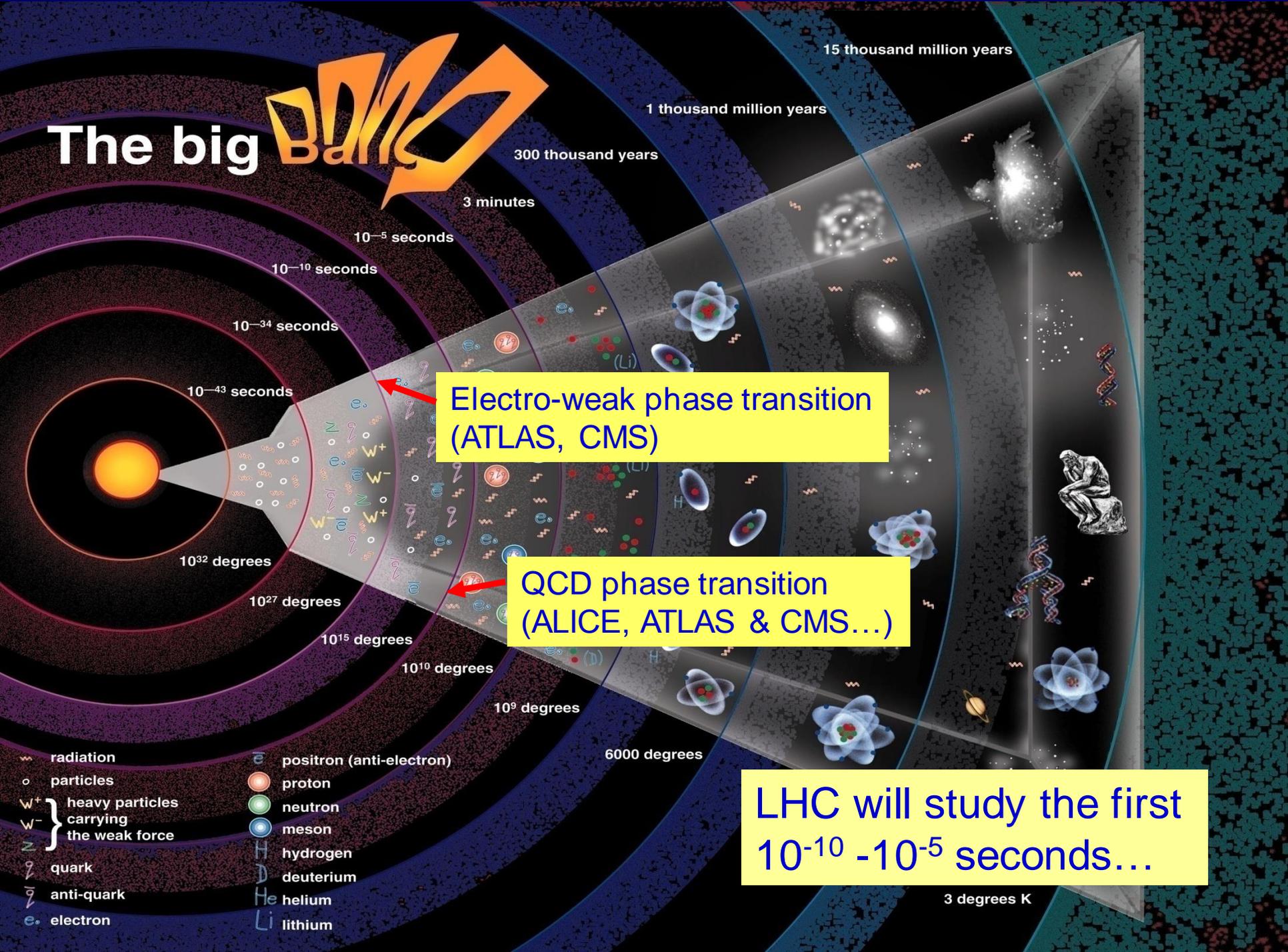
CDF arXiv:1203.0275v1 [hep-ex]
 March 2012

Evolution of the Universe

Big Bang



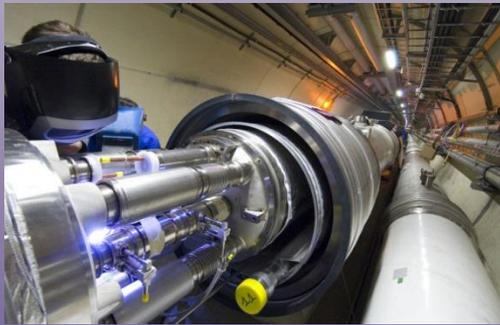
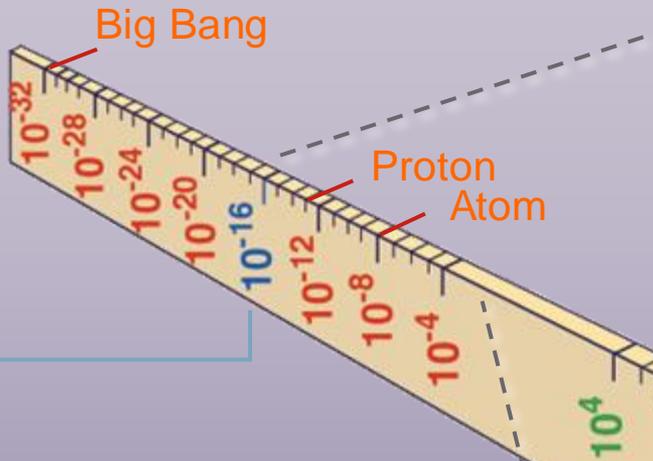
The big Bang



Electro-weak phase transition (ATLAS, CMS)

QCD phase transition (ALICE, ATLAS & CMS...)

LHC will study the first 10^{-10} - 10^{-5} seconds...

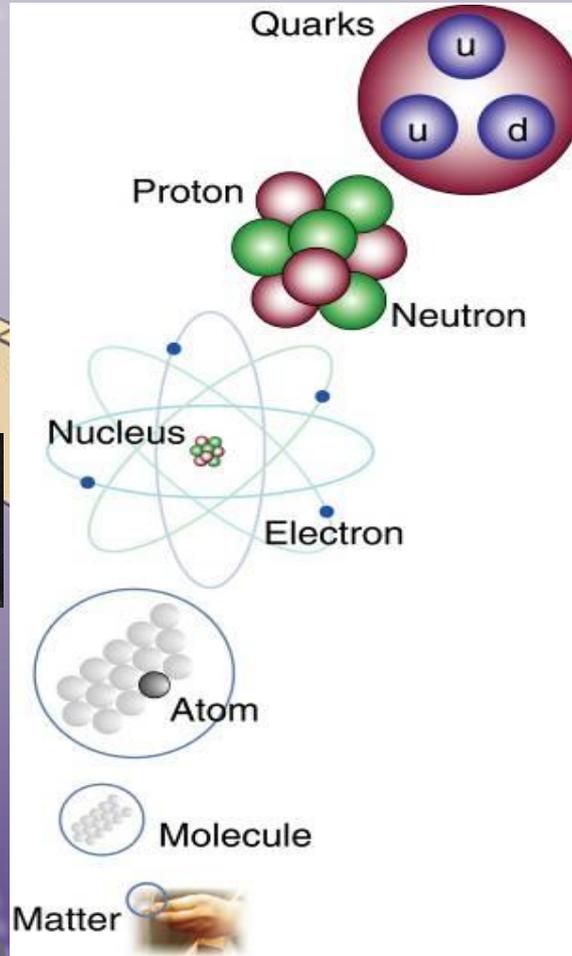
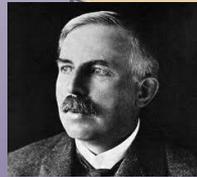


LHC

Super-Microscope

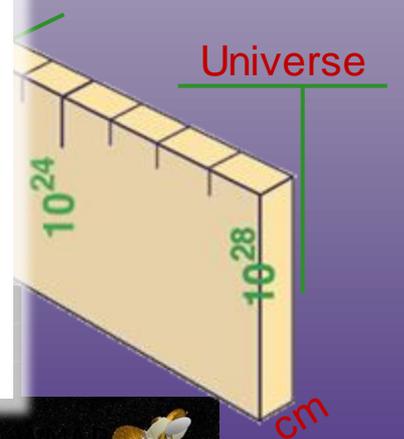


Study physics laws of first moments after Big Bang.
 Increasing Symbiosis between Particle Physics,
 Astrophysics and Cosmology.



Radius of Galaxies

Universe

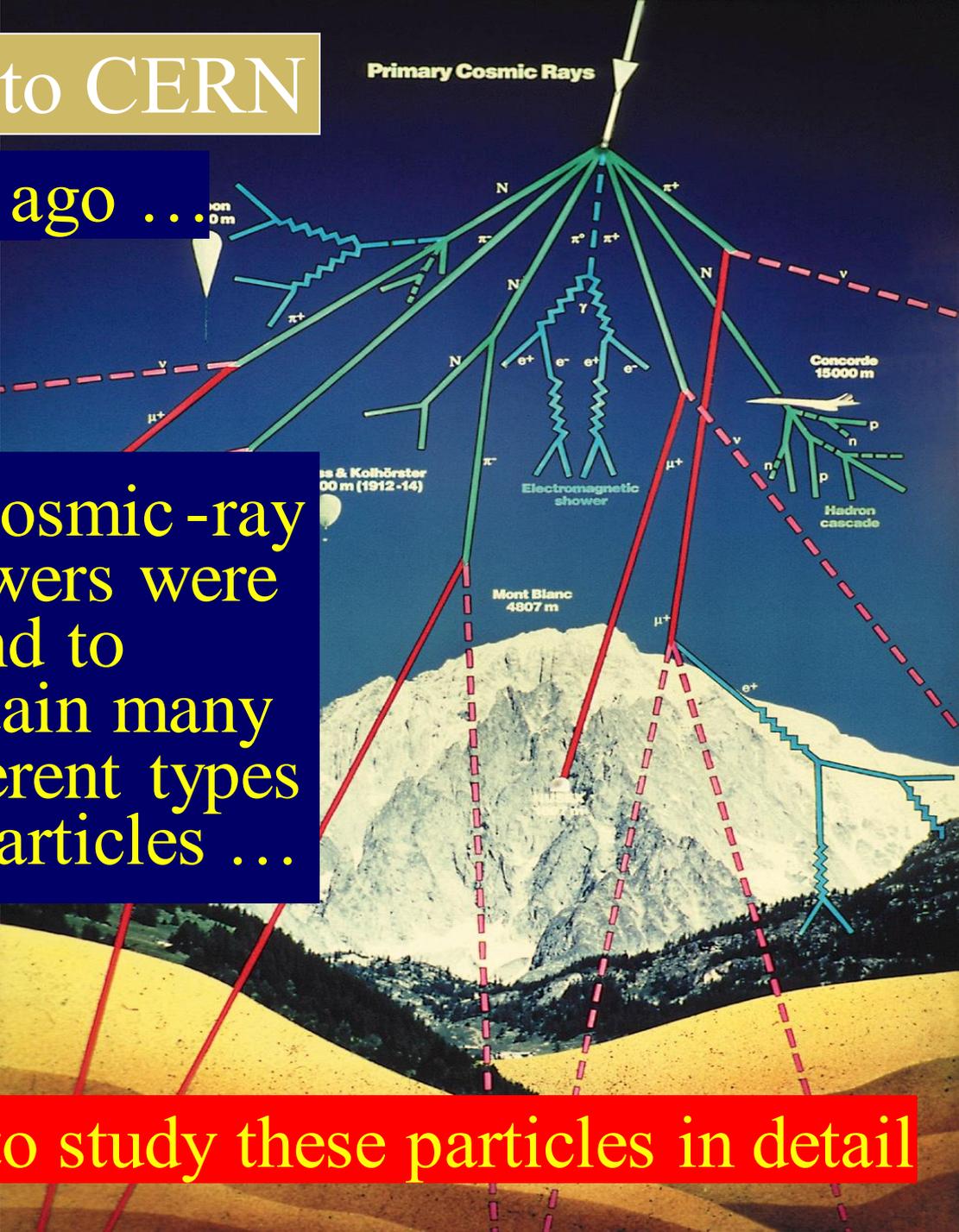
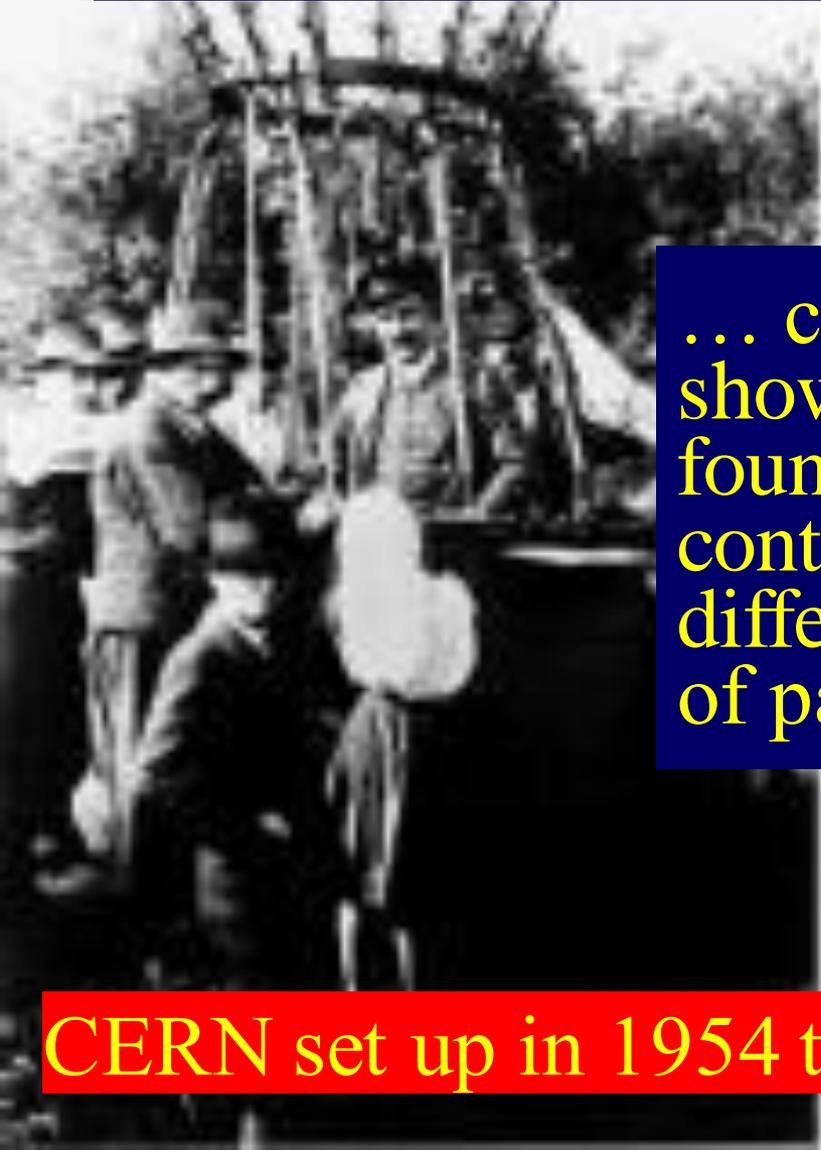


