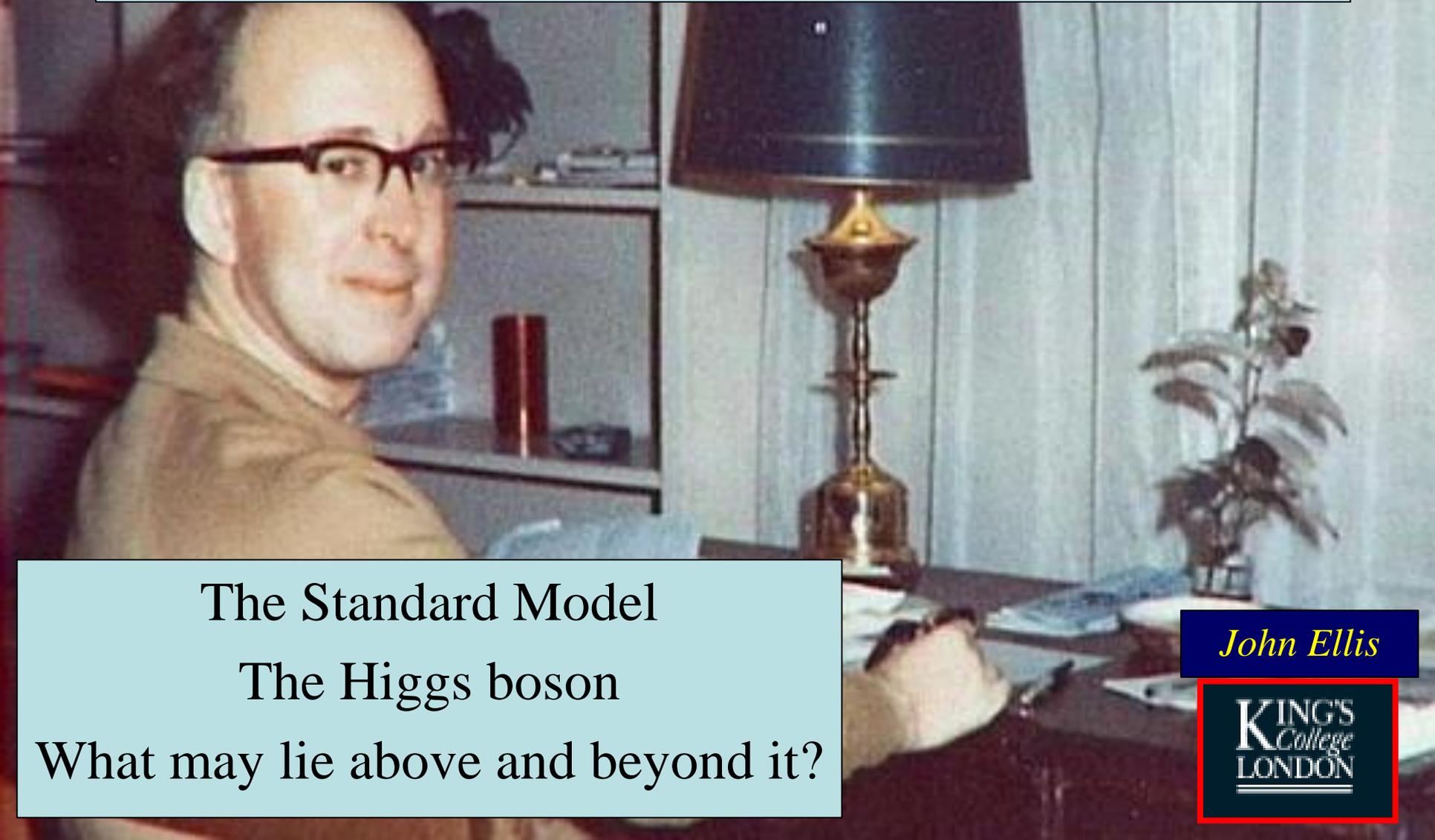


Particle Physics: Perspectives from Theory



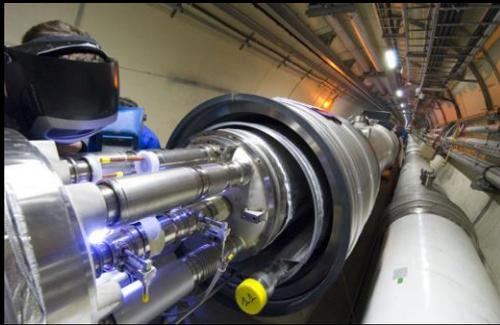
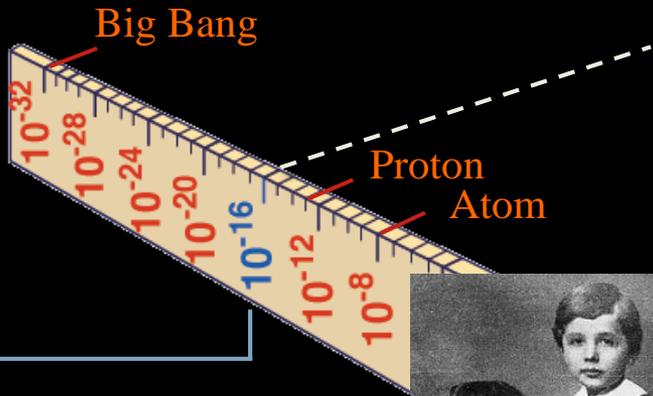
The Standard Model

The Higgs boson

What may lie above and beyond it?

John Ellis

KING'S
College
LONDON

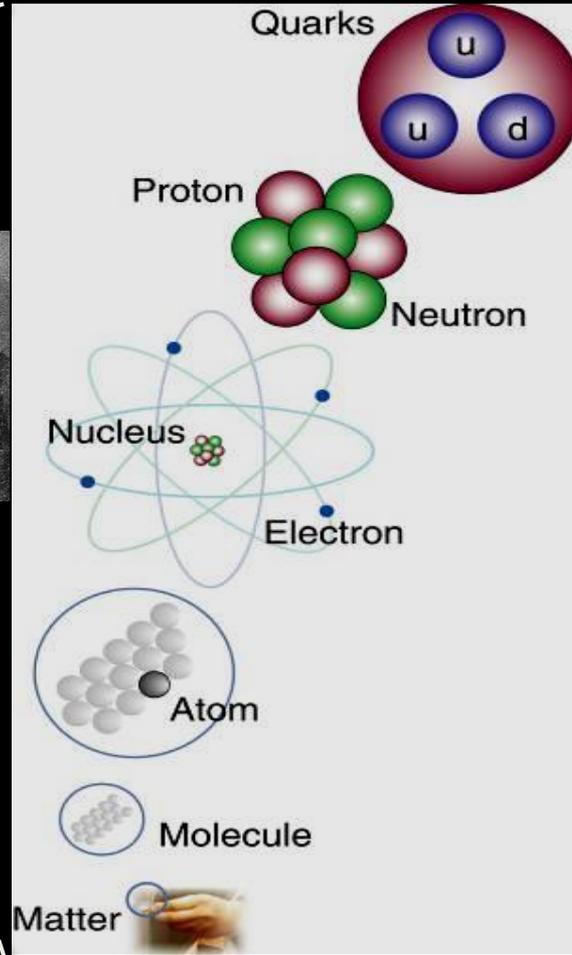
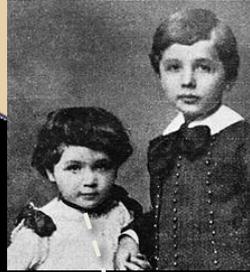


