

An aerial photograph of a rural landscape with a patchwork of green and brown fields. A large, circular white line is drawn over the landscape, representing the path of the Large Hadron Collider (LHC) tunnel. The line starts on the left, curves around the bottom, and continues on the right. A blue rectangular box is overlaid on the top half of the image, containing the title text in yellow. Another blue rectangular box is overlaid on the bottom half of the image, containing the speaker's name and affiliation in yellow, and the event details in white.

# Discovery Science with the Large Hadron Collider

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Department of Physics, University of Oxford

APPEAL  
University of Oxford  
9 June 2012



# The 'Standard Model'

= Cosmic DNA

## The matter particles



## The fundamental interactions



Gravitation

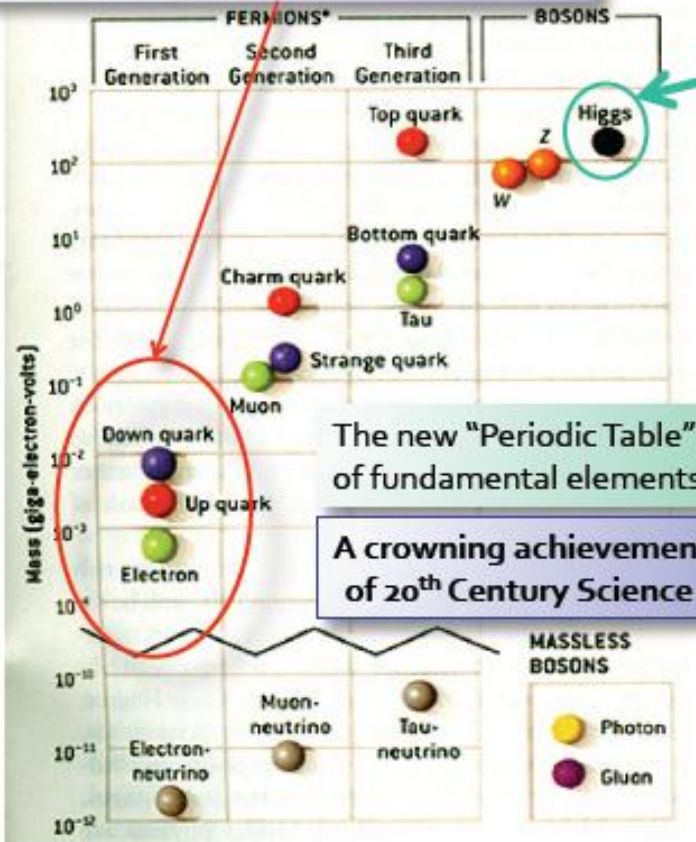
electromagnetism

weak nuclear force

strong nuclear force

# The Standard Model of Particle Physics

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



The new "Periodic Table" of fundamental elements

A crowning achievement of 20<sup>th</sup> Century Science

## The Standard Model

1 Missing piece: Higgs

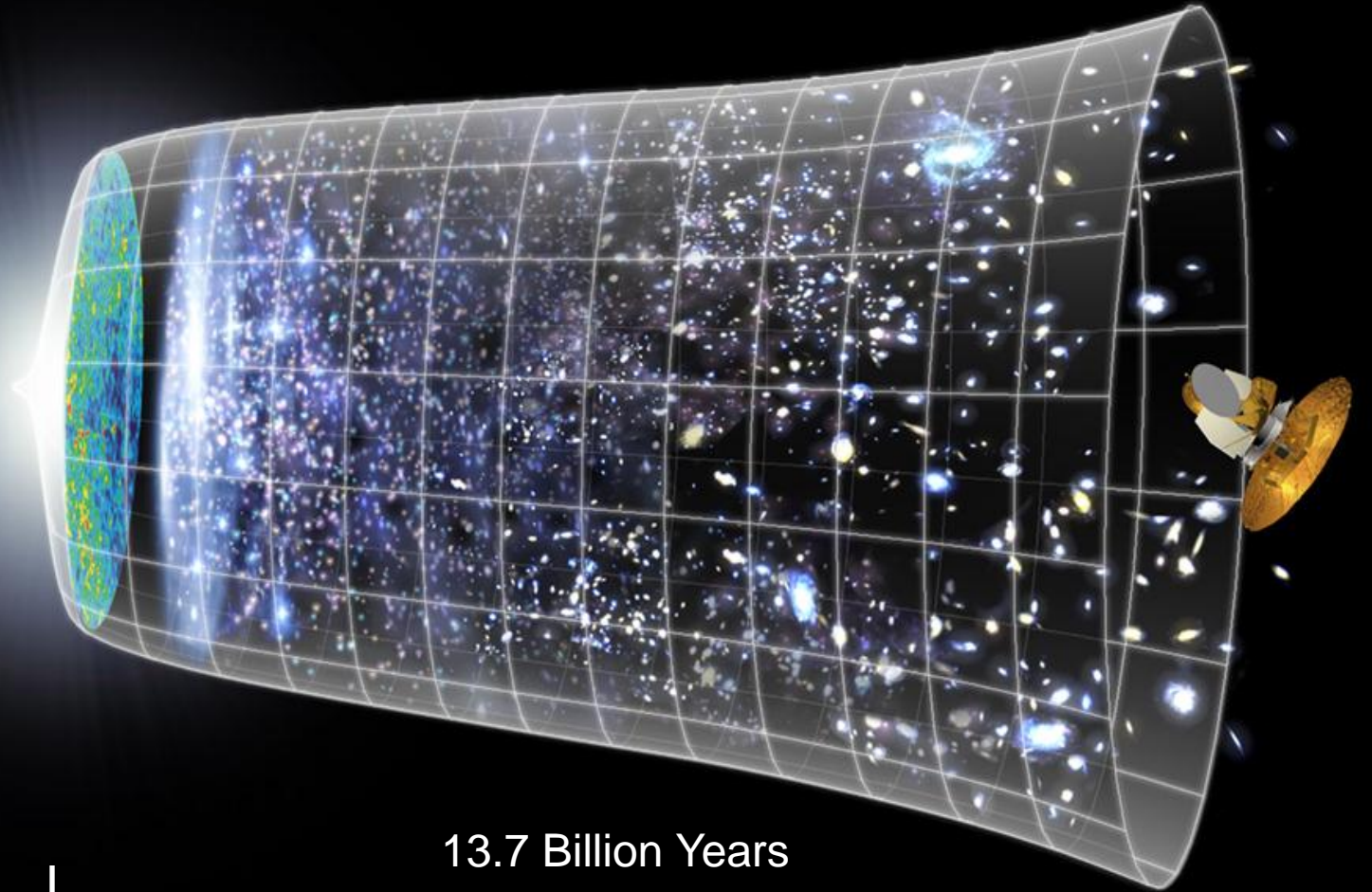
	Measurement	Fit	$ O_{meas} - O_{fit}  / O_{meas}$
$\Delta\alpha_{had}^{(5)}(m_Z)$	$0.02758 \pm 0.00035$	0.02766	0.00008
$m_Z$ [GeV]	$91.1875 \pm 0.0021$	91.1874	0.00001
$\Gamma_Z$ [GeV]	$2.4952 \pm 0.0023$	2.4957	0.00020
$\sigma_{had}^0$ [nb]	$41.540 \pm 0.037$	41.477	0.015
$R_b$	$20.767 \pm 0.025$	20.744	0.0011
$A_{fb}^{0,b}$	$0.01714 \pm 0.00095$	0.01640	0.0043
$A_1(P_e)$	$0.1465 \pm 0.0032$	0.1479	0.0095
$R_b$	$0.21629 \pm 0.00066$	0.21585	0.0020
$R_c$	$0.1721 \pm 0.0030$	0.1722	0.0006
$A_{fb}^{0,b,c}$	$0.0992 \pm 0.0016$	0.1037	0.045
$A_{fb}^{0,c}$	$0.0707 \pm 0.0035$	0.0741	0.048
$A_b$	$0.923 \pm 0.020$	0.935	0.013
$A_c$	$0.670 \pm 0.027$	0.668	0.003
$A_1(SLD)$	$0.1513 \pm 0.0021$	0.1479	0.023
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	$0.2324 \pm 0.0012$	0.2314	0.0043
$m_W$ [GeV]	$80.392 \pm 0.029$	80.371	0.0026
$\Gamma_W$ [GeV]	$2.147 \pm 0.060$	2.091	0.026
$m_t$ [GeV]	$171.4 \pm 2.1$	171.7	0.0017

Summer, 2006

Confirmed at sub 1% level

# Evolution of the Universe

Big Bang



13.7 Billion Years

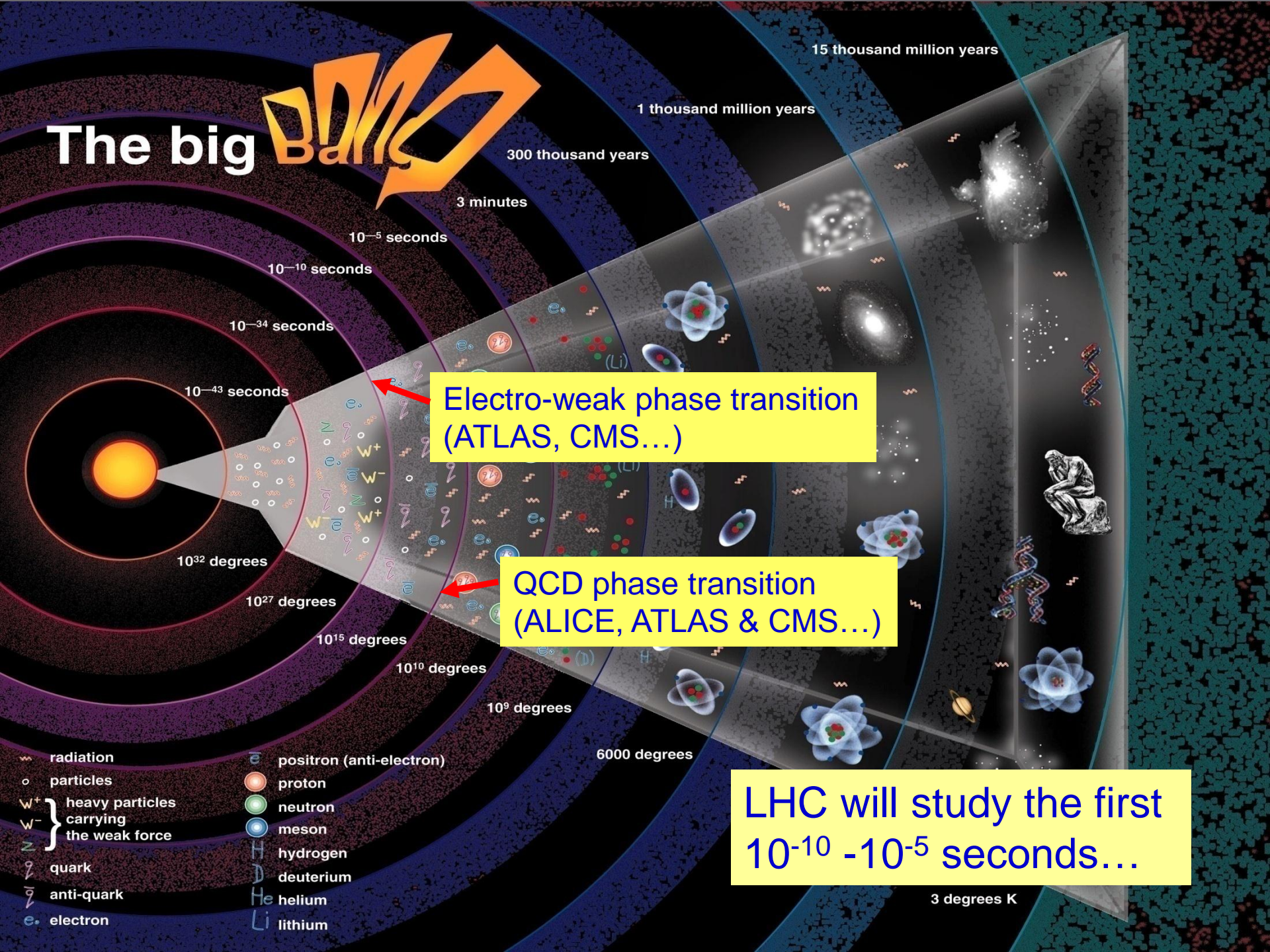
$10^{28}$  cm

Today

NASA WMAP



# The big Bang



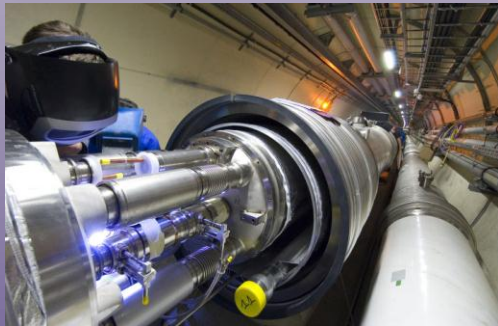
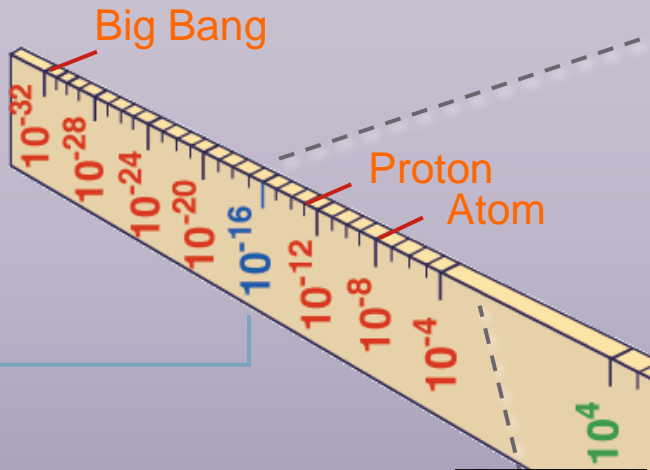
Electro-weak phase transition (ATLAS, CMS...)