From Cosmic Rays to CERN

Discovered a century ago ...

... cosmic-ray showers were found to contain many different types of particles ...

CERN set up in 1954 to study these particles in detail



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?
(the physicists' Holy Grail)



Higgs Boson



All particles generated at the Big Bang without mass.

Interacting with the Higgs field, particles acquire mass.

Greater the interaction, the greater the mass.

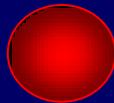
Higgs field fills the whole universe.

British physicist Peter Higgs proposed (1964) the so-called Higgs Boson particle associated with eponymous mechanism & field.

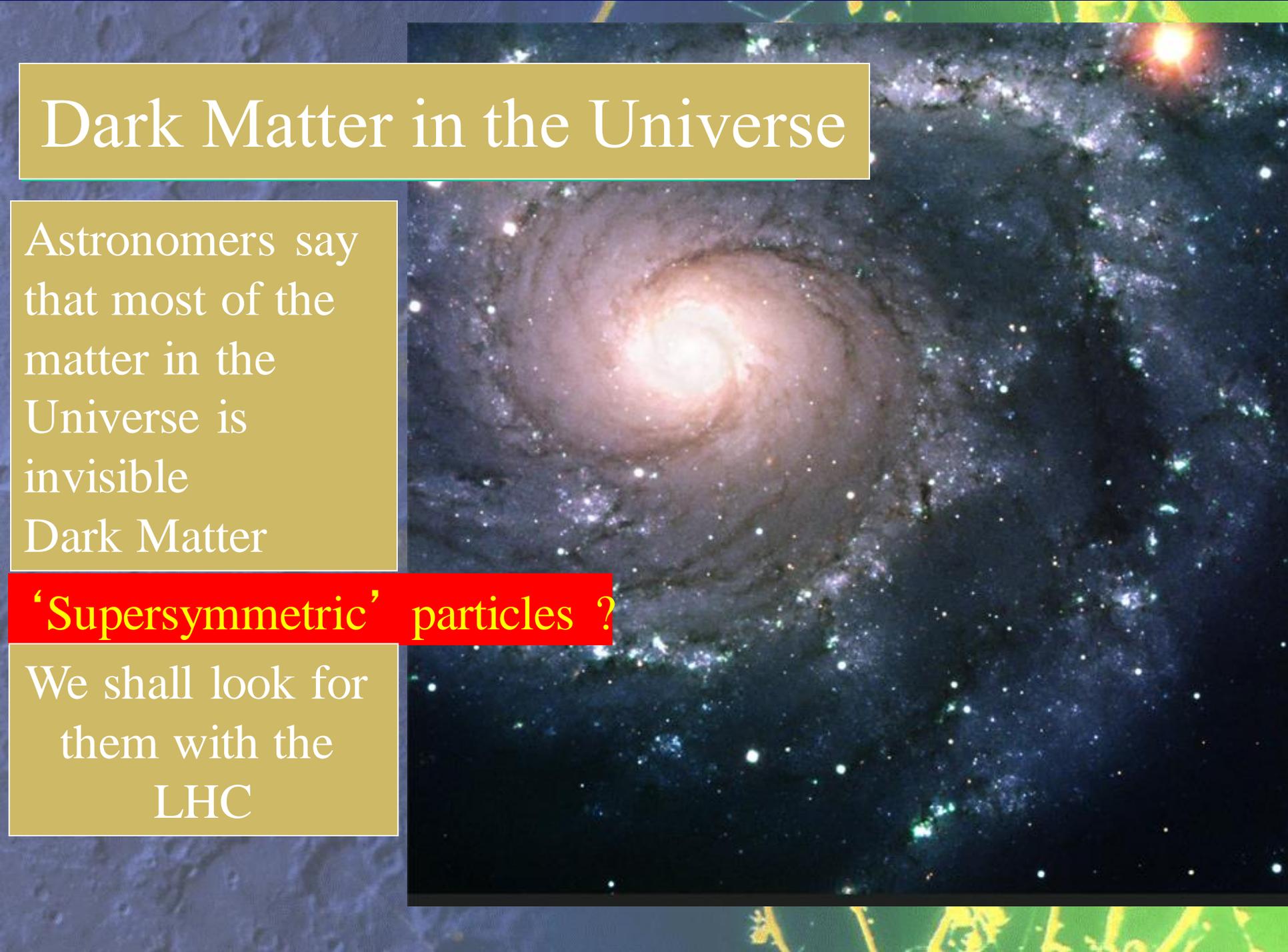
**Interaction with
the Higgs field**



**Friction with
viscous liquid**



Dark Matter in the Universe

The background of the slide is a composite image. On the left, there is a close-up of a spiral galaxy with a bright central core and several distinct spiral arms. On the right, there is a field of stars, with a prominent bright orange star in the upper right corner and many smaller, multi-colored stars scattered throughout.

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

‘Supersymmetric’ particles ?

We shall look for
them with the
LHC

Where does the Matter come from?

Dirac predicted the existence of antimatter:
same mass
opposite internal properties:
electric charge, ...

Discovered in cosmic rays
Studied using accelerators



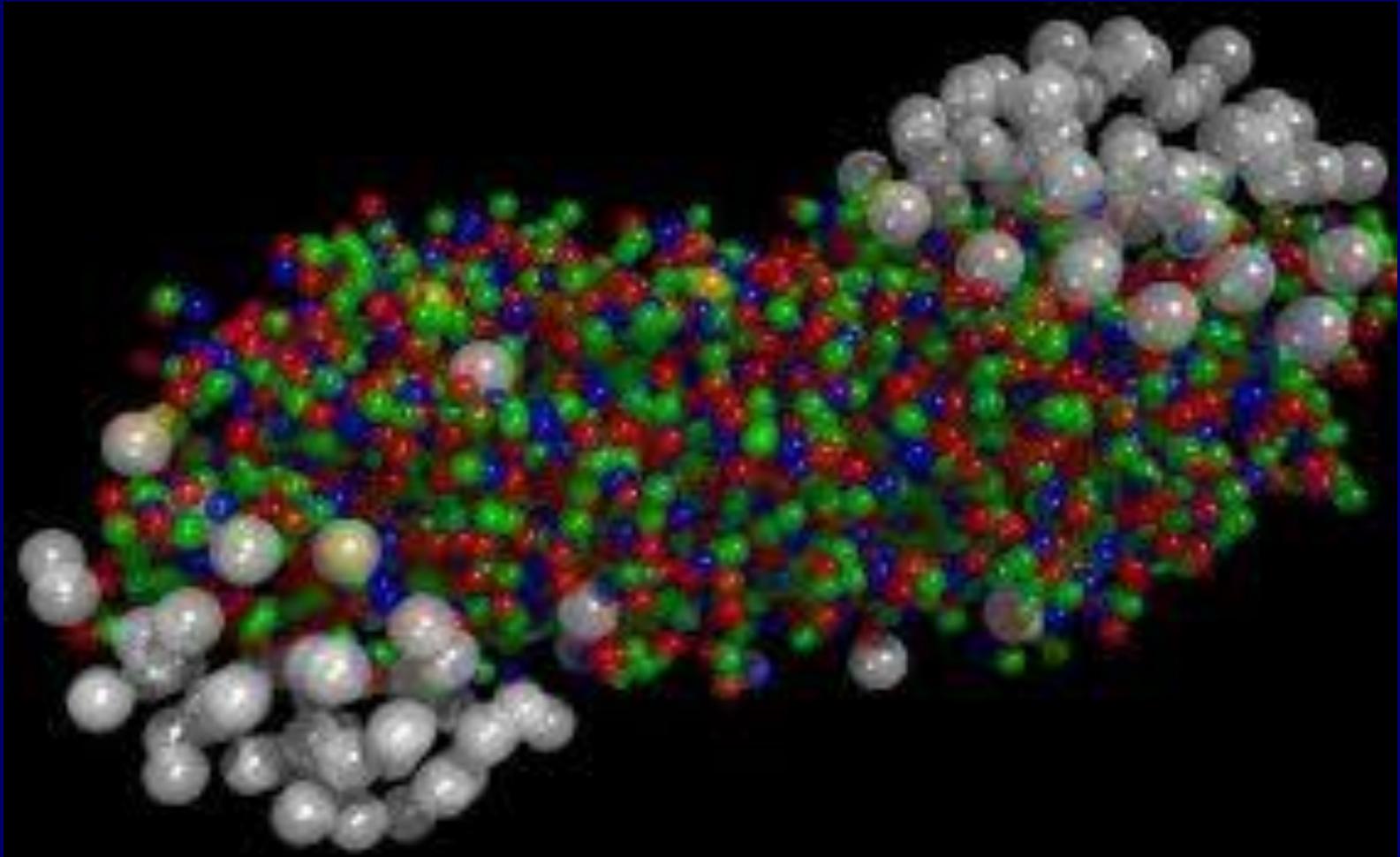
Matter and antimatter not quite equal and opposite: WHY?

2008 Nobel Physics Prize: Kobayashi & Maskawa

Is this why the Universe contains mainly matter, not antimatter?