LHC

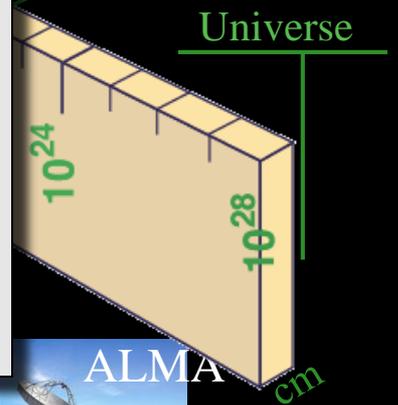
Super-Microscope



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



Radius of Galaxies



“Where do we come from?
What are we?
Where are we going?”



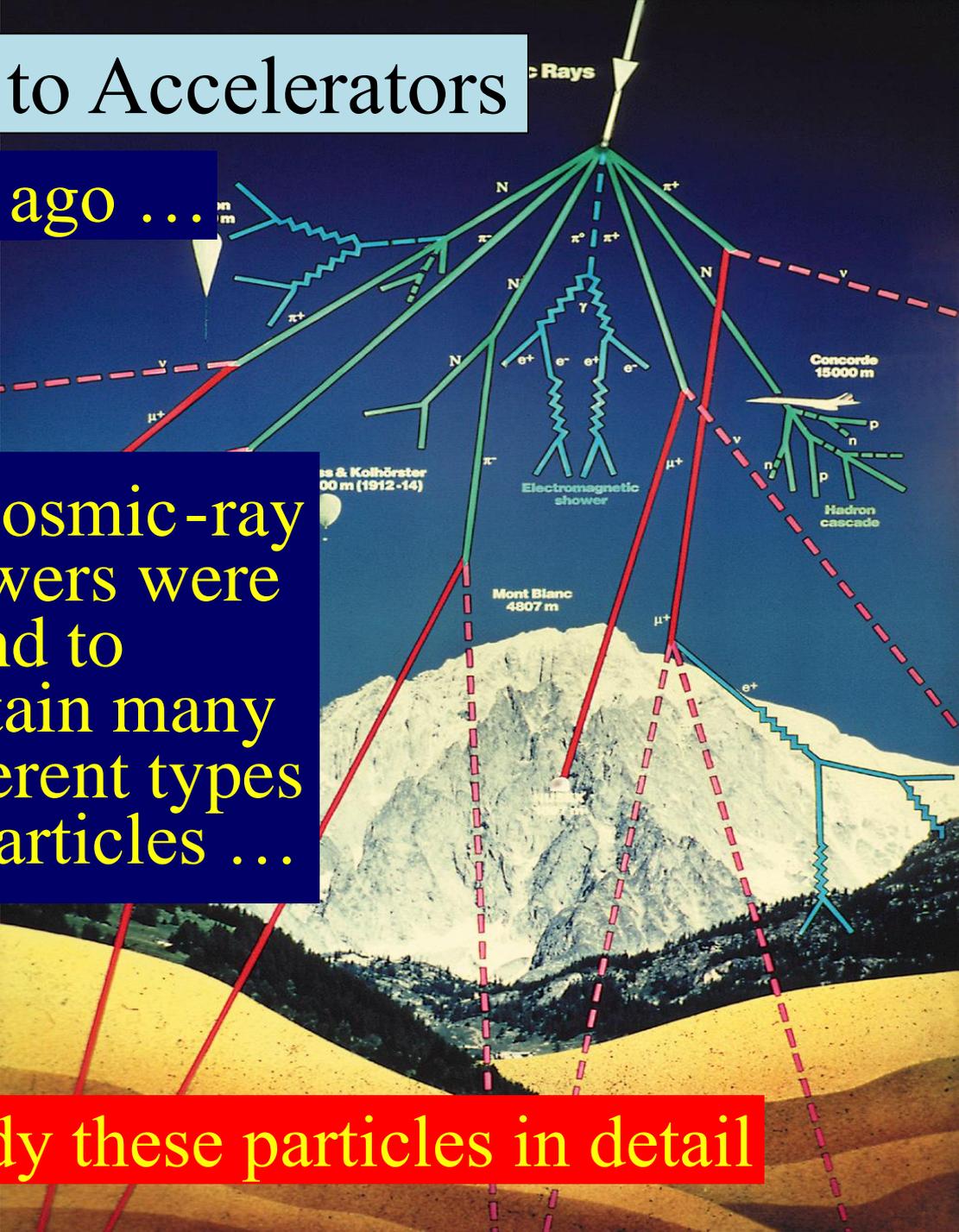
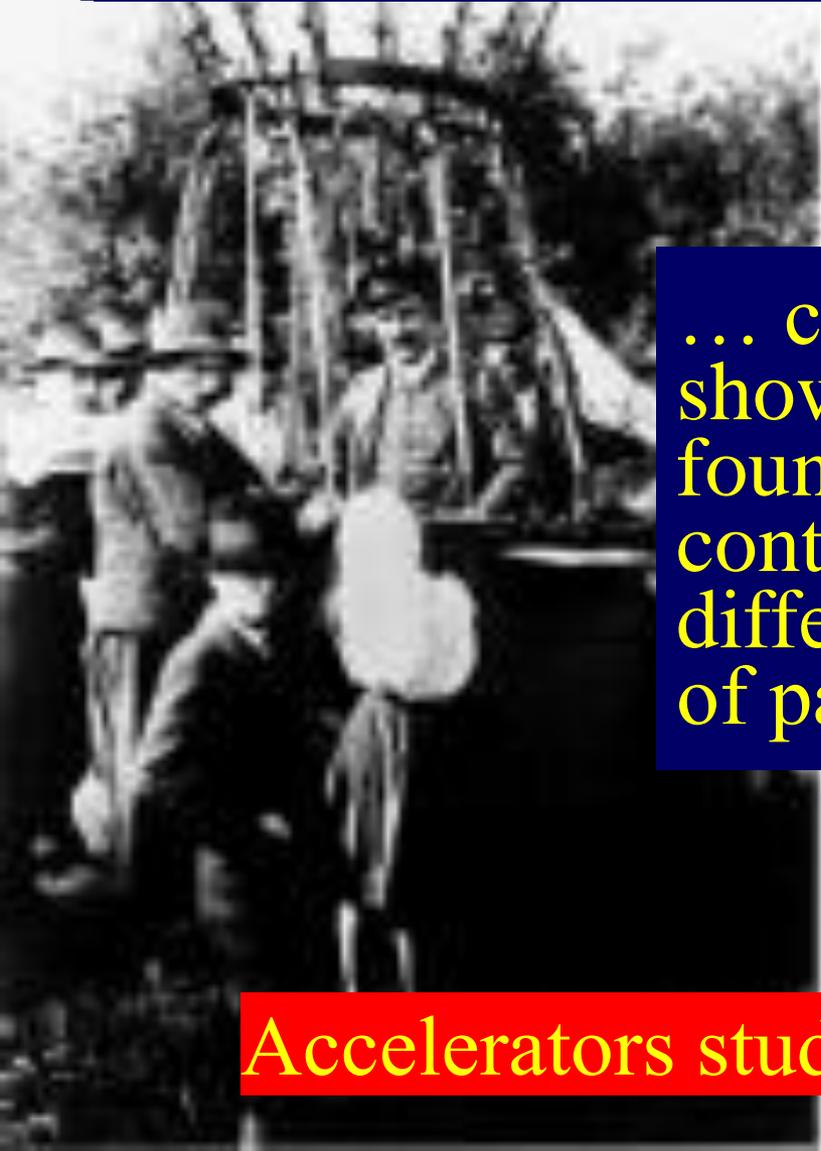
The aim of particle physics, CERN & the LHC:
What is the Universe made of?