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

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

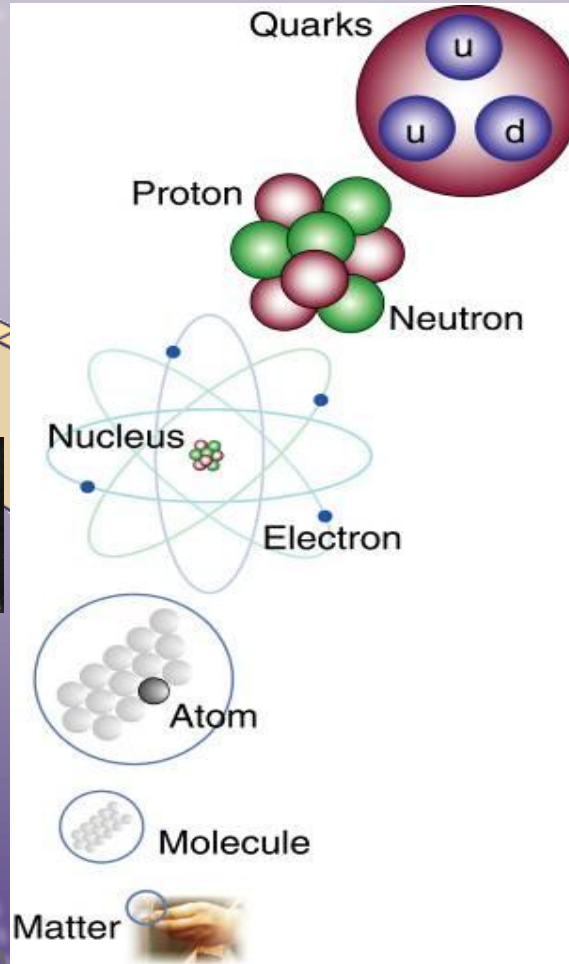
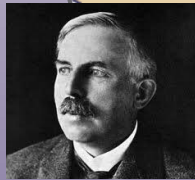
- ☞ radiation
- particles
- W<sup>+</sup> } heavy particles carrying the weak force
- W<sup>-</sup> }
- Z
- q quark
- q̄ anti-quark
- e<sup>-</sup> electron
- e<sup>+</sup> positron (anti-electron)
- p proton
- n neutron
- M meson
- H hydrogen
- D deuterium
- He helium
- Li lithium





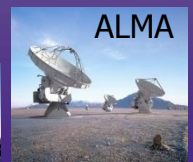
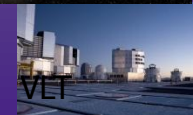
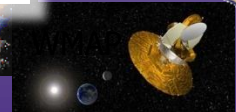
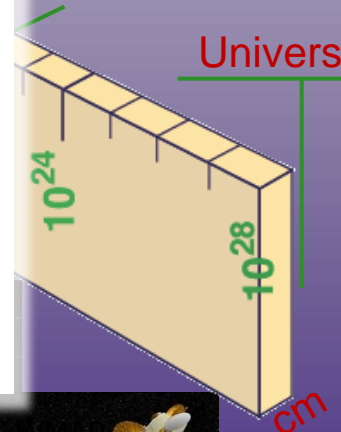
LHC

Super-Microscope



Radius of Galaxies

Universe



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

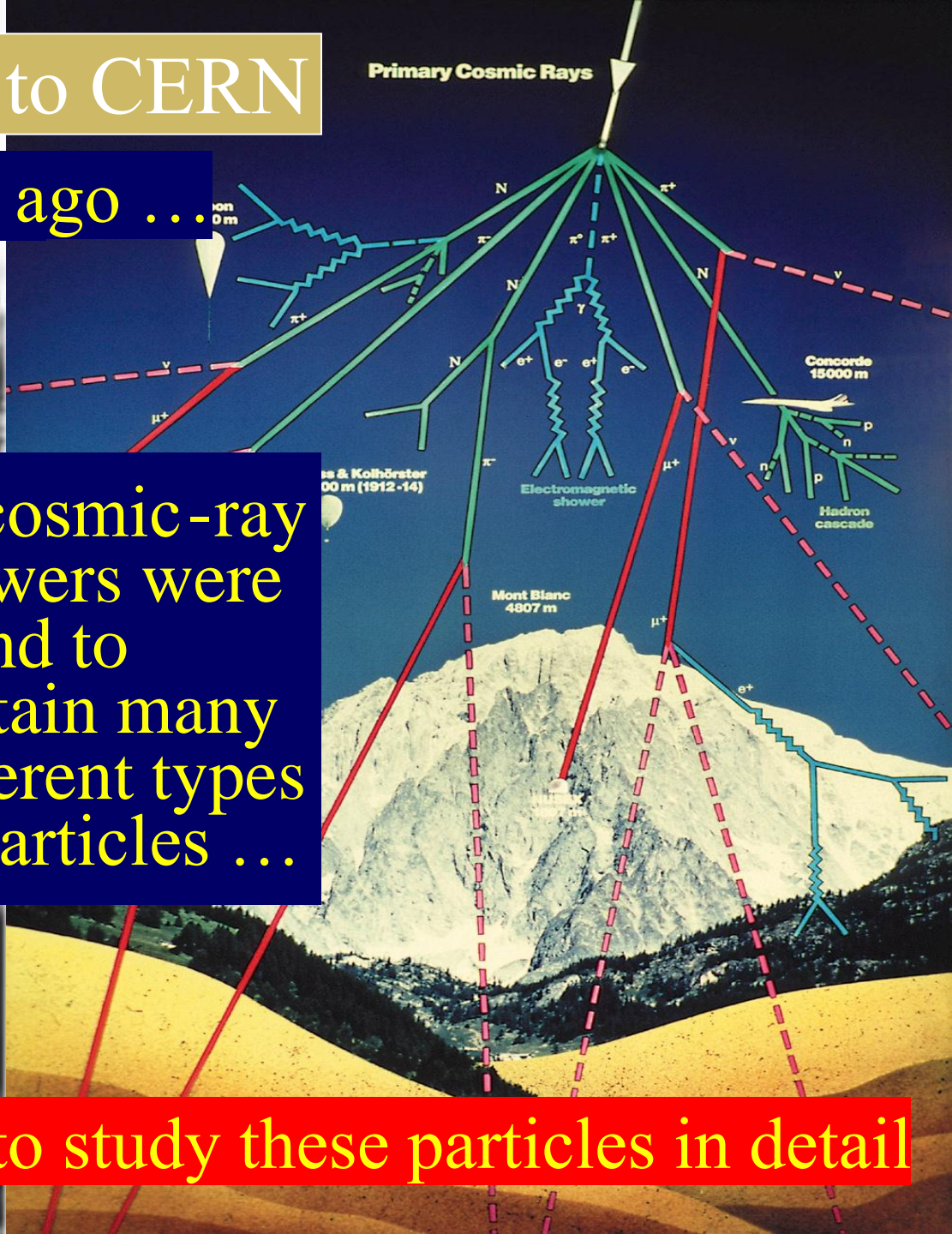
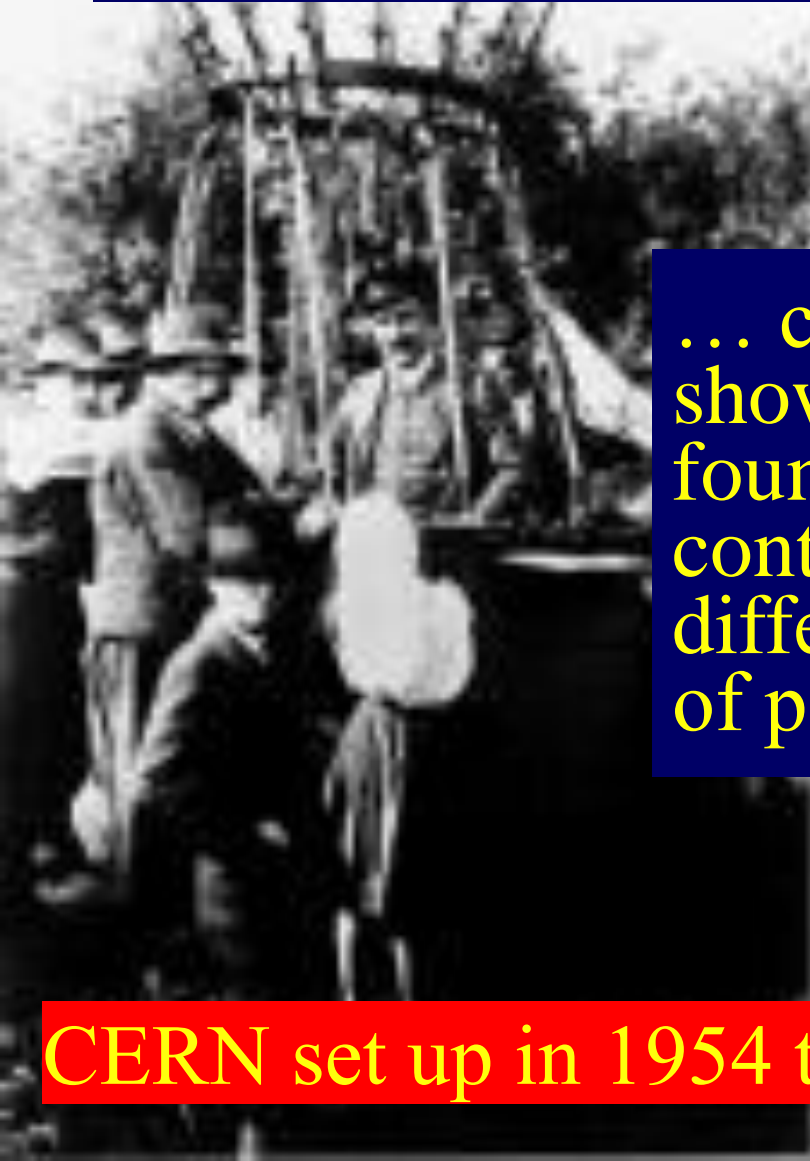


# From Cosmic Rays to CERN

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)