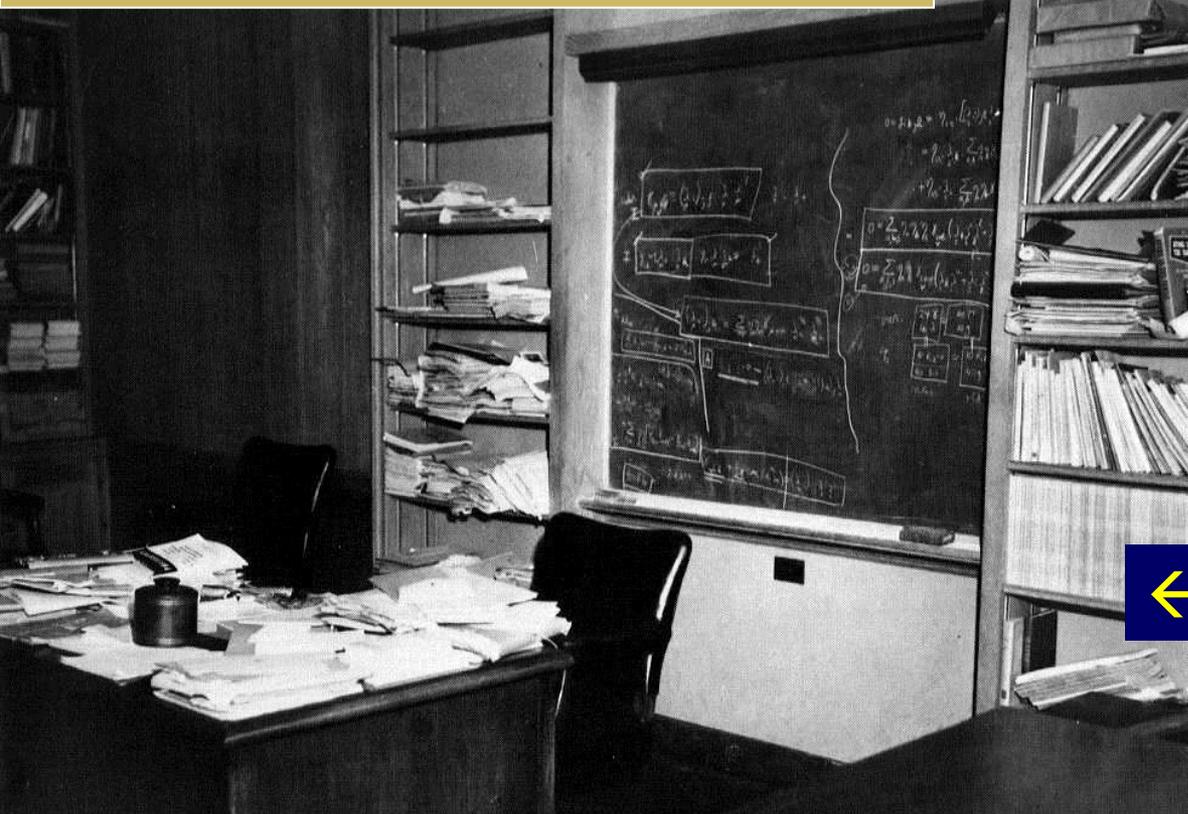
LHC experiments will look for answer

ALICE and Quark-Gluon Plasma



Pb Pb collisions may liberate quarks

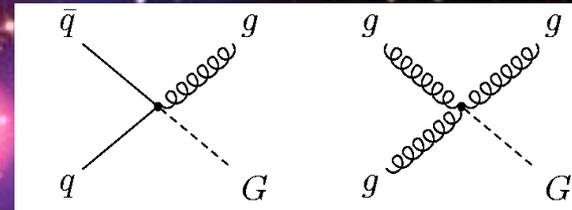
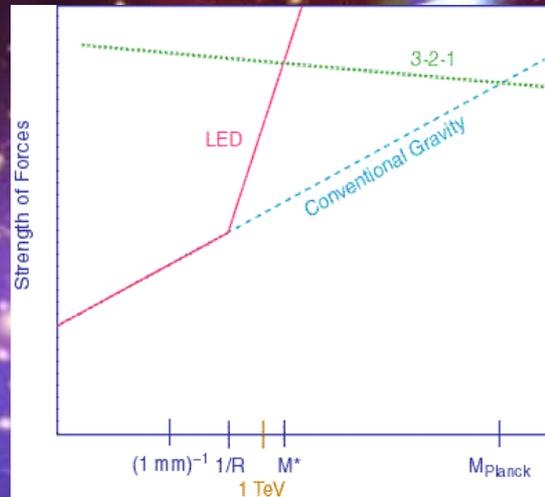
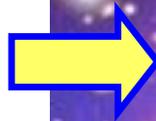
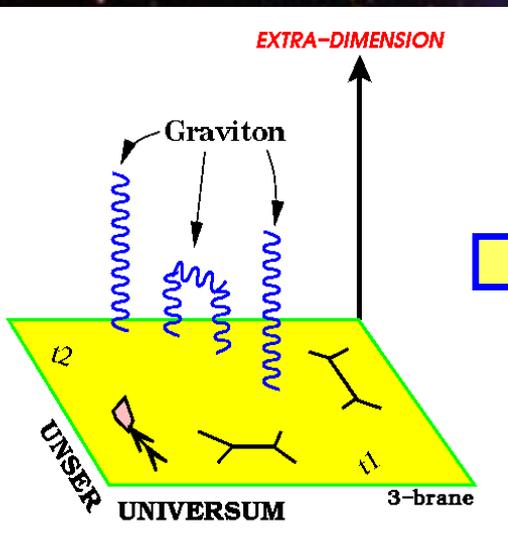
Unify the
Fundamental
Interactions:
Einstein's Dream ...



← ... but he never succeeded

Maybe with extra dimensions of space?

Extra Space Dimensions?



Signatures

Eg monojet events
 monophoton events
 Z' like resonances
 KK excitations
 ...

The gravity force becomes strong!

Microscopic black hole results in high-multiplicity, high sum-ET events

To answer these questions:

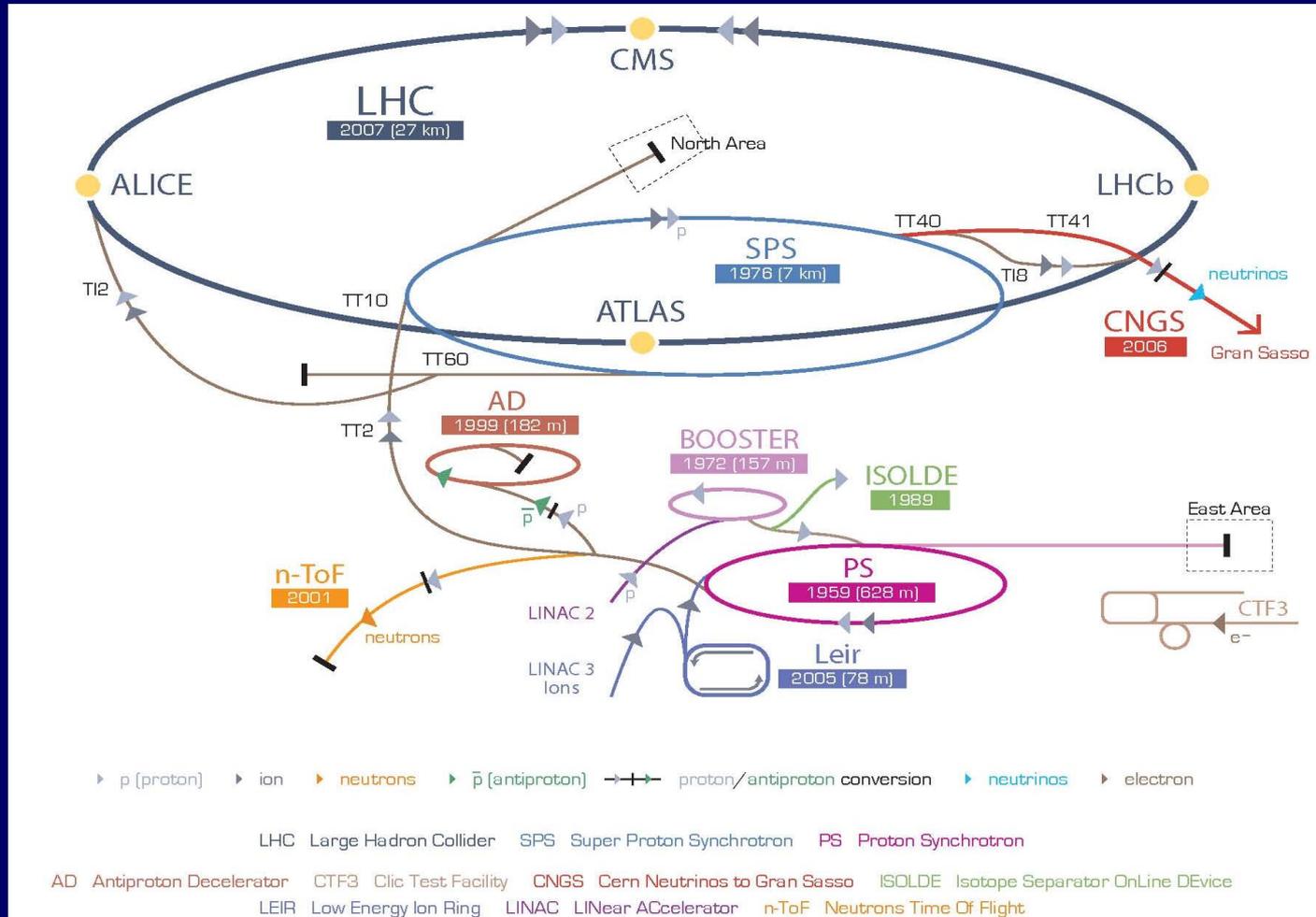
The Large Hadron Collider (LHC)

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:

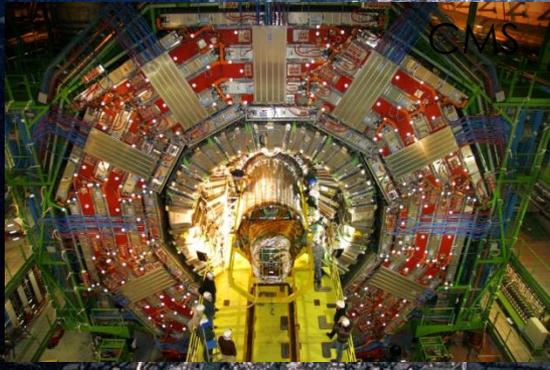
- Origin of mass
- Nature of Dark Matter
- Primordial Plasma
- Matter vs Antimatter

CERN Accelerator Complex

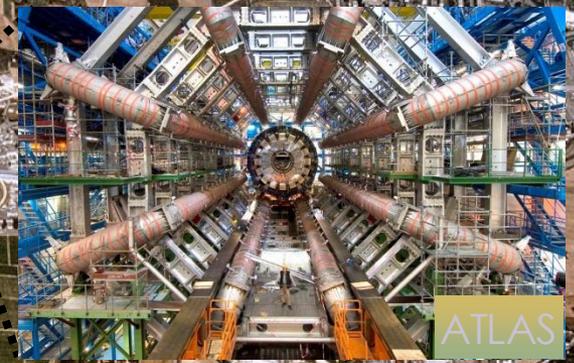


Enter a New Era in Fundamental Science

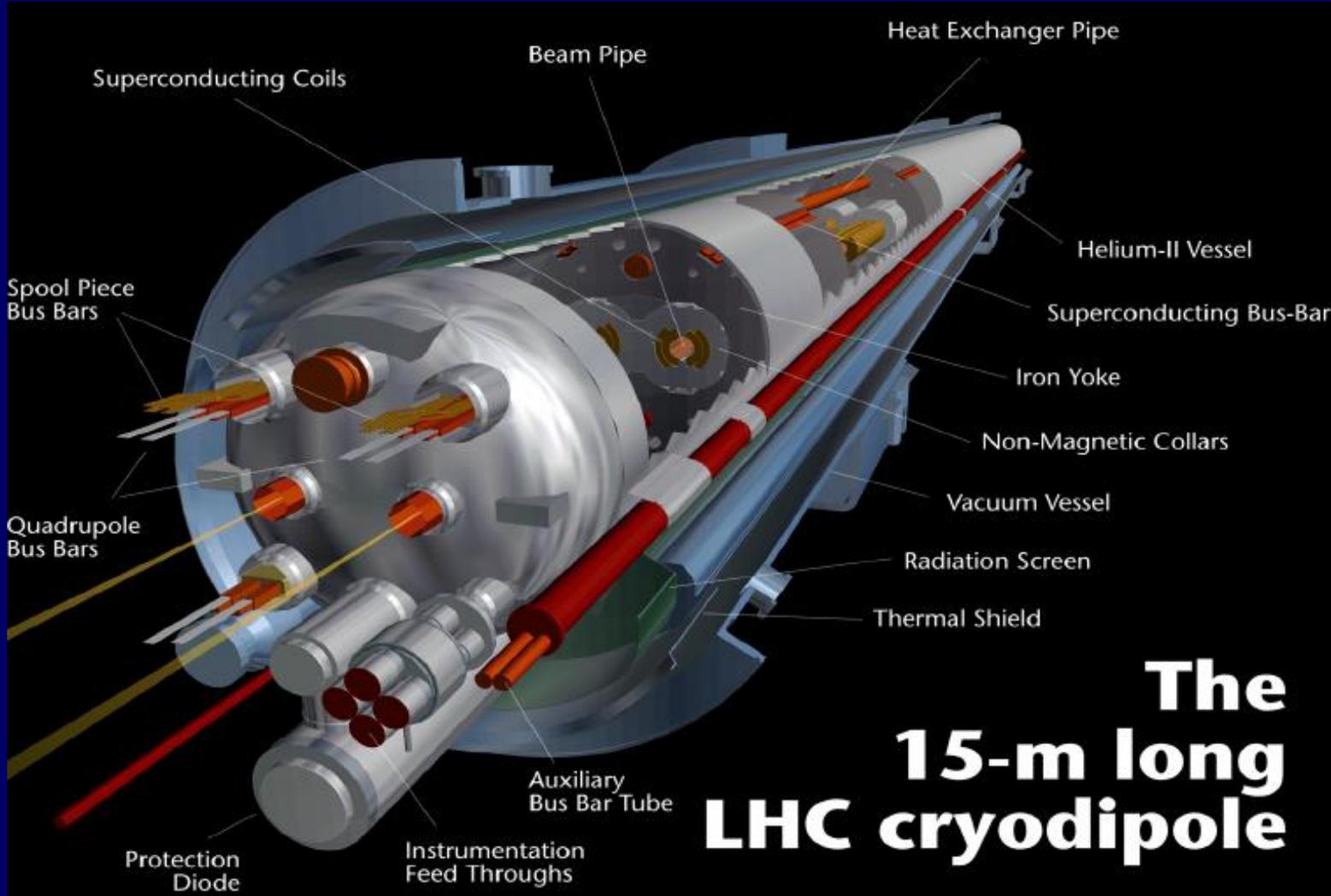
Start-up of the Large Hadron Collider (**LHC**), one of the largest and truly global scientific projects ever, is the most exciting turning point in particle physics.