From Cosmic Rays to Accelerators

Discovered a century ago ...

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

Accelerators study these particles in detail

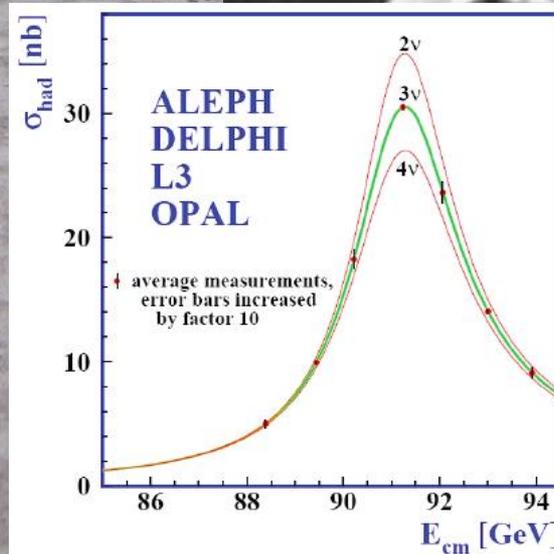
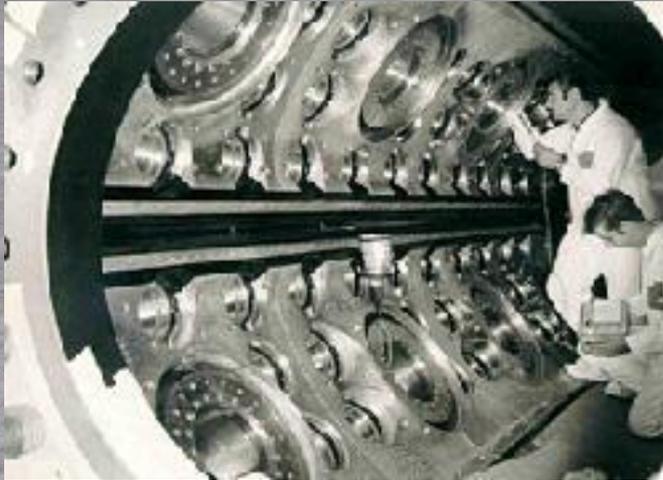


The 'Standard Model' of Particle Physics

Proposed by Abdus Salam,
Glashow & Weinberg

Crucial tests in
Experiments
at CERN, etc.

In agreement with all
confirmed laboratory
experiments



The 'Standard Model'

= Cosmic DNA

The matter particles



Where does mass come from?

The fundamental interactions



Gravitation electromagnetism weak nuclear force strong nuclear force

Gauguin's Questions in the Language of Particle Physics

- What is matter made of?
 - Why do things weigh?
- What is the origin of matter? **LHC Run 2**
- What is the dark matter that fills the Universe? **LHC Run 2**
- How does the Universe evolve?
- Why is the Universe so big and old? **LHC Run 2**
- What is the future of the Universe? **LHC Run 2**



Our job is to ask - and answer - these questions

BUT

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)**



KING'S
College
LONDON

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



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

Hiker sinks deep,
moves very slowly:
Particle with large mass



A Phenomenological Profile of the Higgs Boson

- First attempt at systematic survey

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

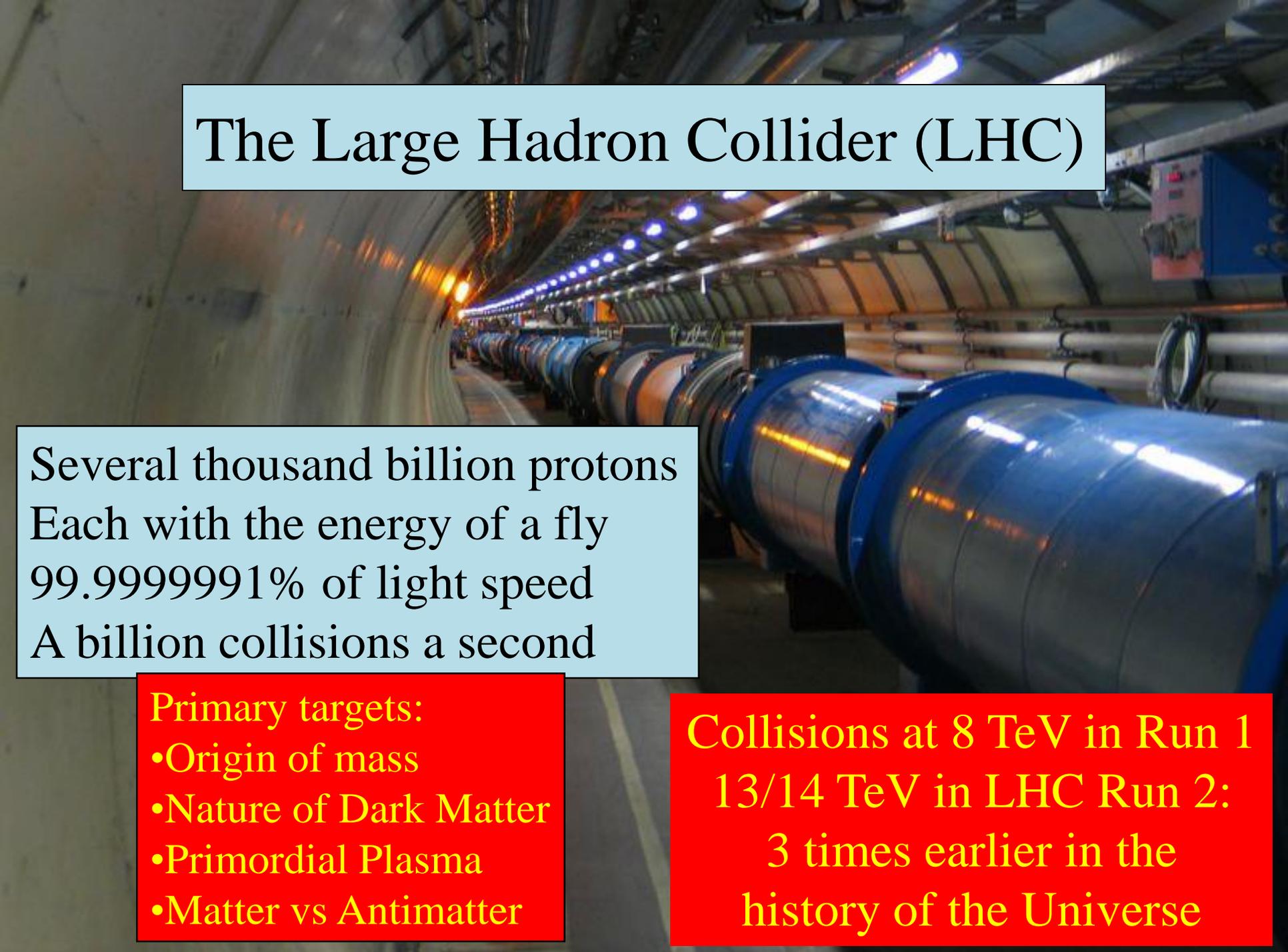
John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