# Dark Matter in the Universe

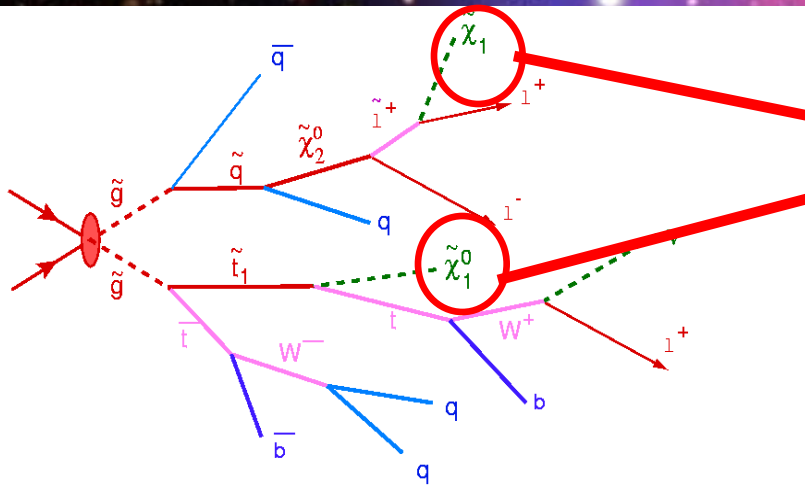
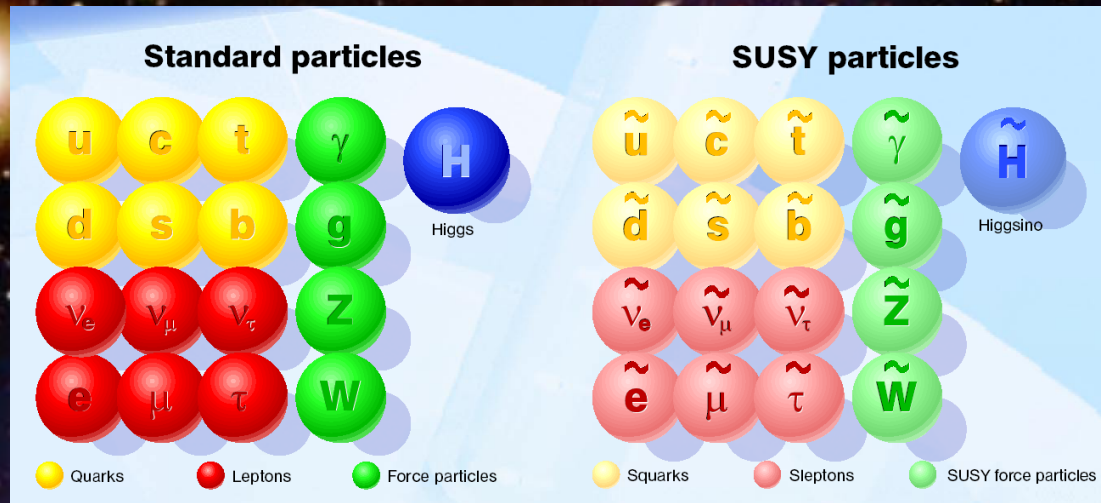
The background of the slide is a composite image. On the left, there is a close-up of a spiral galaxy with a bright central core and distinct spiral arms. On the right, there is a field of stars, with a prominent bright orange star in the upper right corner. The overall color palette is dark, with blues, purples, and oranges.

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

**‘Supersymmetric’ particles ?**

We shall look for  
them with the  
LHC

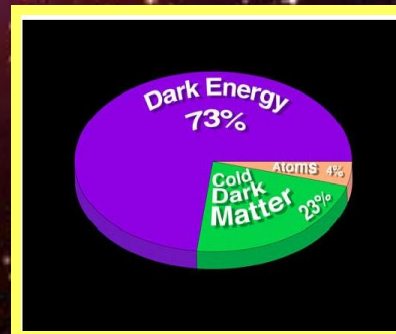
# Supersymmetry: A New Symmetry in Nature



Candidate Particles for Dark Matter  
 $\Rightarrow$  Produce Dark Matter in the lab

SUSY particle production at the LHC

3 isolated leptons  
 + 2 b-jets  
 + 4 jets  
 +  $E_t^{\text{miss}}$





# 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



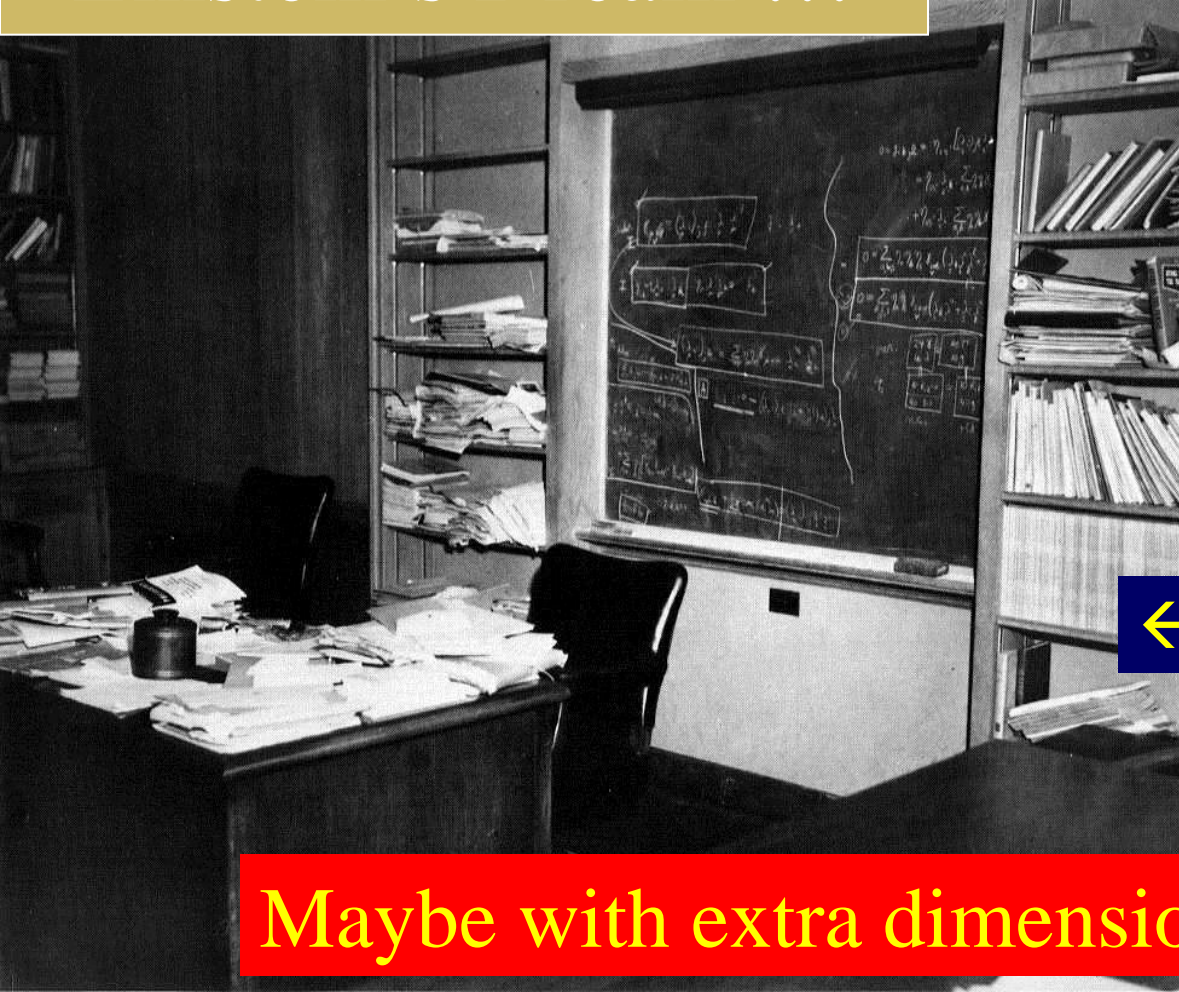
Matter and antimatter not quite equal and opposite: WHY?

2008 Nobel Physics Prize: Kobayashi & Maskawa

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

LHC experiments will look for answer

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

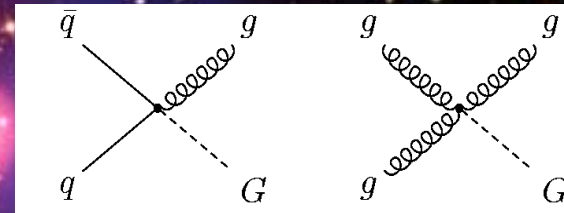
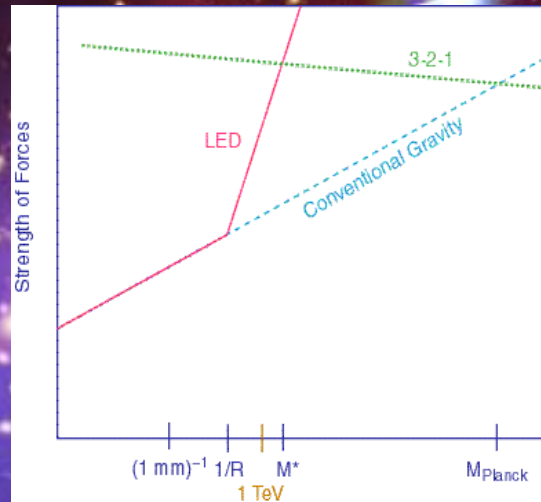
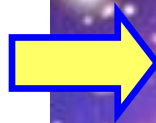
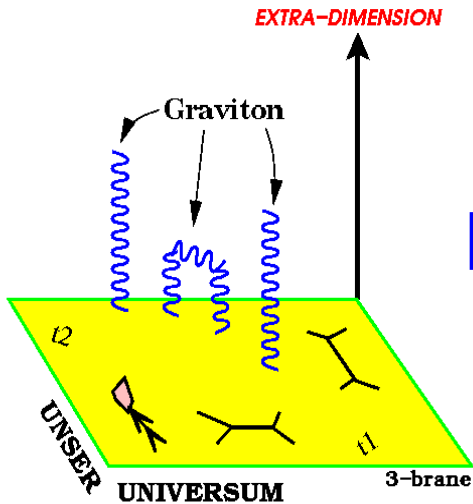


← ... but he never succeeded

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!

To answer these questions:

## The Large Hadron Collider (LHC)

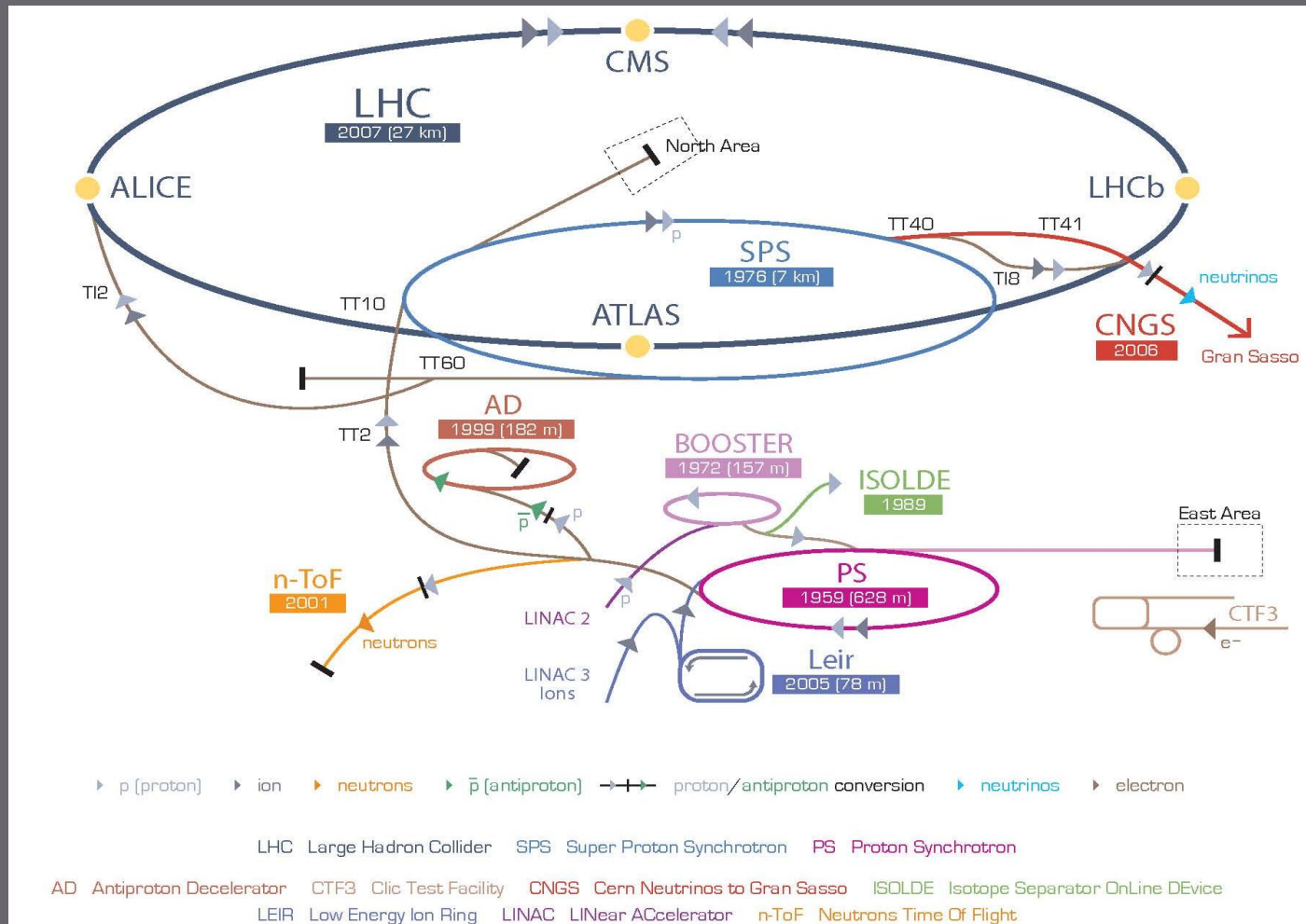
Several thousand billion protons  
Each with the energy of a fly  
99.9999991% of light speed  
Orbit 27km ring 11 000 times/second  
A billion collisions a second