Exploration of a new energy frontier
Proton-proton collisions at $E_{\text{CM}} = 14 \text{ TeV}$



LHC Main Bending Cryodipole



8.5 T
nominal field

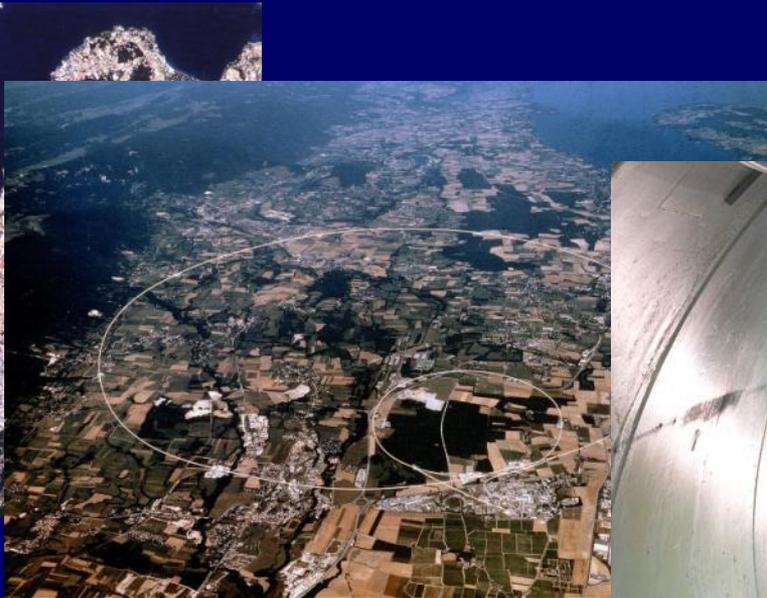
12 kA
nominal field

**The
15-m long
LHC cryodipole**



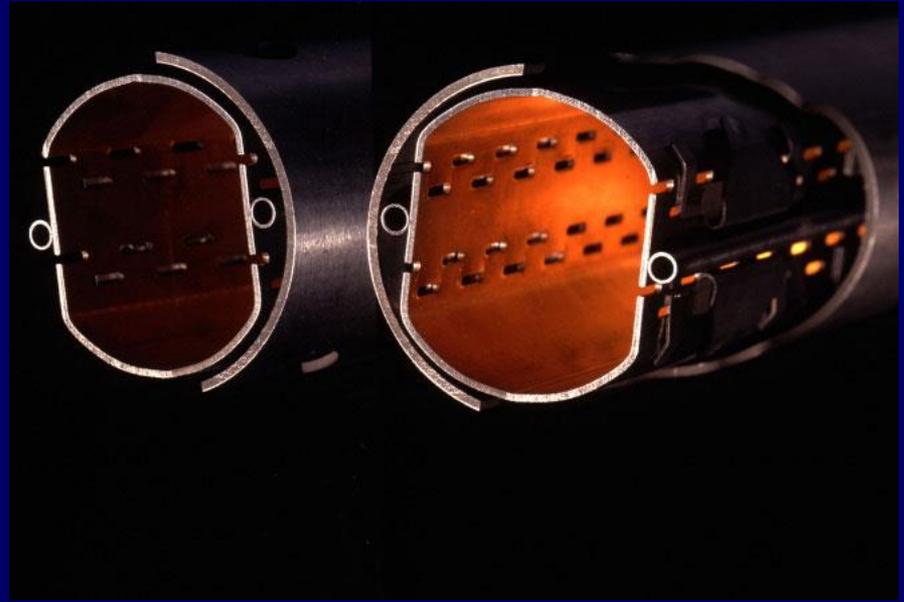
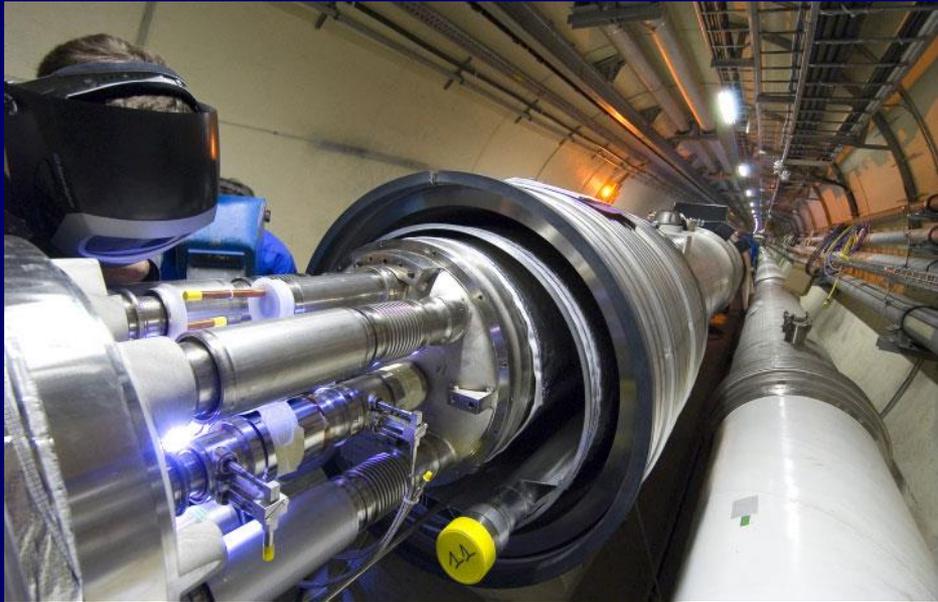
The LHC Arcs

The **fastest** racetrack on the planet...



Trillions of protons will race around the 27km ring in opposite directions over 11,000 times a second, travelling at 99.999999991 per cent the speed of light.

The **emptiest** space in the solar system...



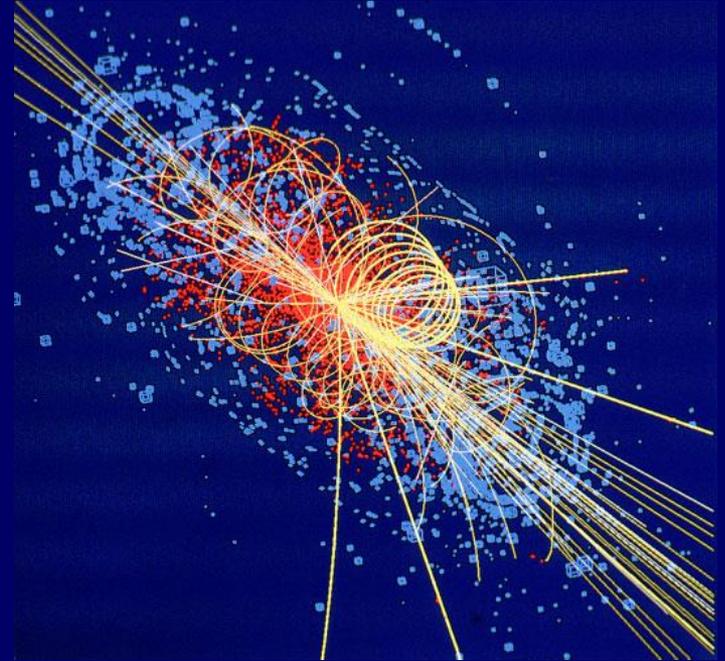
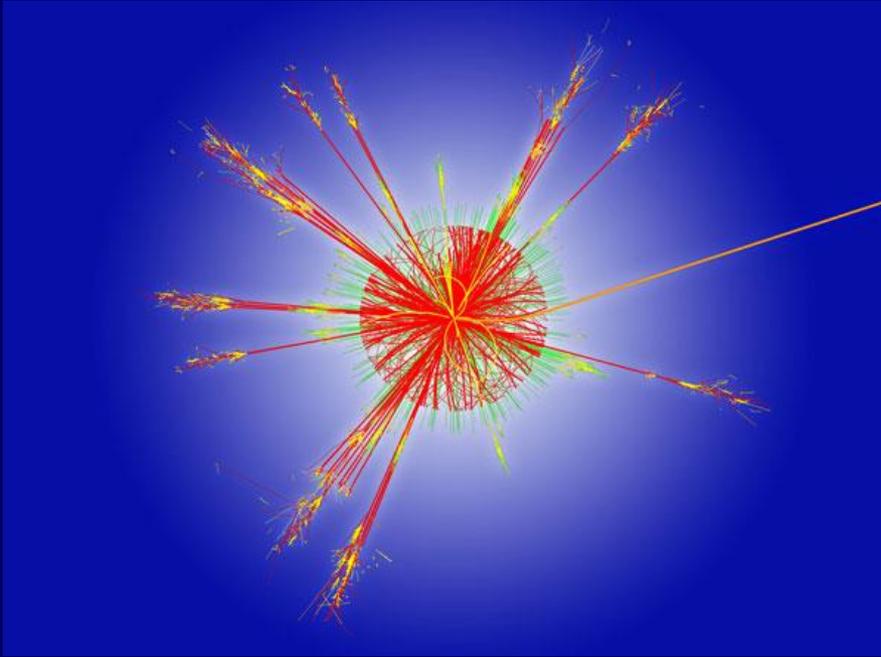
To accelerate protons to almost the speed of light requires a vacuum as empty as interplanetary space. There is 10 times more atmosphere on the moon than there will be in the LHC.

One of the **coldest** places in the universe...



With an operating temperature of about -271 degrees Celsius, just 1.9 degrees above absolute zero, the LHC is colder than outer space.

The **hottest** spots in the galaxy...

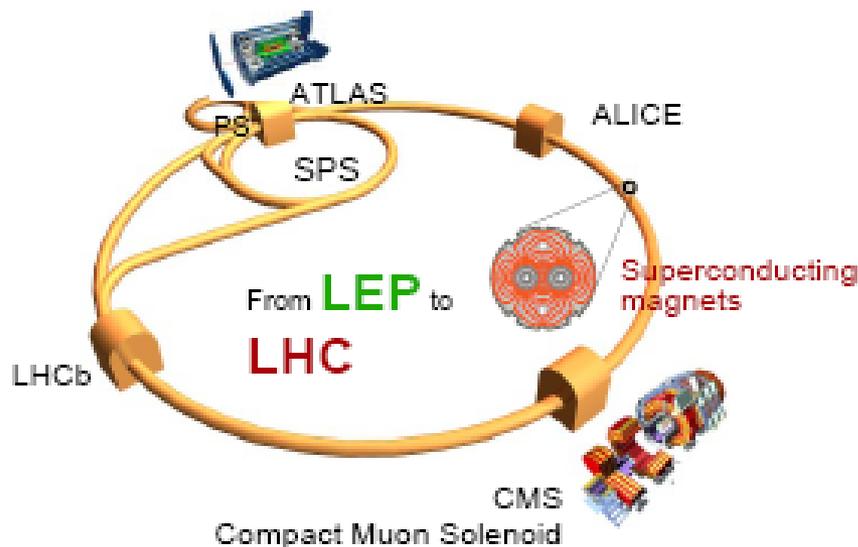


When two beams of protons collide, they will generate temperatures 1000 million times hotter than the heart of the sun, but in a minuscule space.