The Large Hadron Collider (LHC)

The background image shows the interior of the LHC tunnel. It is a long, curved tunnel with a series of blue superconducting magnets lining the walls. The magnets are arranged in a circular pattern, and the tunnel is illuminated by blue lights. The perspective is from the end of the tunnel, looking down its length.

Several thousand billion protons
Each with the energy of a fly
99.9999991% of light speed
A billion collisions a second

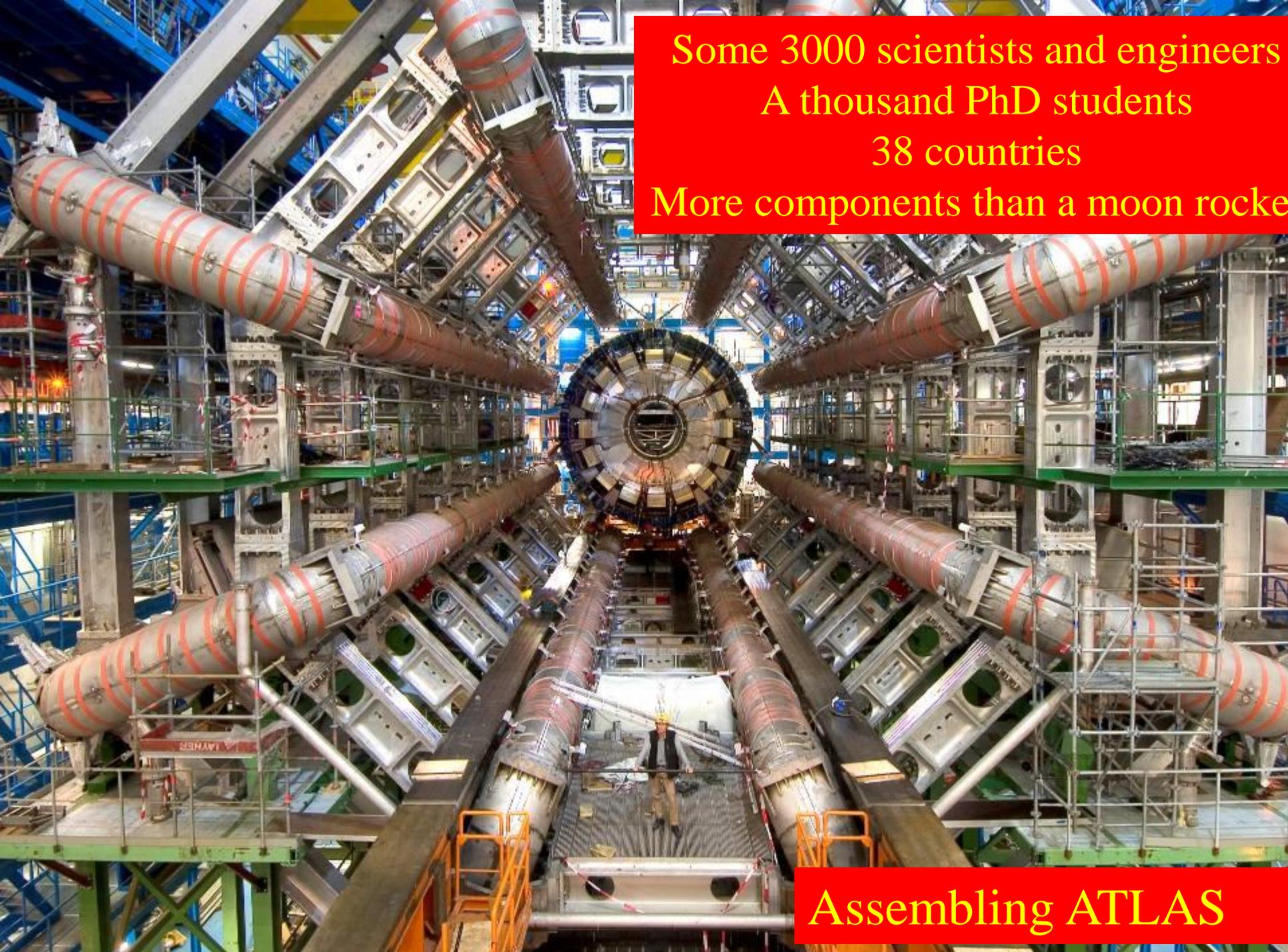
Primary targets:

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

Collisions at 8 TeV in Run 1
13/14 TeV in LHC Run 2:
3 times earlier in the
history of the Universe

A Simulated Higgs Event @ LHC





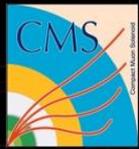
Some 3000 scientists and engineers
A thousand PhD students
38 countries
More components than a moon rock