Primary targets:

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



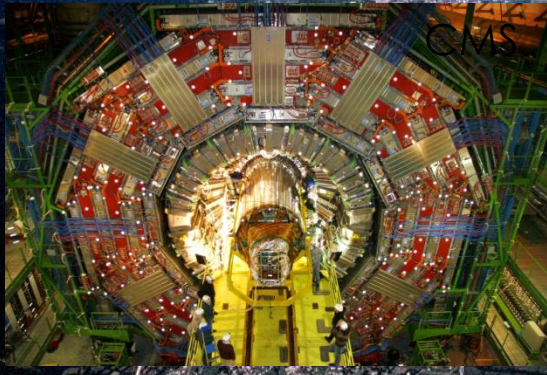
# CERN Accelerator Complex



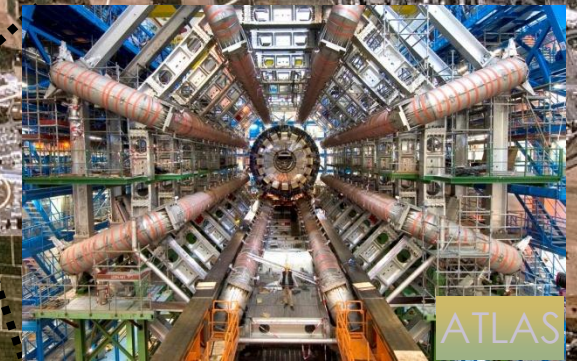


# Enter a New Era in Fundamental Science

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.

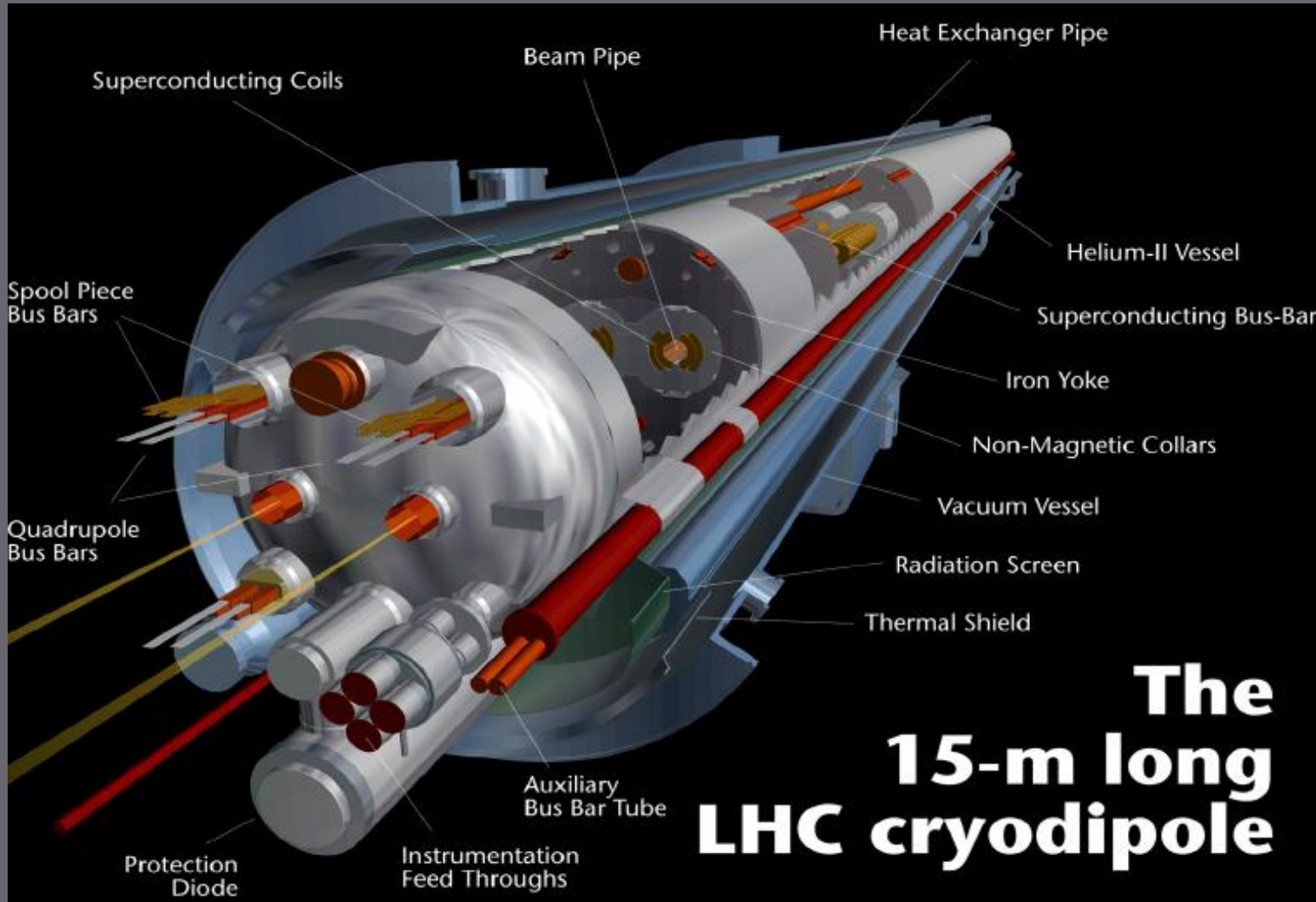


Exploration of a new energy frontier  
Proton-proton collisions at  $E_{\text{CM}} = 14 \text{ TeV}$





# LHC Main Bending Cryodipole



8.5 T  
nominal field

12 kA  
nominal field

**The  
15-m long  
LHC cryodipole**



**The LHC Arcs**

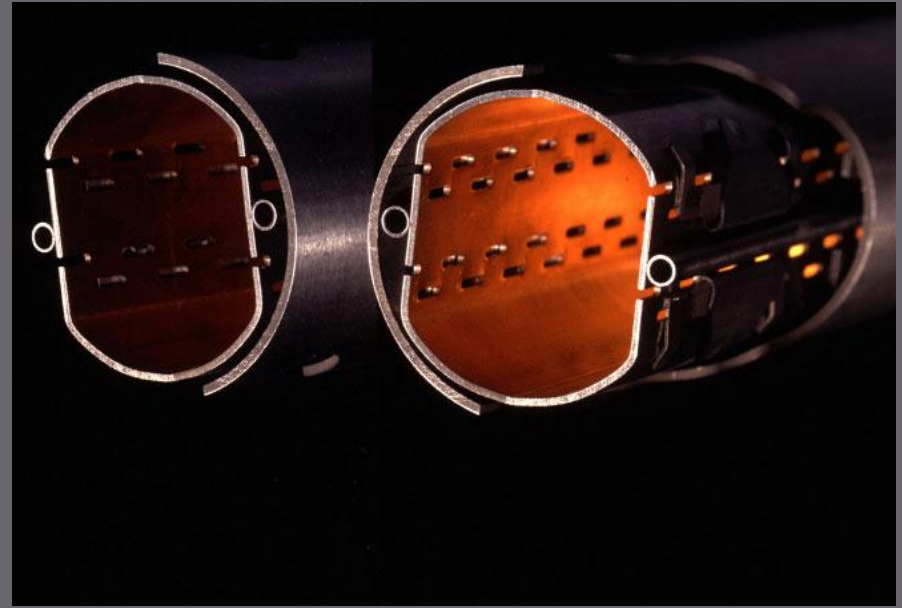
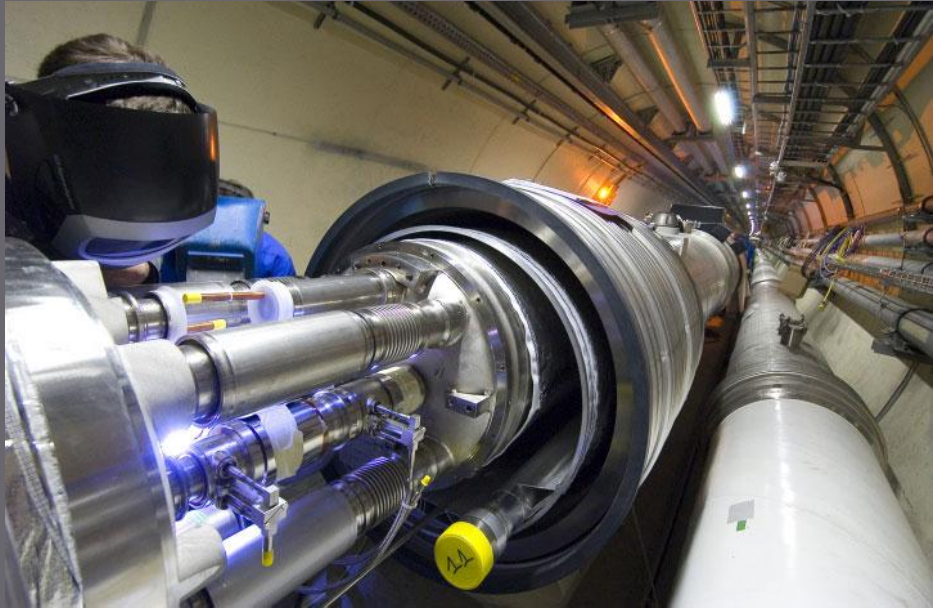


# The **fastest** racetrack on the planet...



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.