The Large Hadron Collider

Require Accelerator with

- largest possible primary energy (limited by size of LEP tunnel and highest magnetic field practicable)
- largest possible luminosity (quarks carrying a large fraction of primary proton energy are rare)



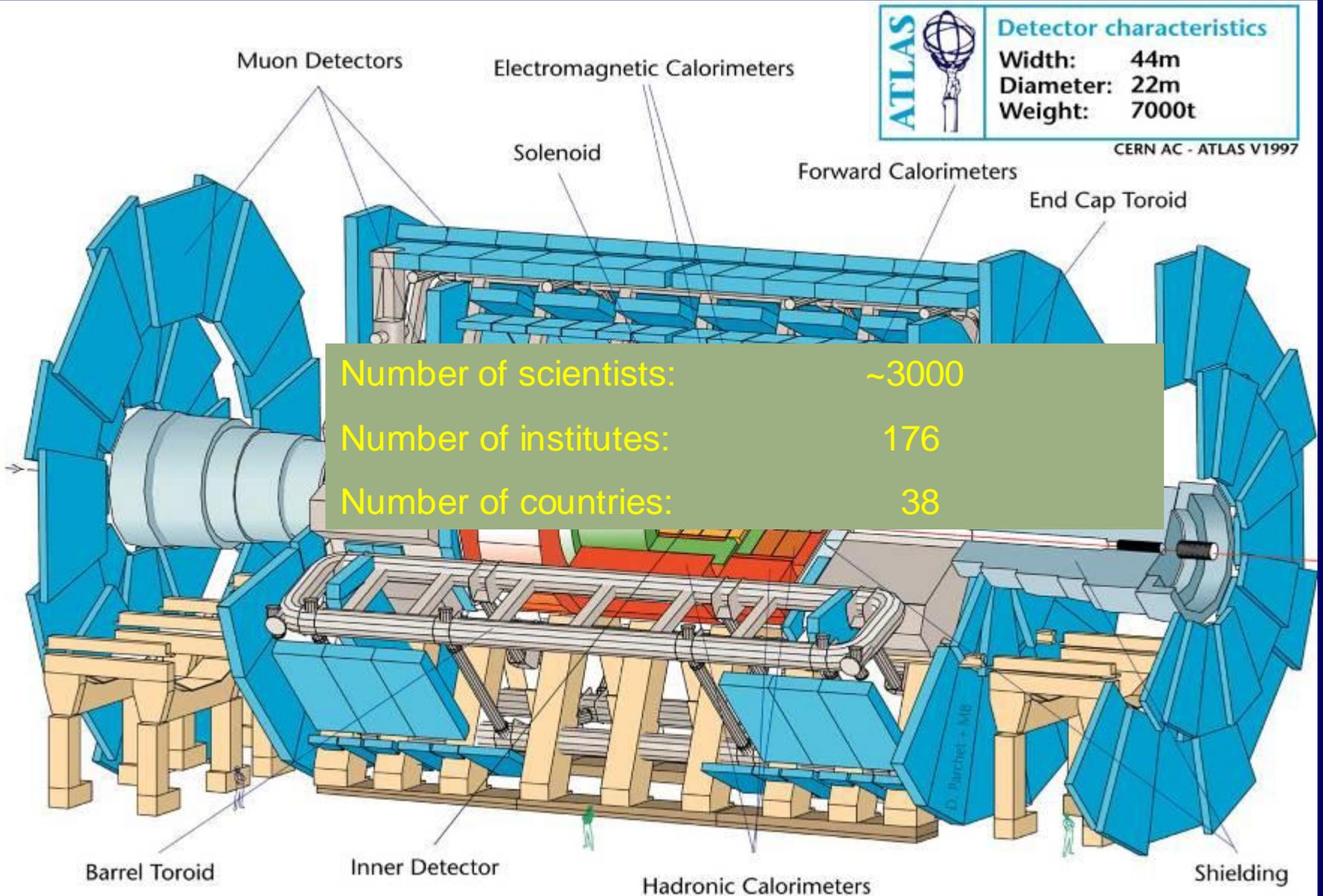
High repetition rate

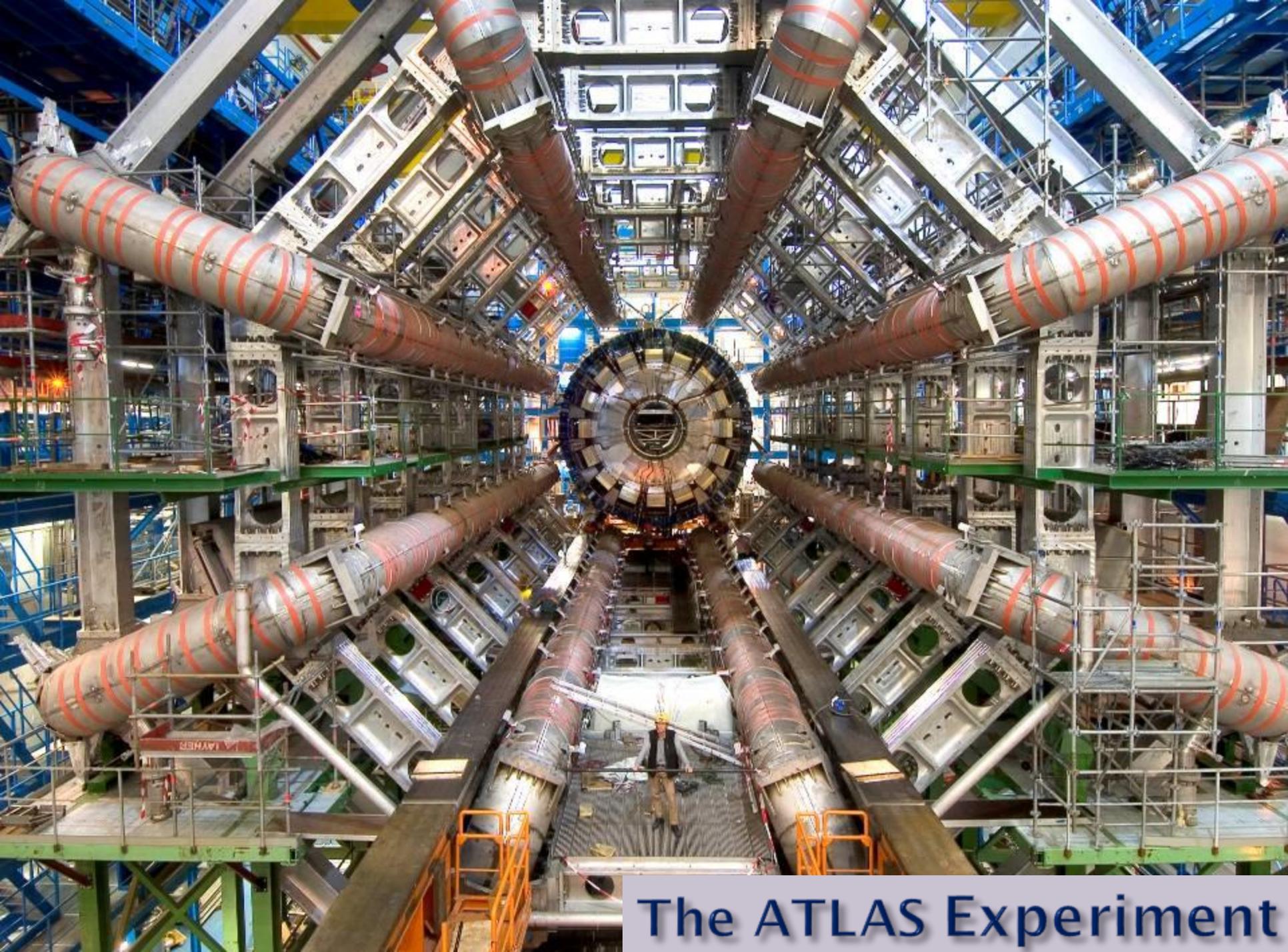
40 MHz or

25 ns bunch spacing

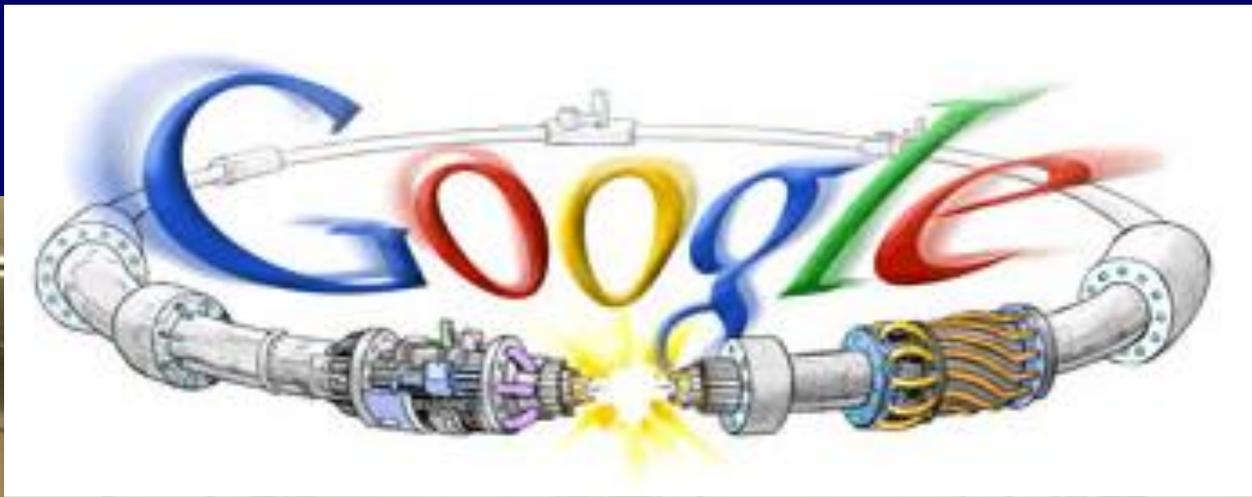
	Beams	Energy GeV	Luminosity
LEP	e+ e-	200	$10^{32} \text{ cm}^{-2}\text{s}^{-1}$
LHC	p p	14000	10^{34}
	Pb Pb	1,312,000	10^{27}

The ATLAS Experiment



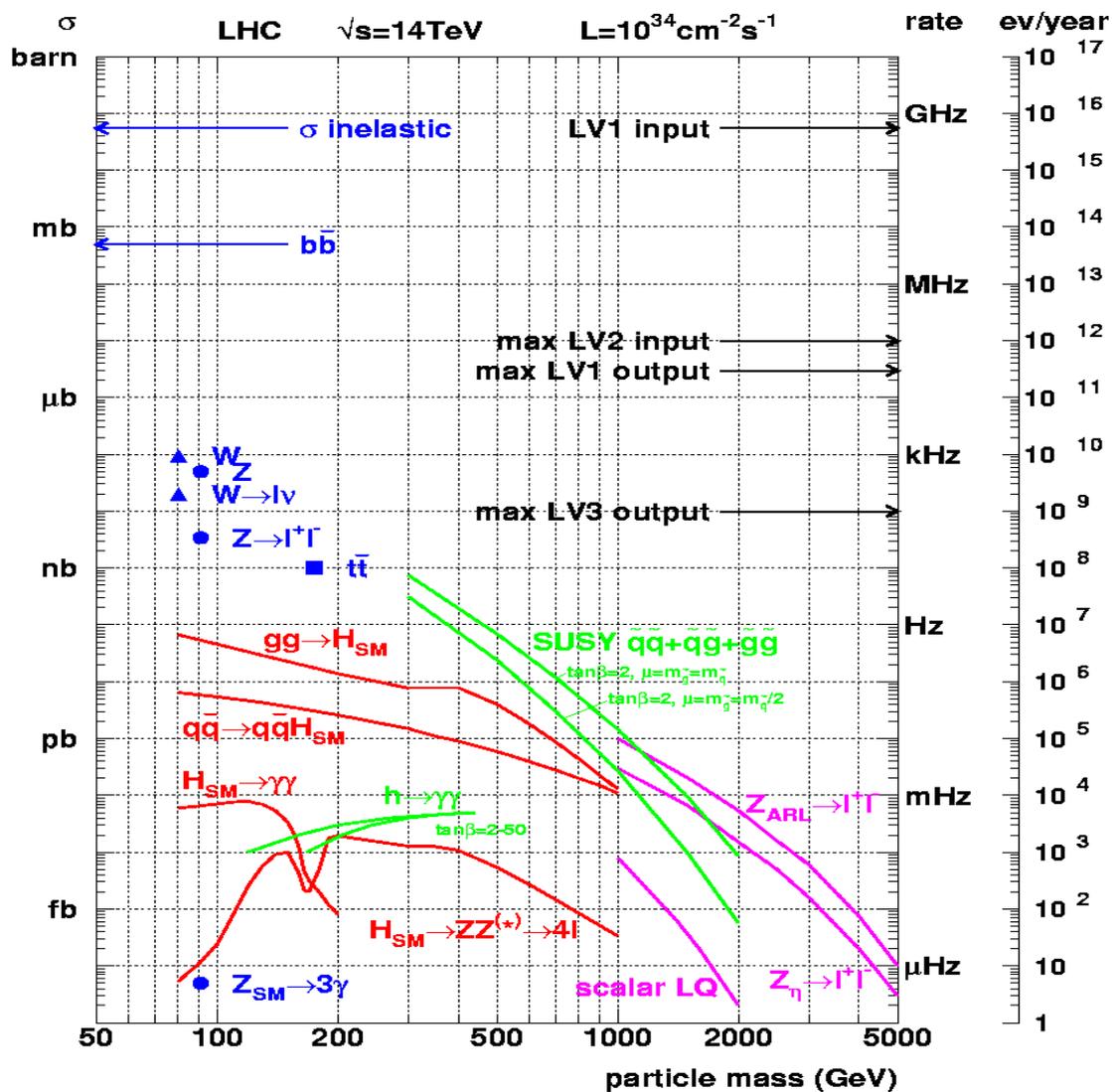


The ATLAS Experiment



A billion people watched on TV

Cross sections at the LHC



“Well known” processes. Don’t need to keep all of them ...

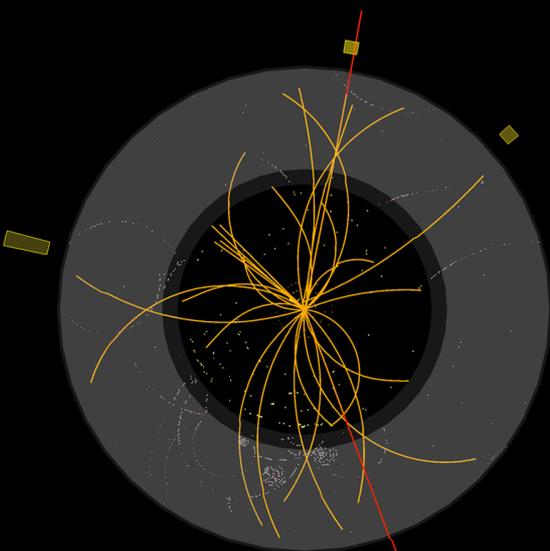
New Physics!!
We want to keep!!