Assembling ATLAS

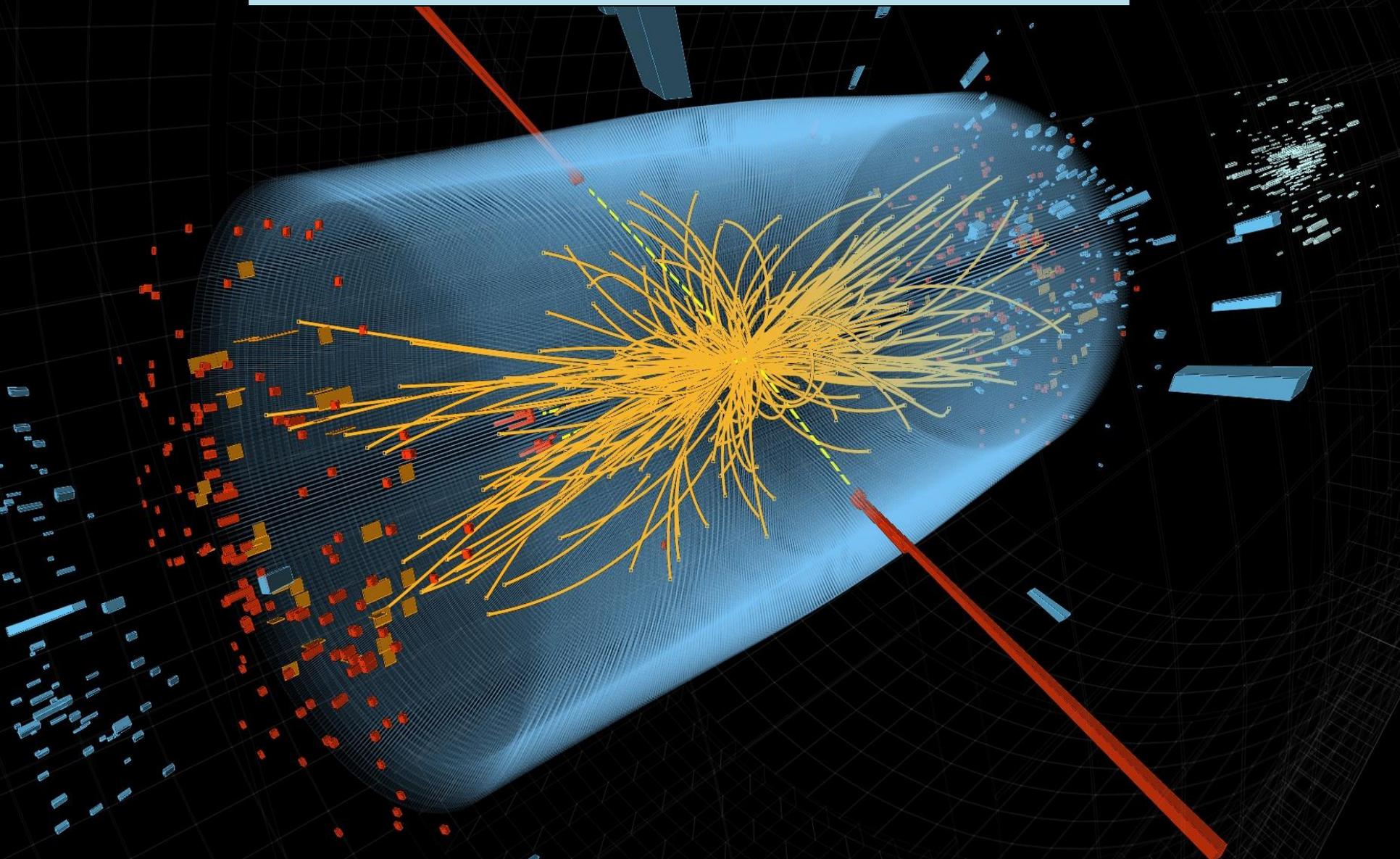
How the Higgs Boson was finally revealed?



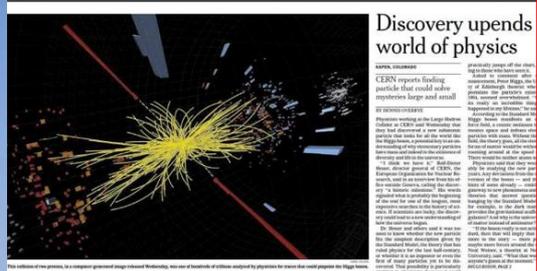
Mass Higgsteria



Interesting Events



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



ヒッグス粒子検出 年内に結論
新素粒子検出 年内に結論
日米欧2チーム

Le Monde newspaper snippet with headline 'Science : la matière dévoilée' and an image of the LHC tunnel.

Science magazine snippet with headline 'Science : la matière dévoilée' and an image of the LHC tunnel.

The Gazette newspaper snippet with headline 'Physicists Find Elusive Particle Seen as Key to Universe' and an image of the particle detector.

MK newspaper snippet with headline 'В ТЕАТРЫ БУДУТ ПУСКАТЬ ПО МОБИЛЬНЫМ ТЕЛЕФОНАМ' and an image of a person.

AD ALGEMEEN DAGBLAD newspaper snippet with headline 'EINDELIJK BELIJK NA 48 JAAR' and an image of a particle detector.

Frankfurter Allgemeine Zeitung newspaper snippet with headline 'Masse macht's' and an image of a person.

CHINADAILY newspaper snippet with headline 'fallada la partícula clave para a comprensión del universo' and an image of a particle detector.

THE HINDU newspaper snippet with headline 'Elusive particle found, looks like Higgs boson' and an image of scientists.

CORRIERE DELLA SERA newspaper snippet with headline 'La particella che può svelare i segreti dell'universo' and an image of scientists.

gazeta newspaper snippet with headline 'Czastke Higgsa fizycy najpierw wymyślił, potem szukali 40 lat BOSKA MASA' and an image of a crowd.

বিশ্বনাথ 'স্বপ্ন' দর্শন newspaper snippet with headline 'আনন্দবাজার পত্রিকা' and an image of a particle detector.