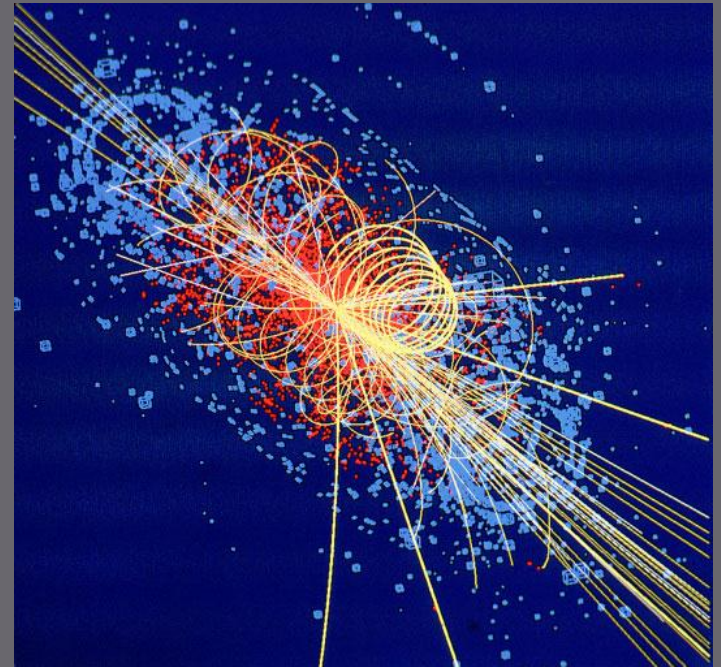
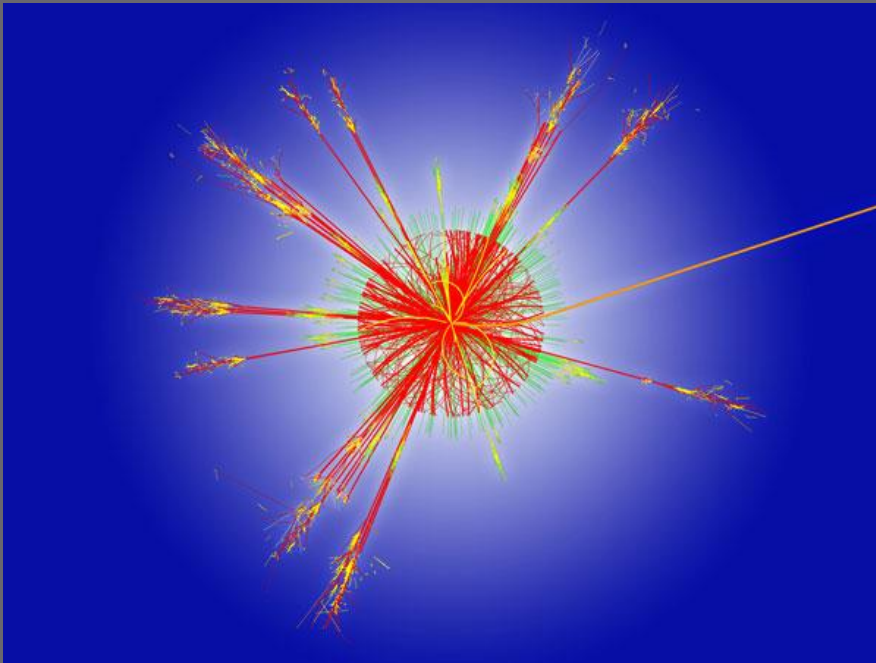


# One of the **coldest** places in the universe...



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...



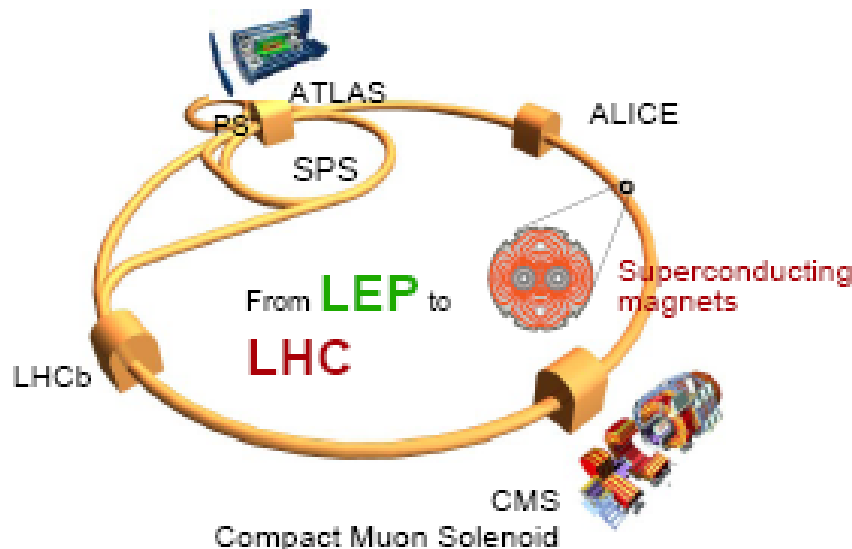
When two beams of protons collide, they will generate temperatures 1000 million times hotter than the heart of the sun, but in a minuscule space.