The Story so Far ...

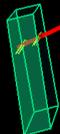


ATLAS EXPERIMENT

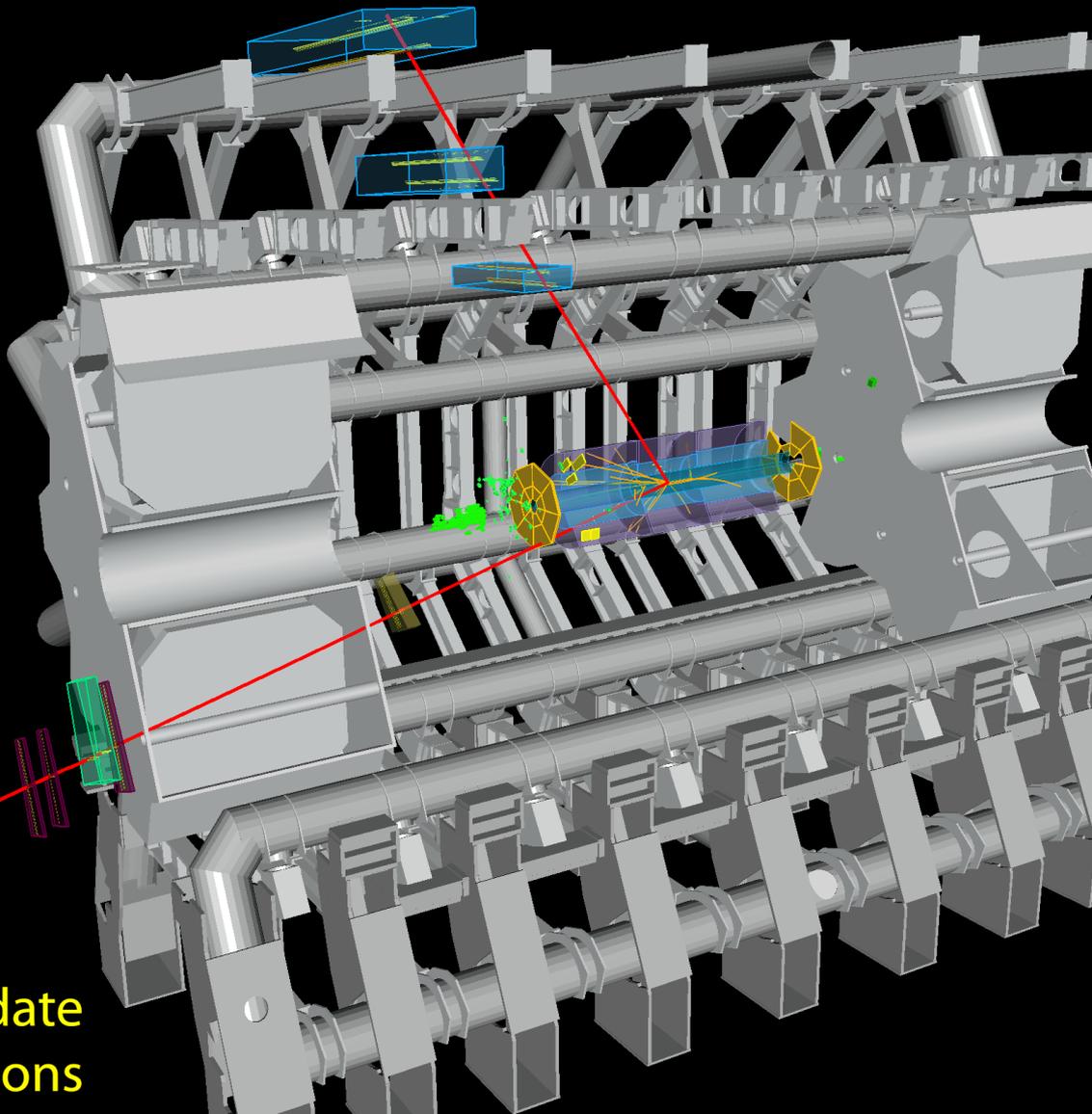
Run: 154822, Event: 14321500
Date: 2010-05-10 02:07:22 CEST



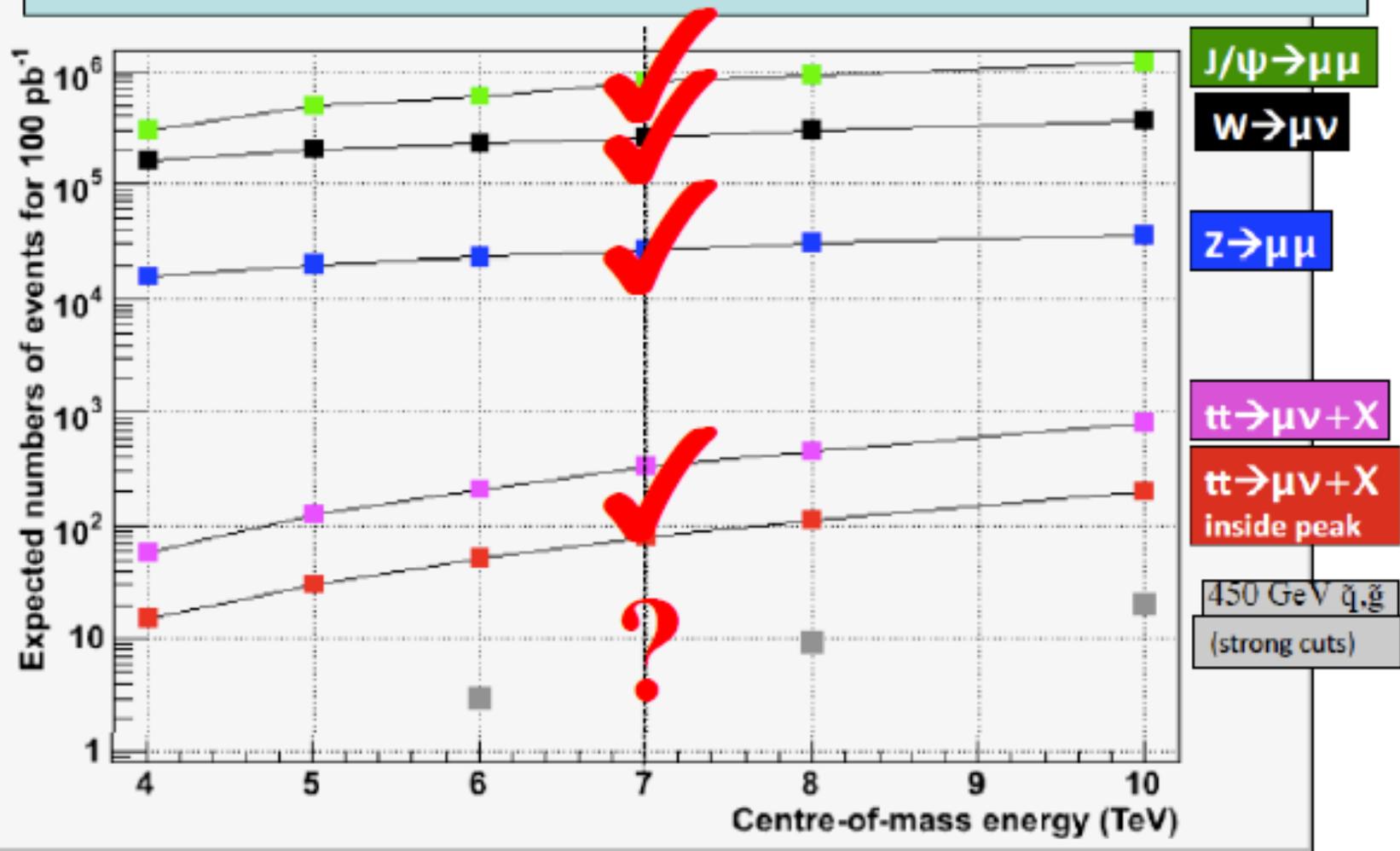
$p_T(\mu^-) = 27 \text{ GeV}$ $\eta(\mu^-) = 0.7$
 $p_T(\mu^+) = 45 \text{ GeV}$ $\eta(\mu^+) = 2.2$
 $M_{\mu\mu} = 87 \text{ GeV}$



**Z $\rightarrow\mu\mu$ candidate
in 7 TeV collisions**



The Story so far – and to come

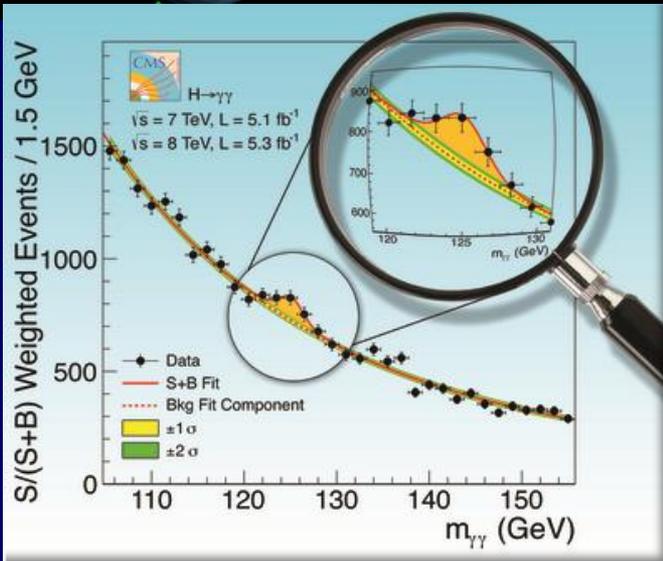
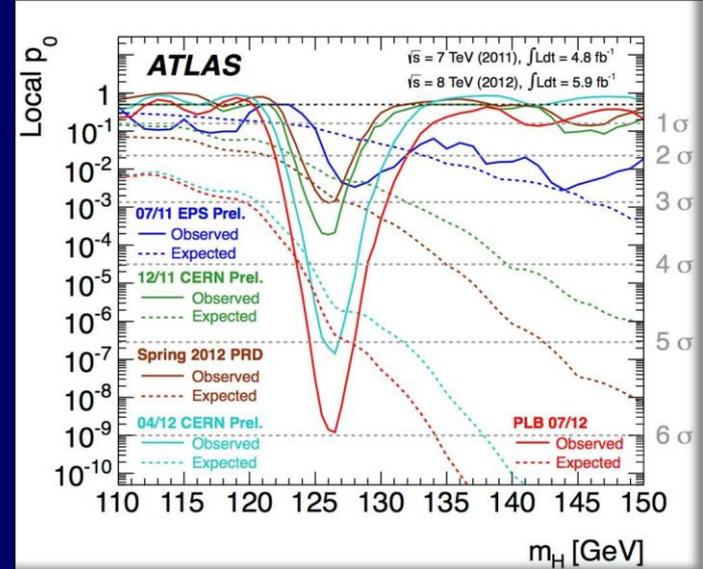
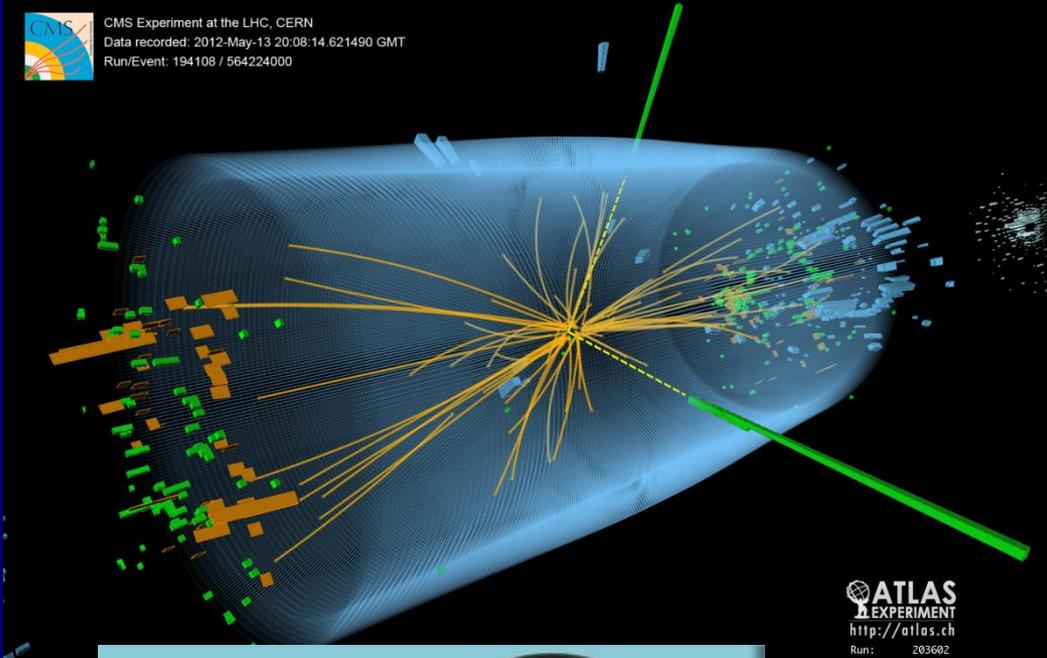