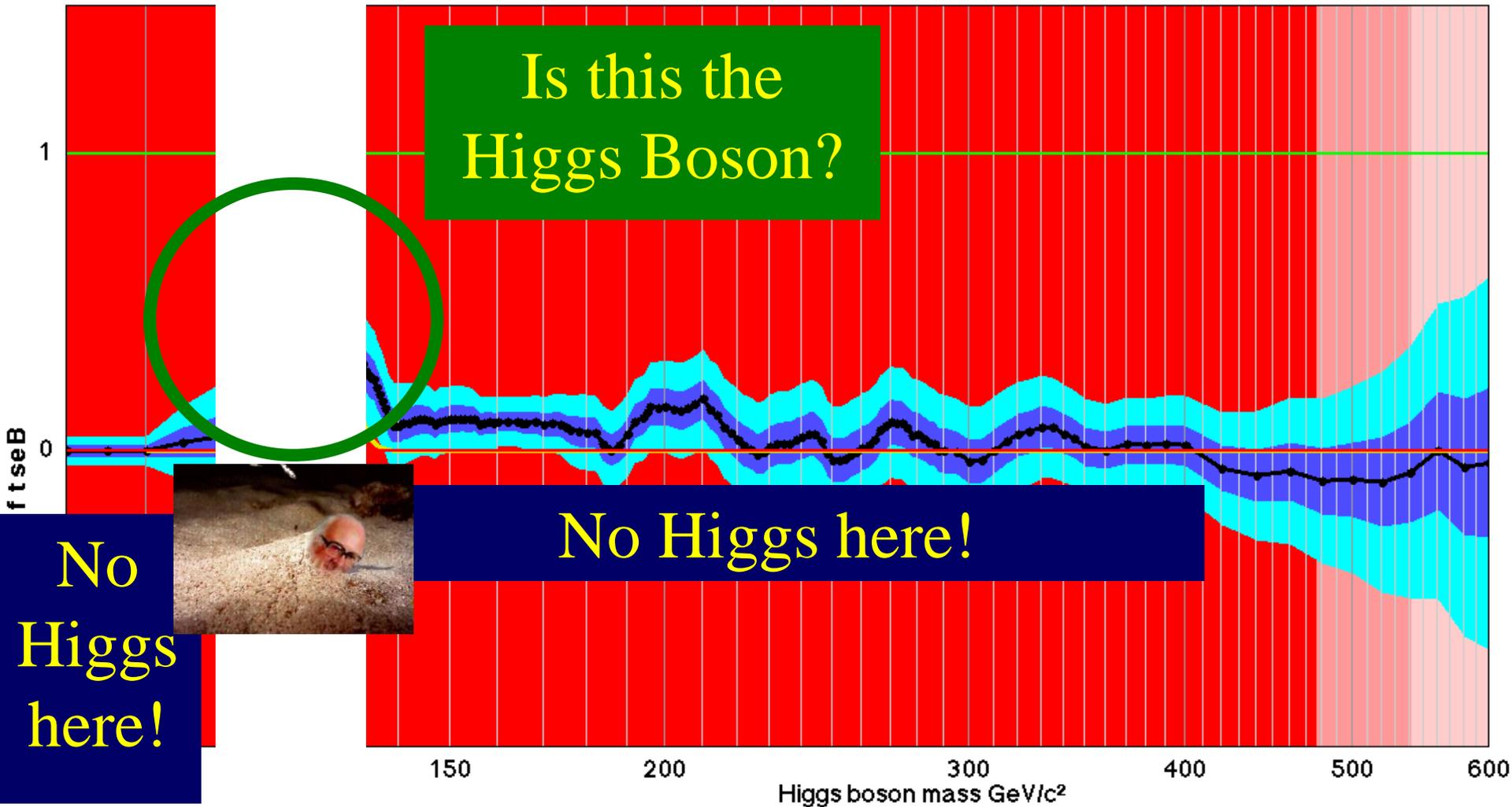
Higgsdependence Day!