# 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)

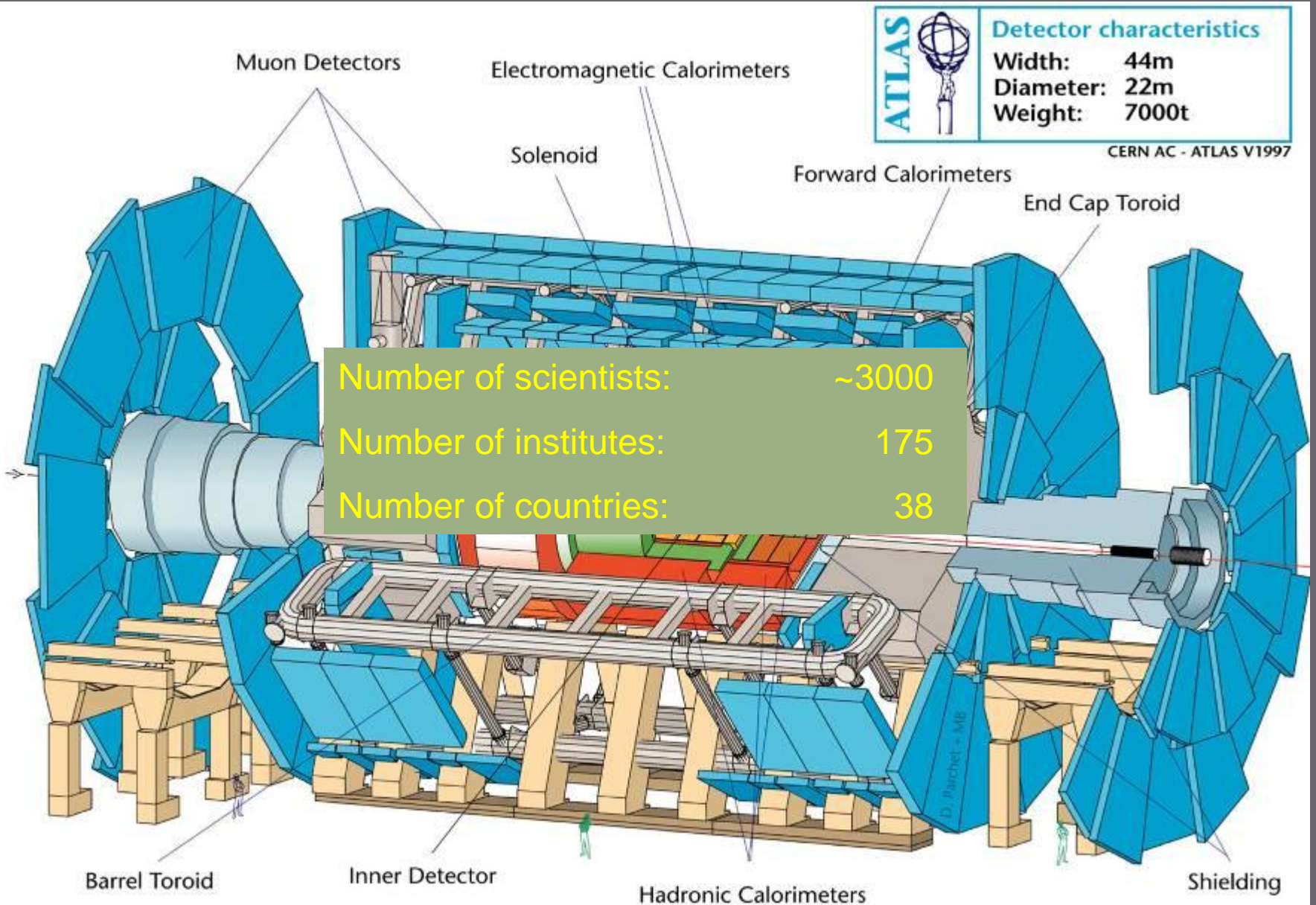


High repetition rate

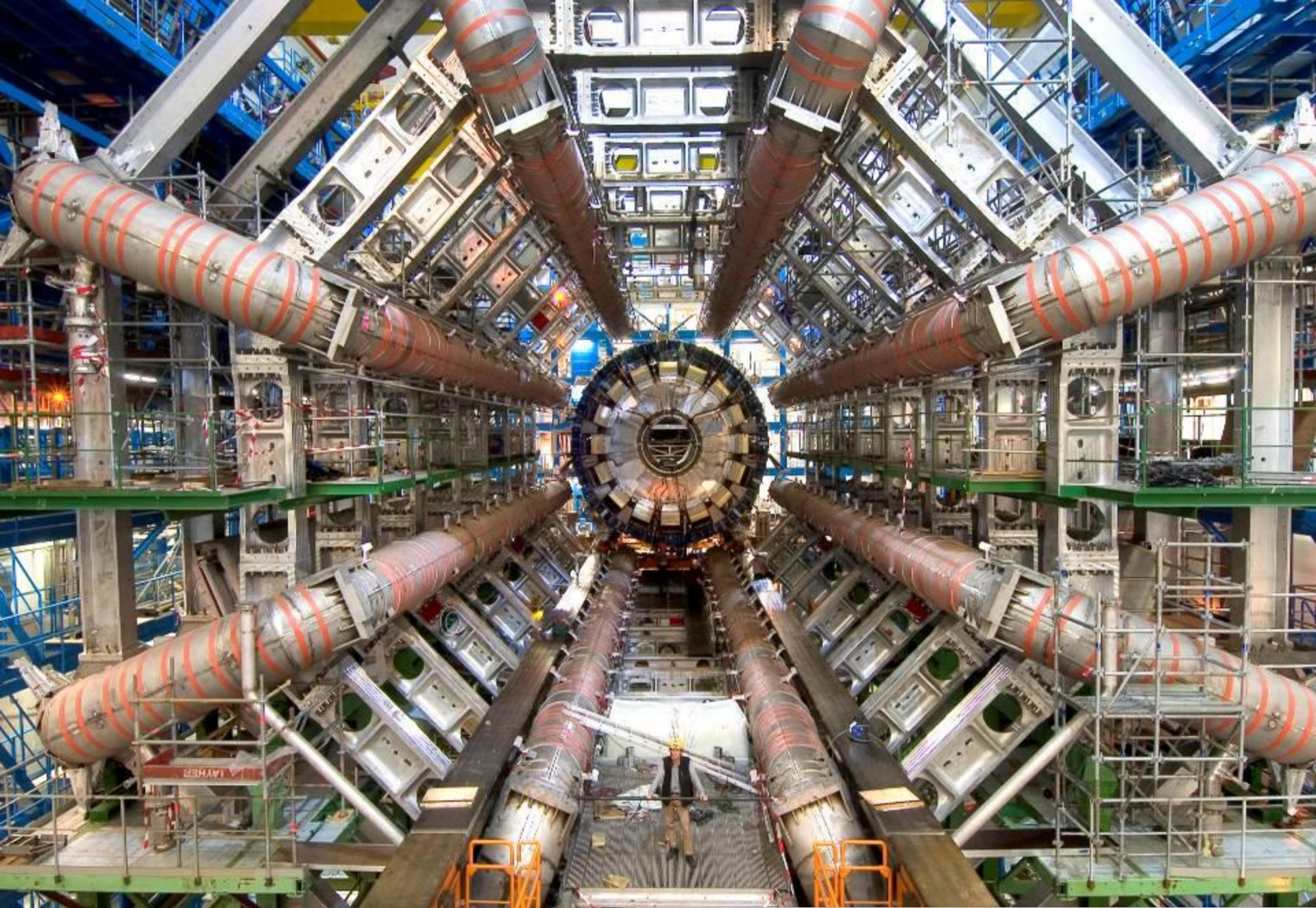
40 MHz or  
25 ns bunch spacing

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

# The ATLAS Experiment







**The ATLAS Experiment**





A billion people watched on TV



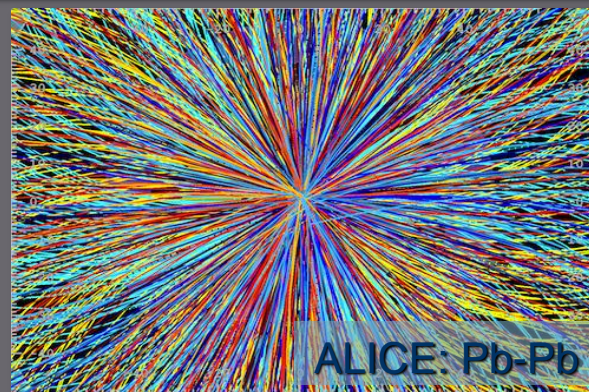
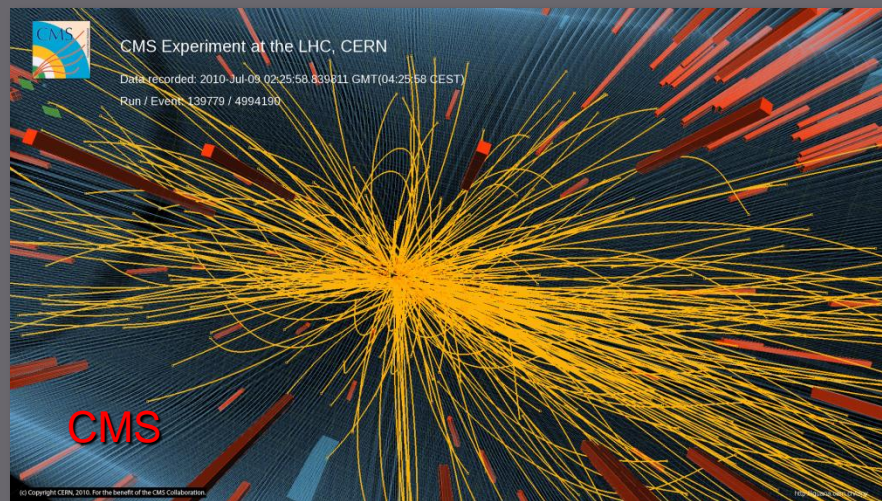
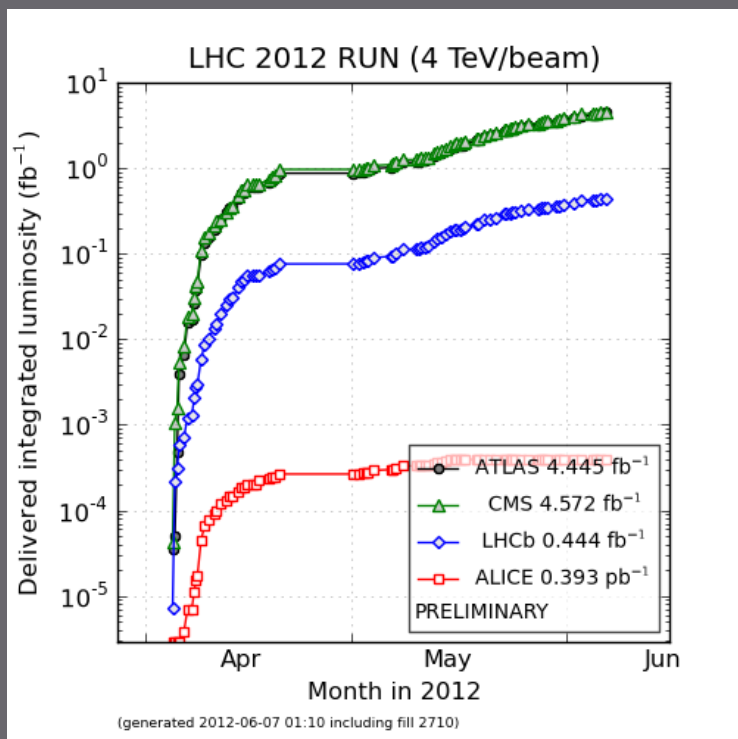
# The LHC Enters Popular Culture



# LHC + Experiments: spectacular start-up on 30 March 2010



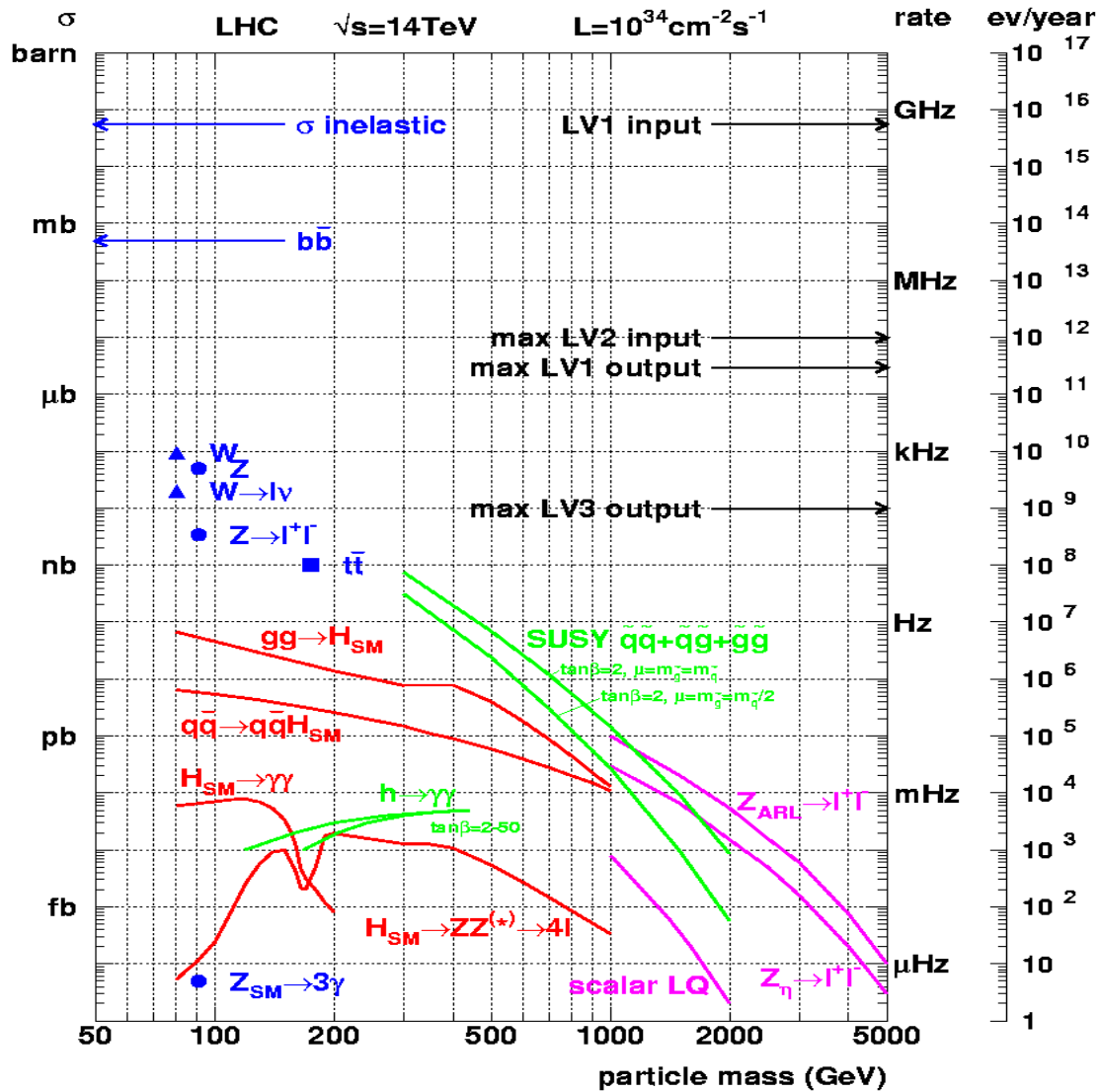
→ Brilliant performances of LHC, experiments and GRID computing during 2010 and 2011 data taking periods



→ 2012 run:  
energy increase (7 TeV  $\rightarrow$  8 TeV), factor 3  
more data expected from LHC



# Cross sections at the LHC



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

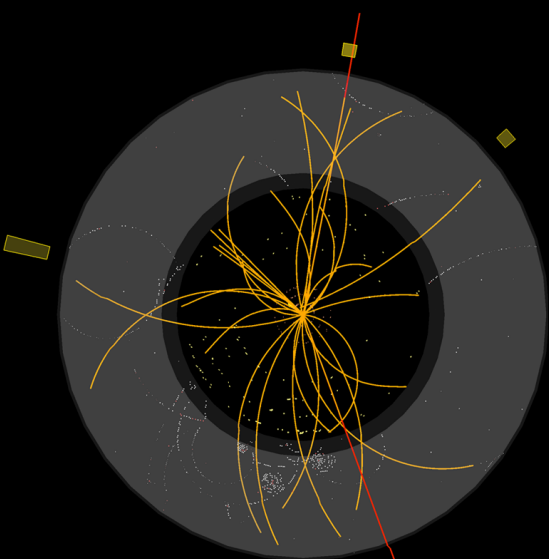
New Physics!!  
We want to keep!!

# The Story so Far ...



# ATLAS EXPERIMENT

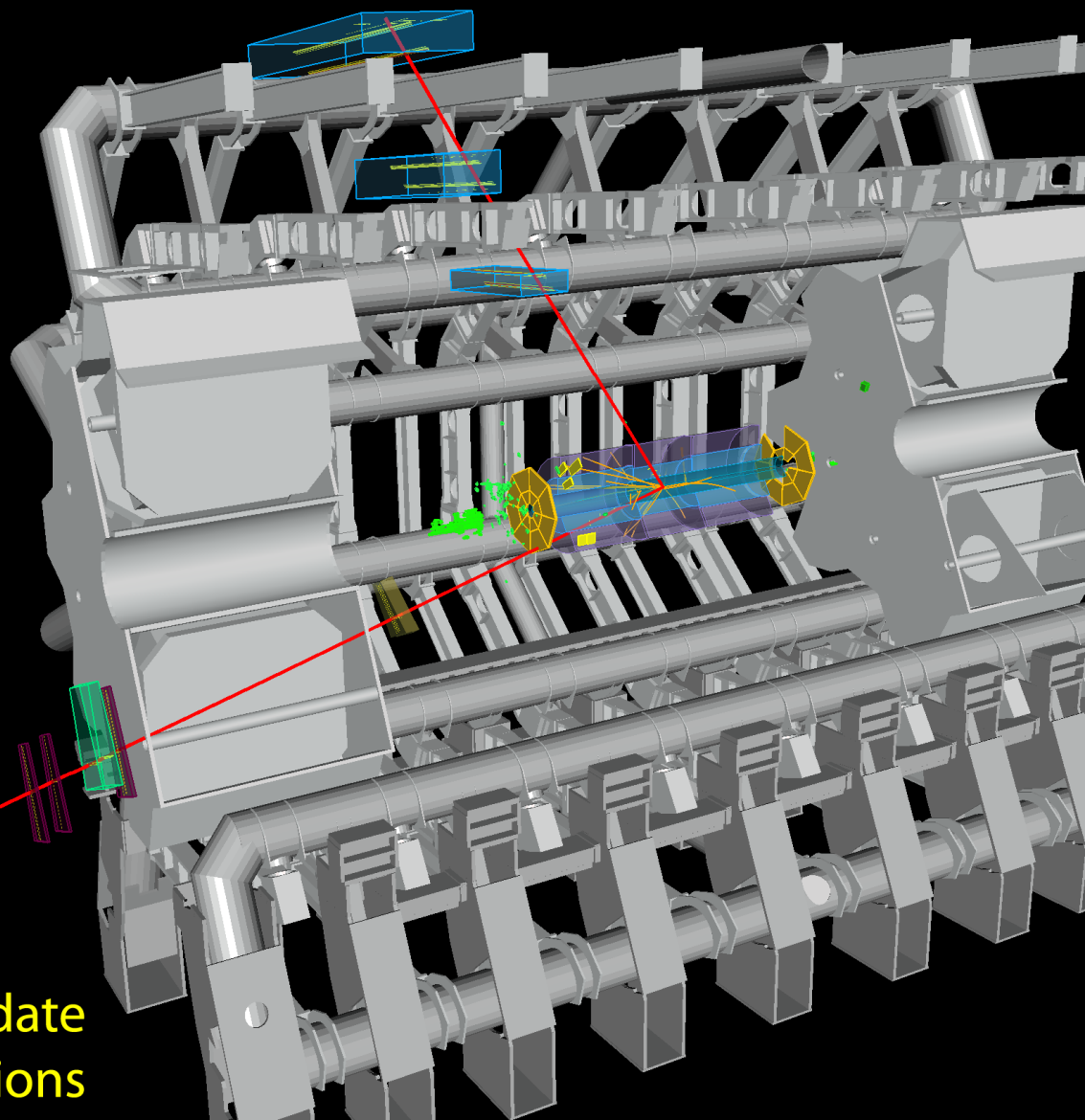
Run: 154822, Event: 14321500  
Date: 2010-05-10 02:07:22 CEST