4 July 2012

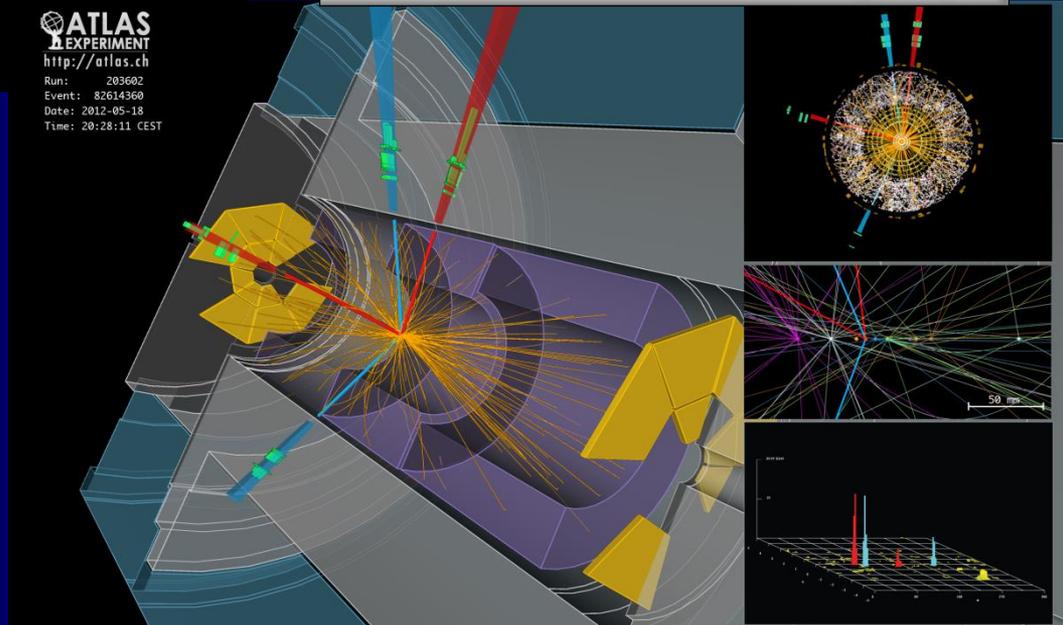
“CERN experiments observe particle consistent with long-sought Higgs boson”



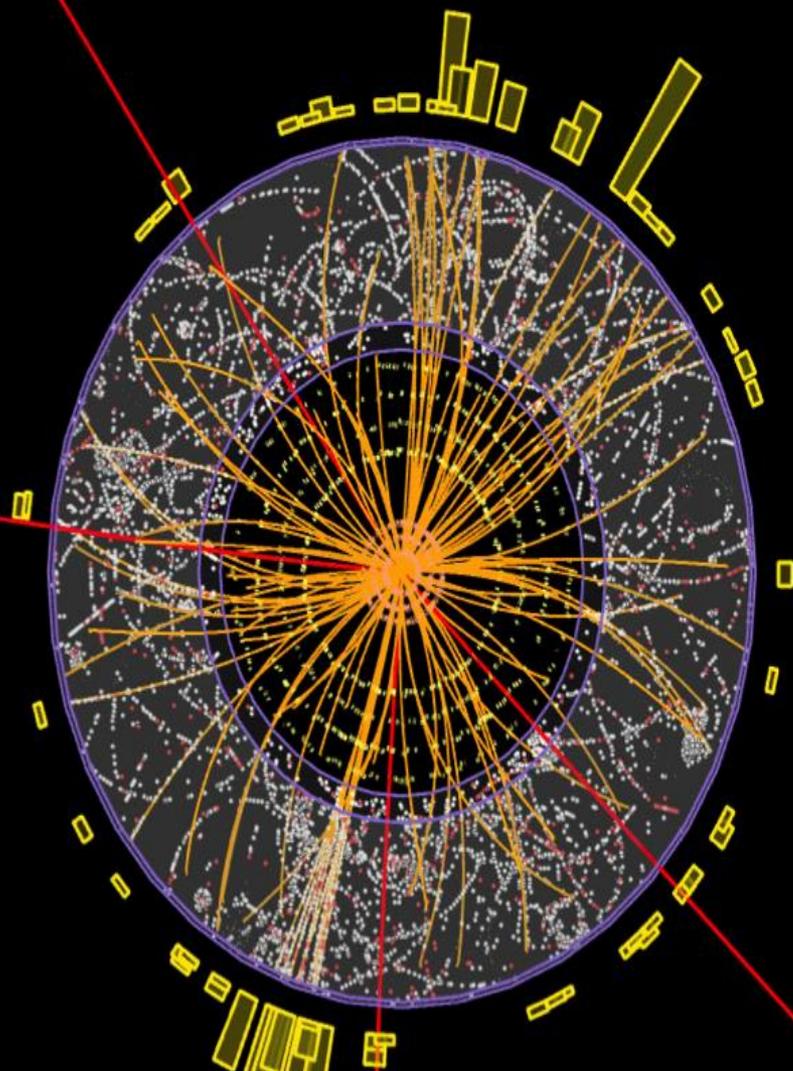
CMS Experiment at the LHC, CERN
 Data recorded: 2012-May-13 20:08:14.621490 GMT
 Run/Event: 194108 / 564224000



ATLAS
 EXPERIMENT
<http://atlas.ch>
 Run: 203602
 Event: 82614360
 Date: 2012-05-18
 Time: 20:28:11 CEST



It's very nice to be right sometimes ...” Peter Higgs



ATLAS
EXPERIMENT
<http://atlas.ch>

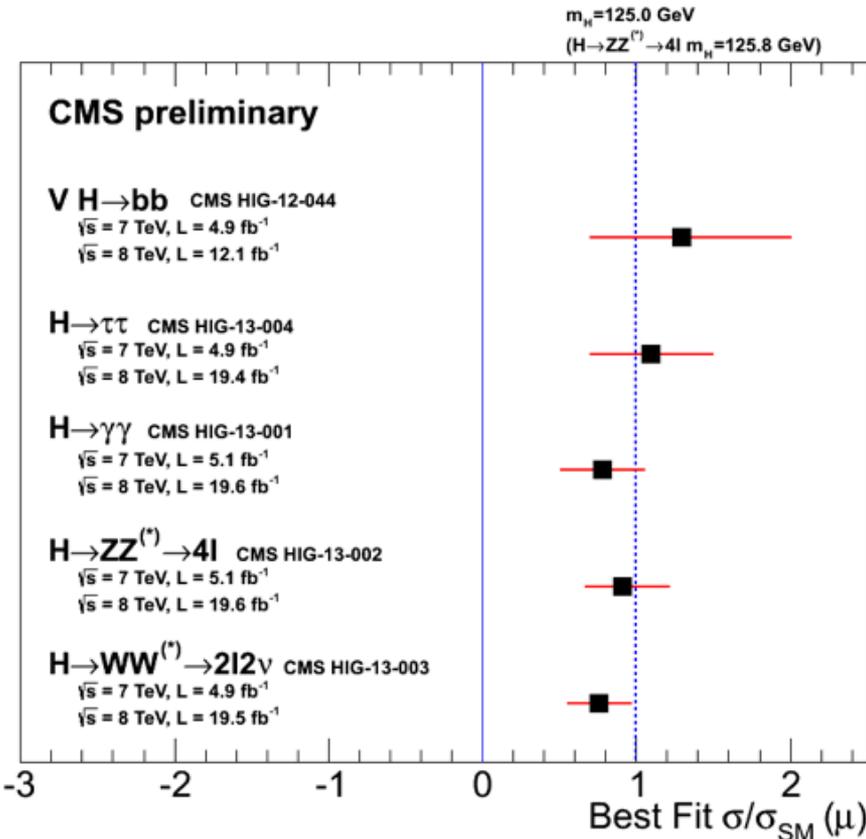
$$M_H = 125.5 \pm 0.2(\text{stat})_{-0.6}^{+0.5}(\text{sys}) \text{ GeV}$$

ATLAS-CONF-2013-014

CMS Combined Results



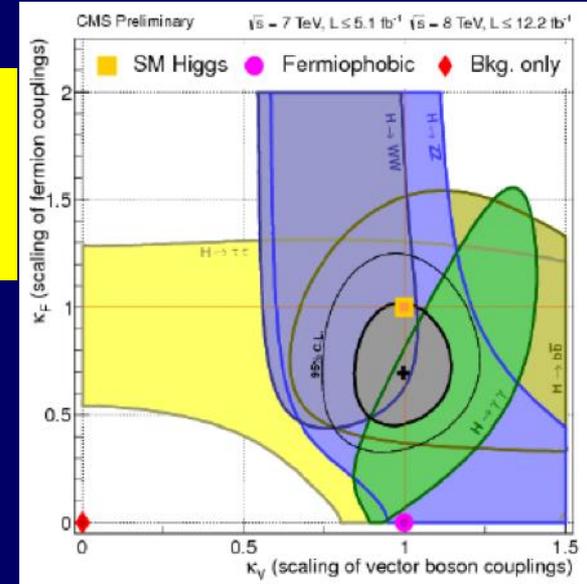
Signal strength with full statistics



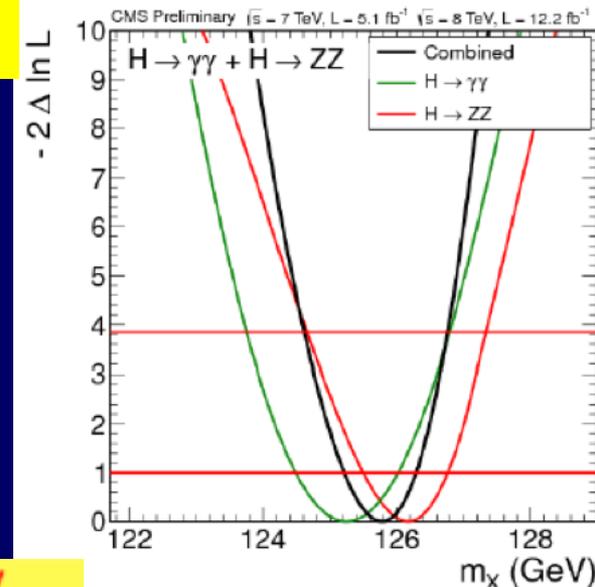
Compatible with the Standard Model

$m_H = 125.8 \pm 0.4(\text{stat}) \pm 0.4(\text{syst})$ GeV

Couplings to fermions and bosons



Higgs Mass



An impressive history...



Acknowledgements

- A very wide range of measurements have shown that SM predictions for known physics have been ~spot on.
 - A tribute to a large amount of work done by our theory colleagues along with the results from the other collider experiments at LEP, Tevatron, HERA, b-factories etc.
- And the Higgs cross section WG and all those theorists who prepared the way for today!

[1] S. Glashow, Nucl. Phys. 22 (1961) 579, doi:10.1016/0029-5582(61)90469-2.
 [2] S. Weinberg, Phys. Rev. Lett. 19 (1967) 1264, doi:10.1103/PhysRevLett.19.1264.
 [3] A. Salam, Weak and electromagnetic interactions, in: N. Svartholm (Ed.), Elementary Particle Physics: Relativistic Groups and Analyticity, Proceedings of the Eighth Nobel Symposium, Almquist and Wiskell, 1968, p. 367.

Electroweak Theory

Electroweak Symmetry Breaking

[4] F. Englert, R. Brout, Phys. Rev. Lett. 13 (1964) 321, doi:10.1103/PhysRevLett.13.321.
 [5] P.W. Higgs, Phys. Lett. 12 (1964) 132, doi:10.1016/0031-9163(64)91136-9.
 [6] P.W. Higgs, Phys. Rev. Lett. 13 (1964) 508, doi:10.1103/PhysRevLett.13.508.
 [7] G. Guralnik, C. Hagen, T.W.B. Kibble, Phys. Rev. Lett. 13 (1964) 585, doi:10.1103/PhysRevLett.13.585.
 [8] P.W. Higgs, Phys. Rev. 145 (1966) 1156, doi:10.1103/PhysRev.145.1156.
 [9] T.W.B. Kibble, Phys. Rev. 155 (1967) 1554, doi:10.1103/PhysRev.155.1554.

The Highlight of a Remarkable Year 2012



Volume 712, Issue 3, 6 June 2012 ISSN 0370-2693

ELSEVIER

PHYSICS LETTERS B

Available online at www.sciencedirect.com
SciVerse ScienceDirect

The cover features two main plots. The top plot shows the $S/(S+B)$ Weighted Events / 1.5 GeV versus m_H (GeV) for the ATLAS experiment. It includes data points, a total fit, and individual fit components for $s1\sigma$ and $s2\sigma$. The bottom plot shows the ATLAS 2011-12 search for the Higgs boson, plotting Local p_0 versus m_H [GeV]. It displays the observed data and the expected background, with significance contours for 2σ through 6σ .