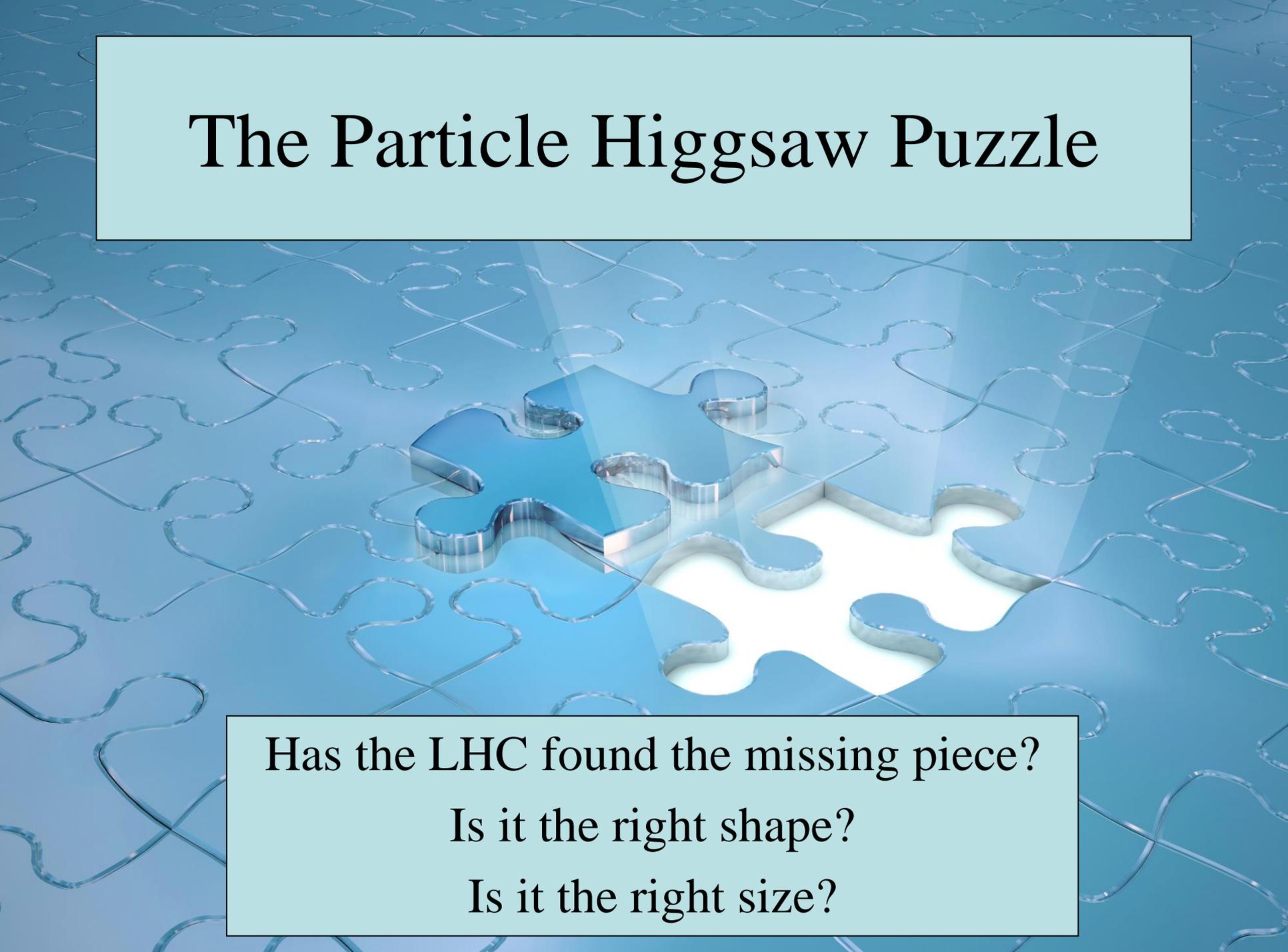
Unofficial Combination of Higgs Data

1/fb - 10/fb

06/03/2013



The Particle Higgsaw Puzzle

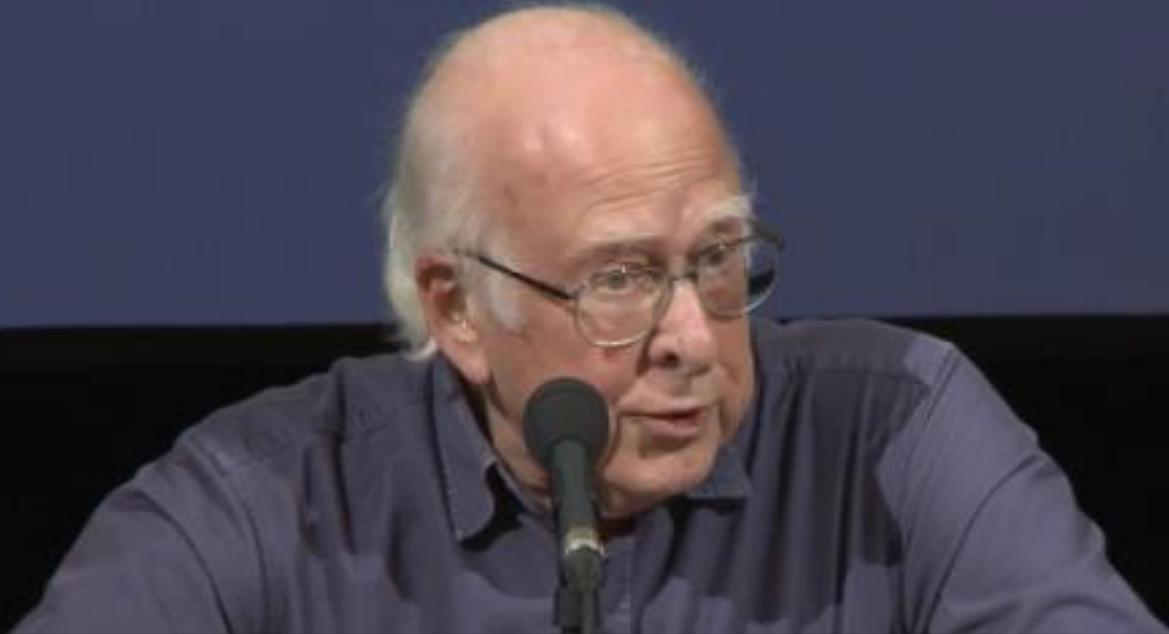
A 3D rendering of a blue puzzle with one piece missing, set against a background of a blue grid with wavy lines. The missing piece is a light blue color, contrasting with the darker blue of the other pieces. The puzzle is centered in the image, and the background has a subtle, repeating pattern of wavy lines.

Has the LHC found the missing piece?

Is it the right shape?

Is it the right size?

Dixit Swedish Academy



Today we believe that “Beyond any reasonable doubt, it is a Higgs boson.” [1]

http://www.nobelprize.org/nobel_prizes/physics/laureates/2013/advanced-physicsprize2013.pdf

[1] = JE & Tevong You, arXiv:1303.3879

Standard Model Particles: Years from Proposal to Discovery

Electron

Photon

Muon

Electron neutrino

Muon neutrino

Down

Strange

Up

Charm

Tau

Bottom

Gluon

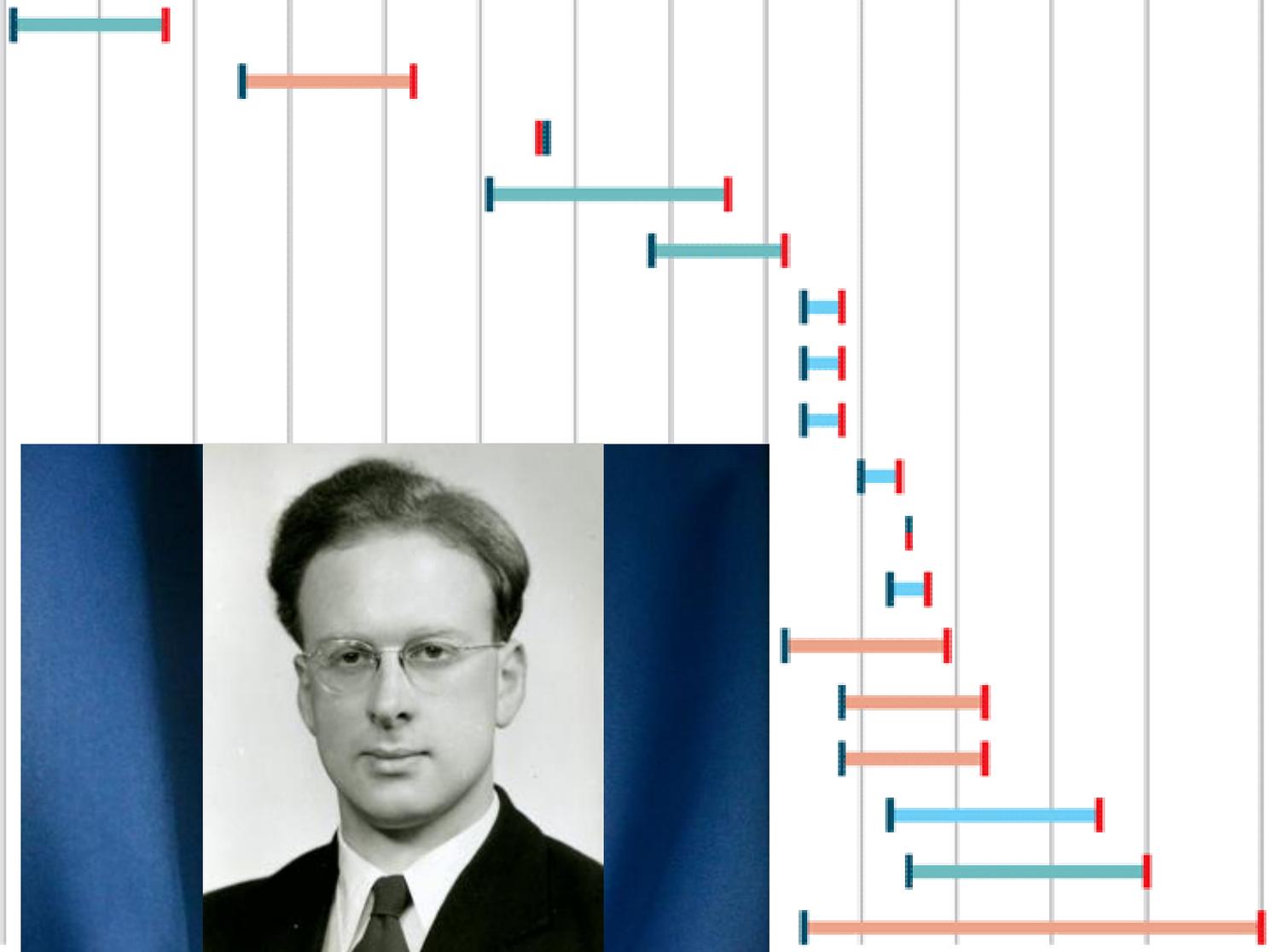
W boson

Z boson

Top

Tau neutrino

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: there would be no nuclei, everything would be radioactive

How does the Higgs trick work?



- « Empty » space is u
- Dark matter
- Origin of matter
- Masses of neutrinos
- Hierarchy problem
- Inflation
- Quantum gravity
- ...