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

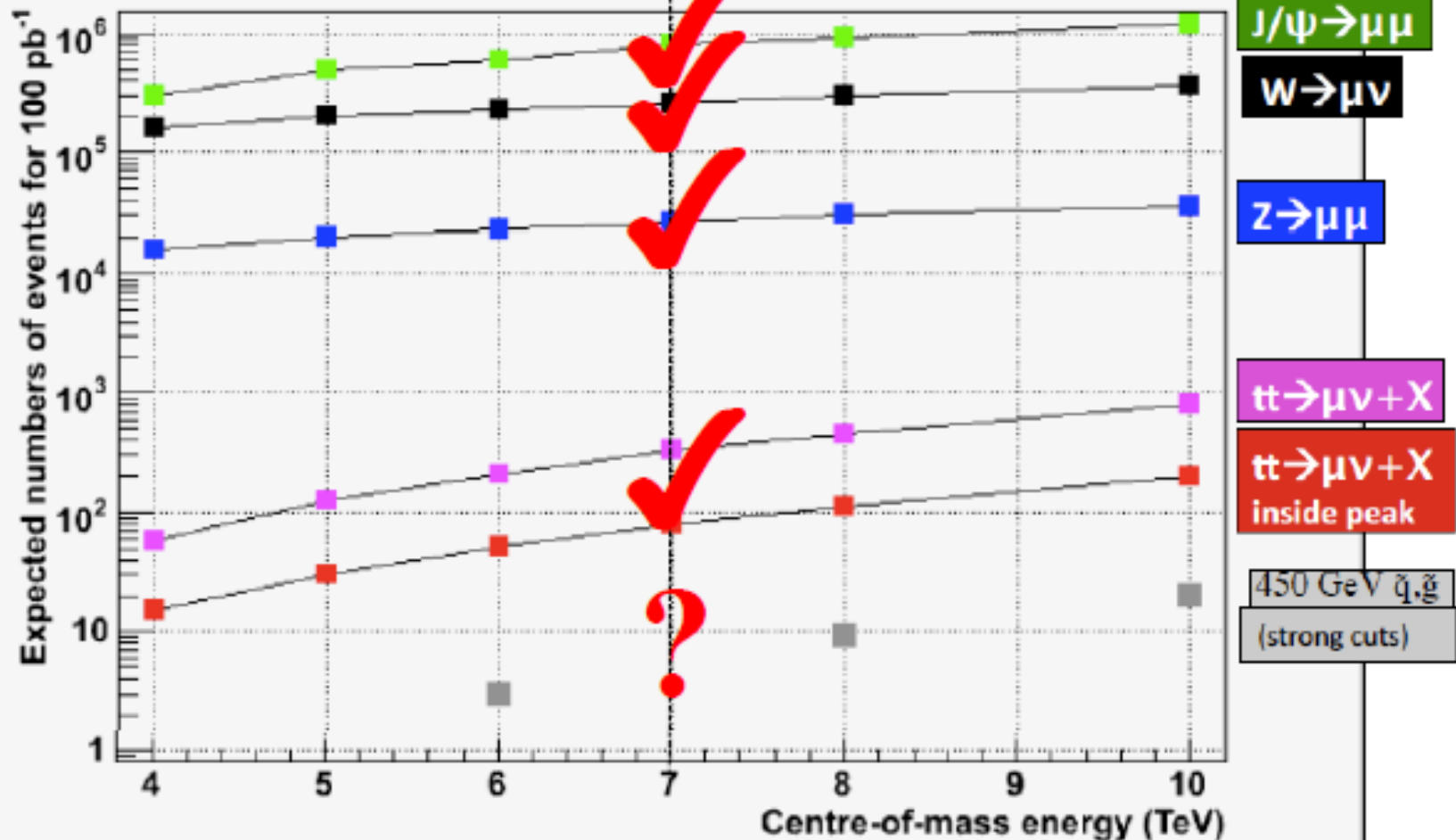


**Z $\rightarrow\mu\mu$  candidate  
in 7 TeV collisions**





# The Story so far – and to come





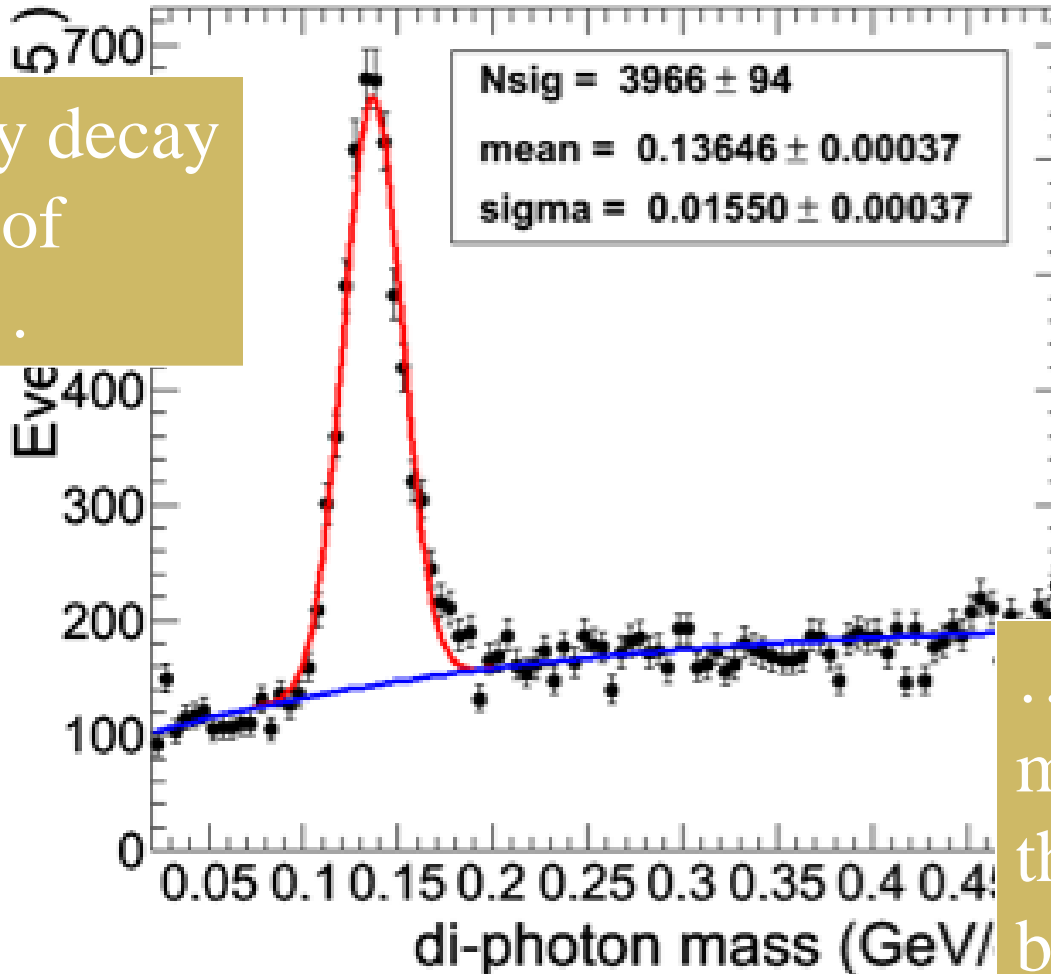
# A Simulated Higgs Event





# No Higgs yet!

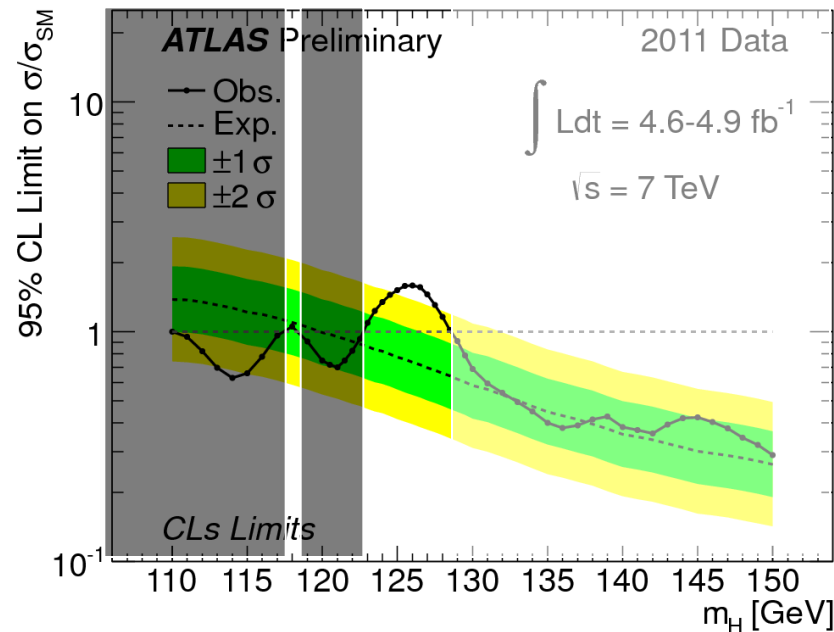
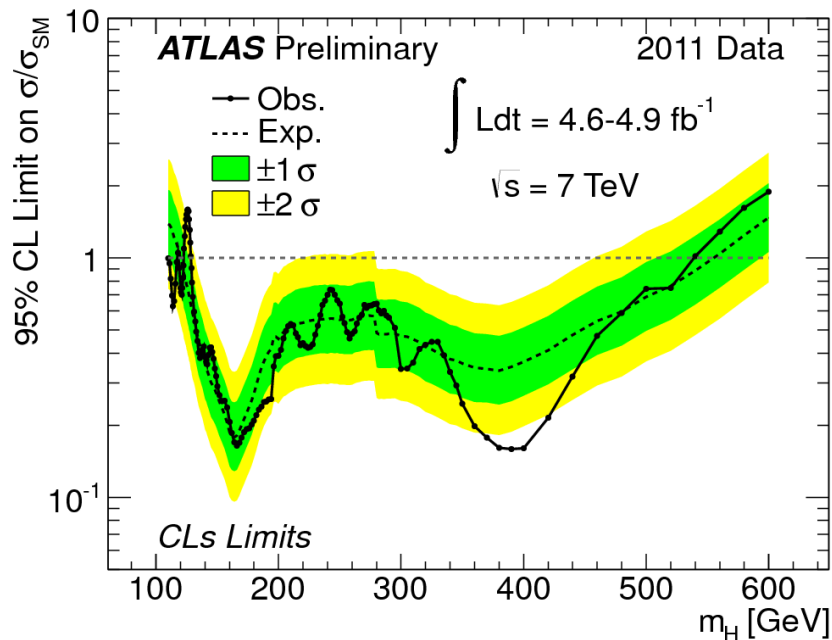
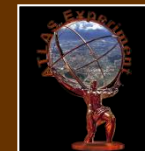
CMS preliminary 2009, 900 GeV data



Higgs may decay into pairs of photons ...

... but the Higgs mass is about a thousand times bigger!