<http://www.elsevier.com/locate/physletb>

The Economist

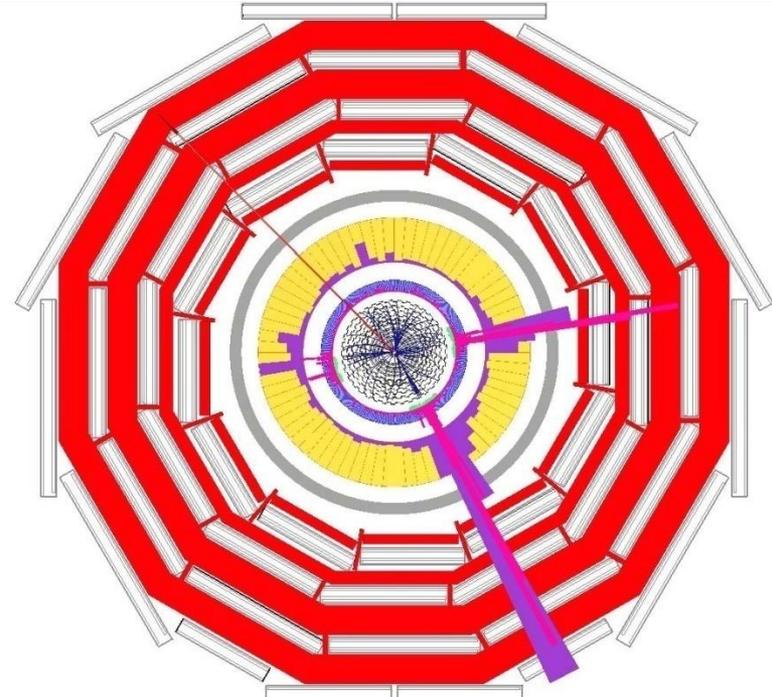
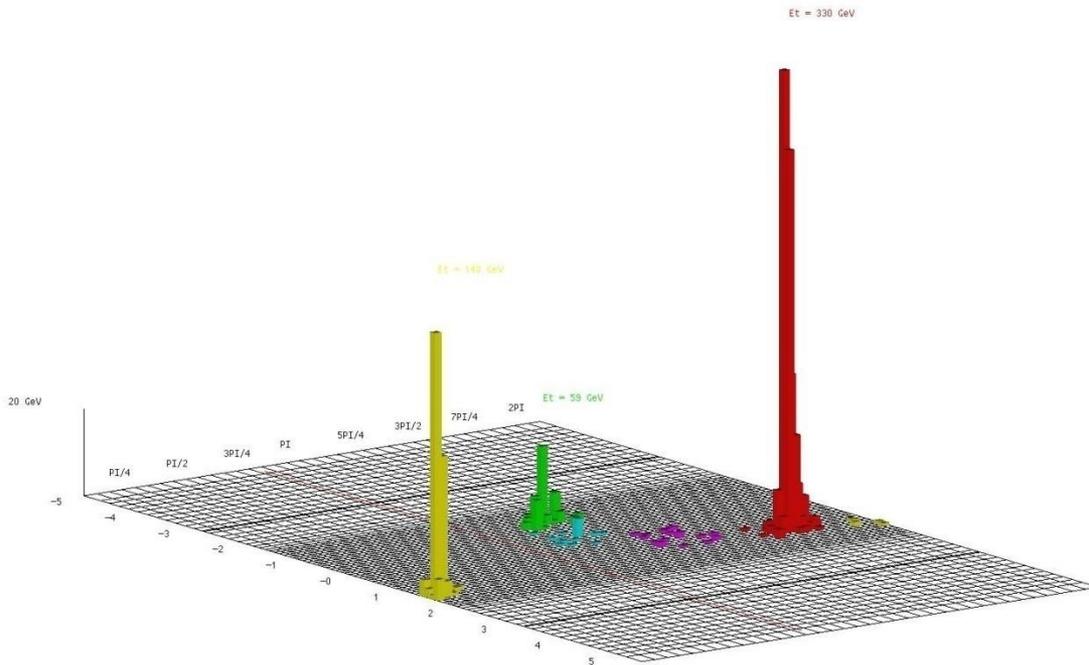
JULY 7TH - 13TH 2012 Economist.com

In praise of charter schools
Britain's banking scandal spreads
Volkswagen overtakes the rest
A power struggle at the Vatican
When Lonesome George met Nora

A giant leap for science

Finding the Higgs boson

Looking for Dark Matter



Missing energy
taken away by dark matter particles

No Black Holes yet!

CMS 4-Jet Event @ 2.36 TeV

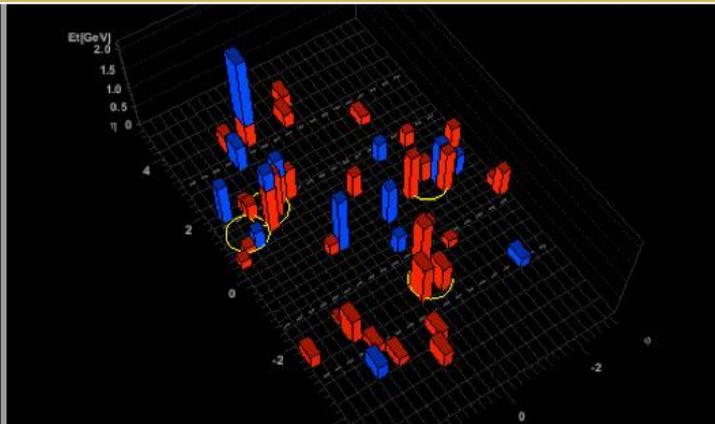
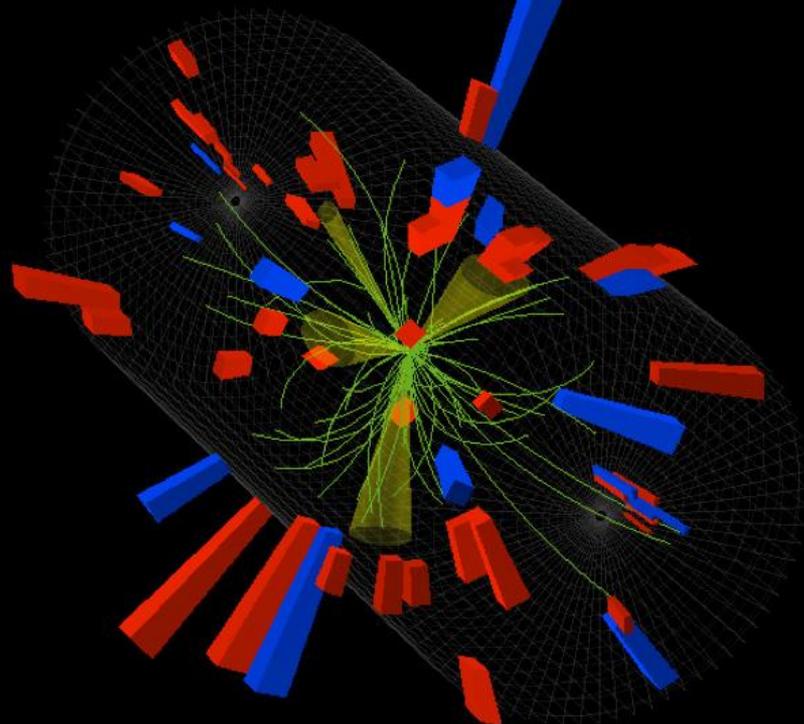


CMS Experiment at the LHC, CERN

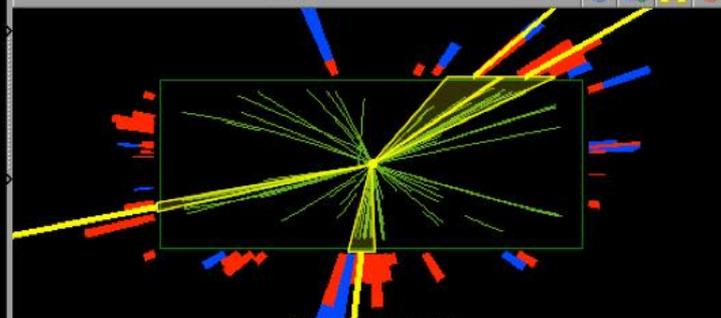
Date Recorded: 2009-12-14 05:41 CET

Run/Event: 124120/16701049

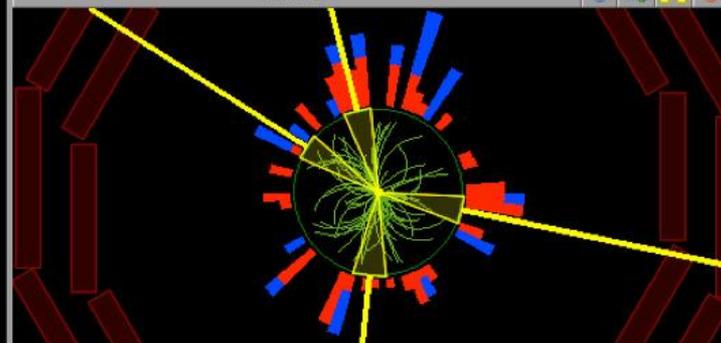
Candidate Multijet Event at 2.36 TeV



Rho Z



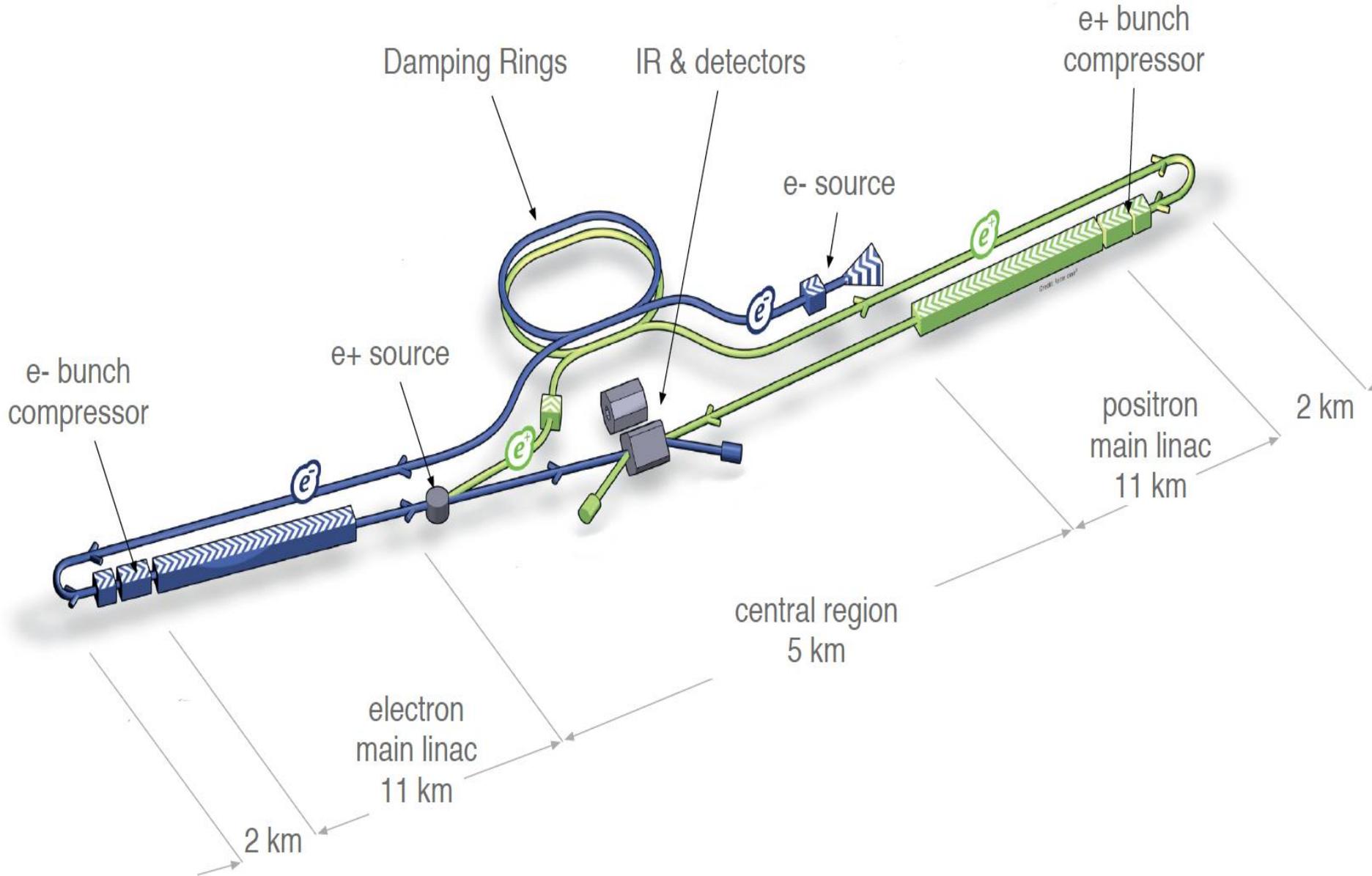
Rho Phi



The LHC

- ▣ Hard work and lots of outstanding results.
- ▣ Integrated luminosity records from accelerator.
- ▣ Great performance of the experiments.
- ▣ Grid computing performing exceptionally.
- ▣ So, what next?

The International Linear Collider (?)





shield wall removed

CERN Summer Student Programme

and
finally...

The LHC is helping to build the next generation of
world scientists and engineers