# ATLAS HIGGS SEARCH



Excluded at 95% CL

$110 < m_H < 122.5 \text{ GeV}$  (except  $117.5-118.5$ )  
 $129 < m_H < 539 \text{ GeV}$

Expected if no signal

120-555 GeV

Excluded at 99% CL

$130 < m_H < 486 \text{ GeV}$

Combining all (12) channels together, full 2011 dataset

NEW: full  
2011 dataset



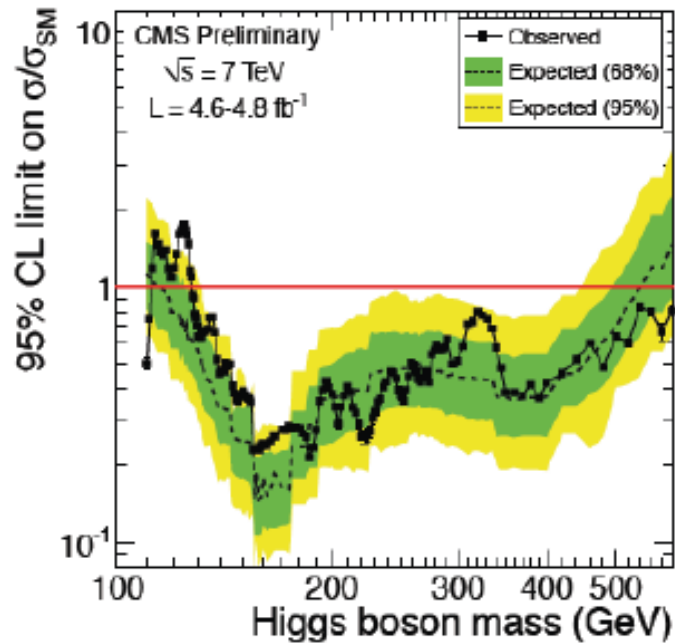
# CMS Higgs Search



J. Incandela CERN/UCSB

April 23, 2012 RRB 34 Meeting

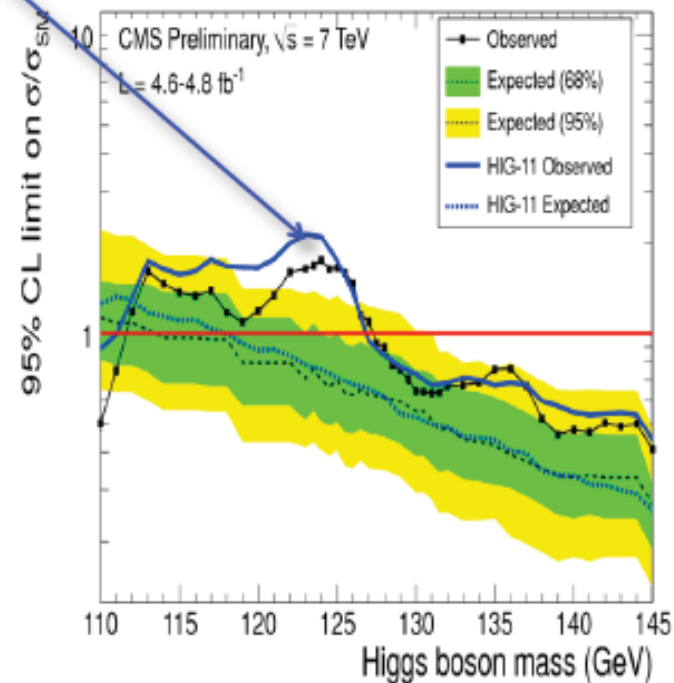
Published



It took ~30 years to experimentally restrict the SM Higgs mass to be above 114 GeV  
 CMS and ATLAS independently eliminated another ~475 GeV of the range in 2011

## New Combination

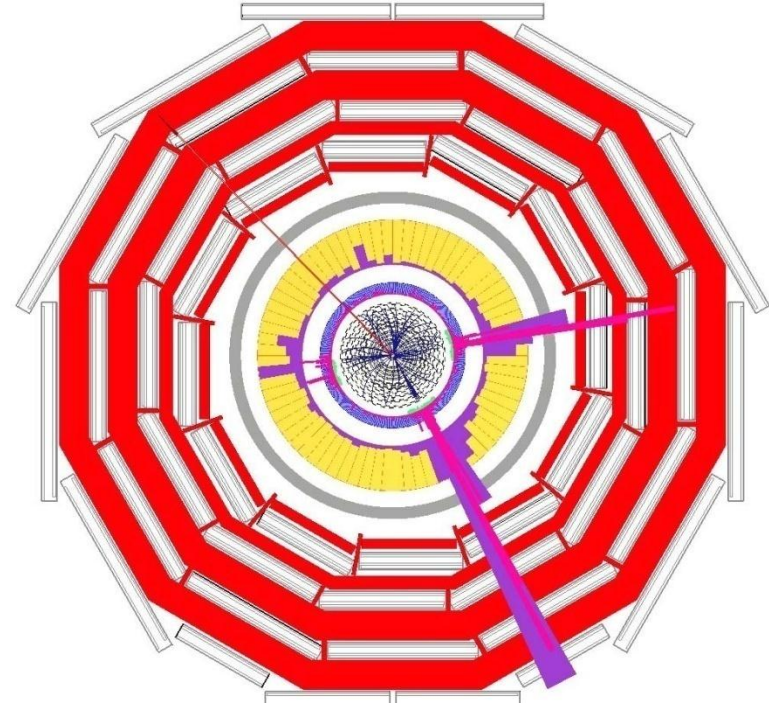
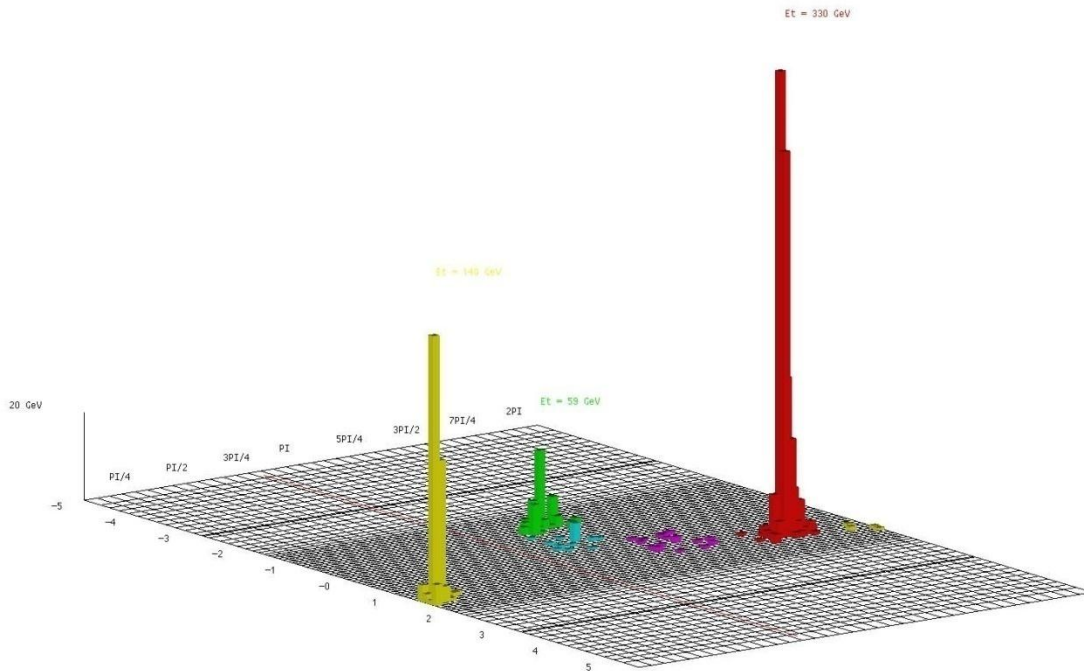
13



Expected exclusion 114.5 - 543 GeV  
 Observed exclusion 127.5 - 600 GeV

13

# Looking for Dark Matter



Missing energy  
taken away by dark matter particles



# No Black Holes yet!

## CMS 4-Jet Event @ 2.36 TeV

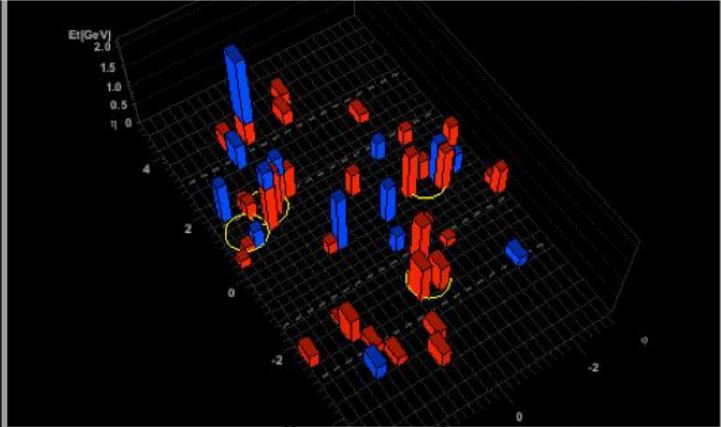
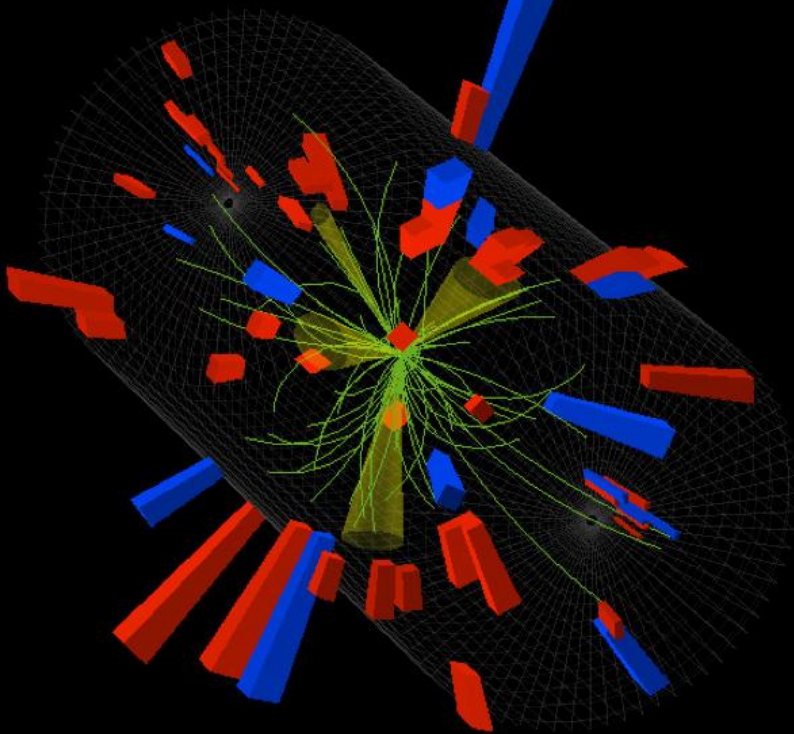


CMS Experiment at the LHC, CERN

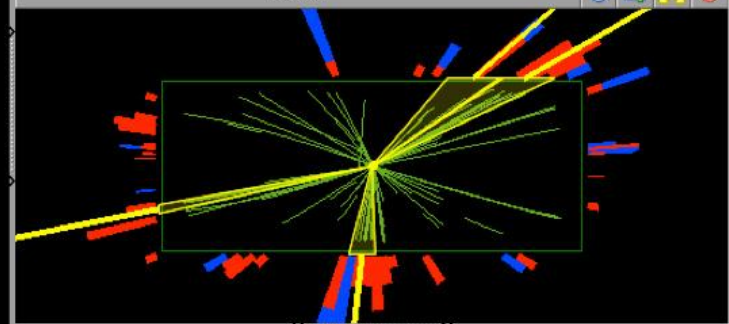
Date Recorded: 2009-12-14 05:41 CET

Run/Event: 124120/16701049

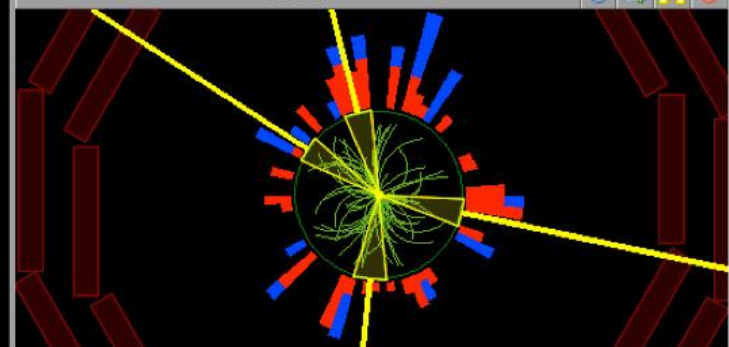
Candidate Multijet Event at 2.36 TeV



Rho Z



Rho Phi



# CERN Summer Student Programme

and  
finally...



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