LHC Run 2

SUSY

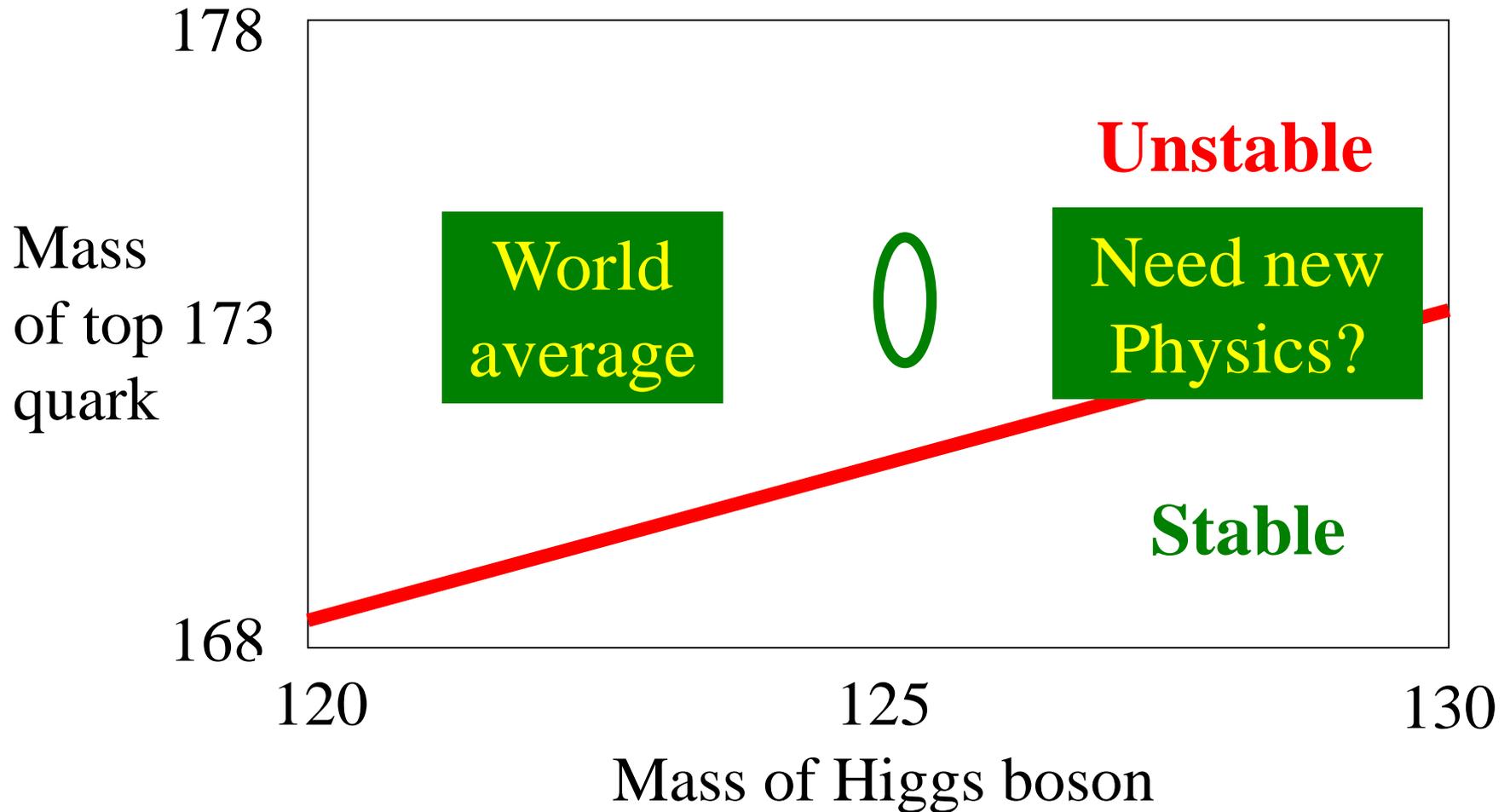
The Standard Model

PIERCE BROSNAN in JAMES BOND 007™
The World Is Not Enough
007™

ALBERT R. BROCCOLLI'S SON PRODUCTIONS PRESENTS PIERCE BROSNAN in JAMES BOND 007™
"THE WORLD IS NOT ENOUGH" SOPHIE MARCEAU ROBERT CAROLLE DENISE RICHARDS ROBBIE COLTRANE and JIMMY DENNY
DESIGNED BY LINDY HEARMING COSTUME DESIGNER DAVID ARNOLD EXECUTIVE PRODUCERS JIM CLARK JIMMIE SMITH ADRIAN BUDDE and JIMMIE SMITH
PRODUCED BY ANTHONY WATE PRODUCED BY NEAL PURVIS & ROBERT WADE PRODUCED BY NEAL PURVIS & ROBERT WADE PRODUCED BY BRUCE FENSTER
DIRECTED BY MICHAEL E. WOLSON PRODUCED BY BARBARA BROCCOLLI PRODUCED BY MICHAEL APPEL
CASTING BY JUDITH GARBAGE
COURTESY OF THE FBI
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Is “Empty Space” Unstable?

- Depends on masses of Higgs boson and top quark



Should it have Collapsed already?

Fluctuate over barrier
in the early Universe?

Not if
supersymmetry:
infinite barrier

We are here



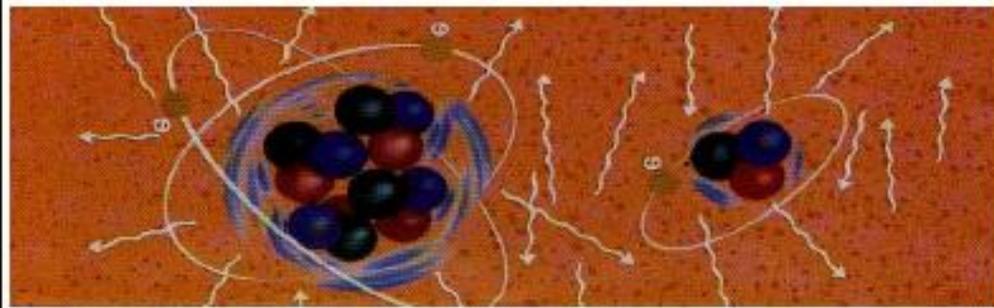
Quantum fluctuations

Tunnel through
barrier now?

The Big Crunch

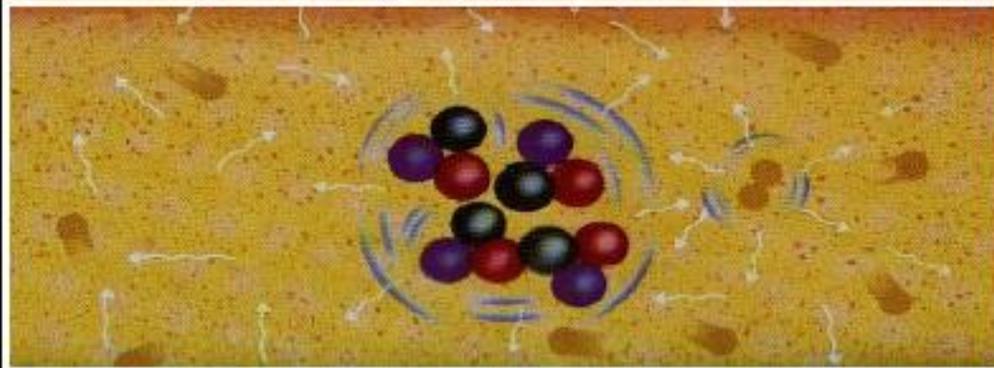


300,000
years



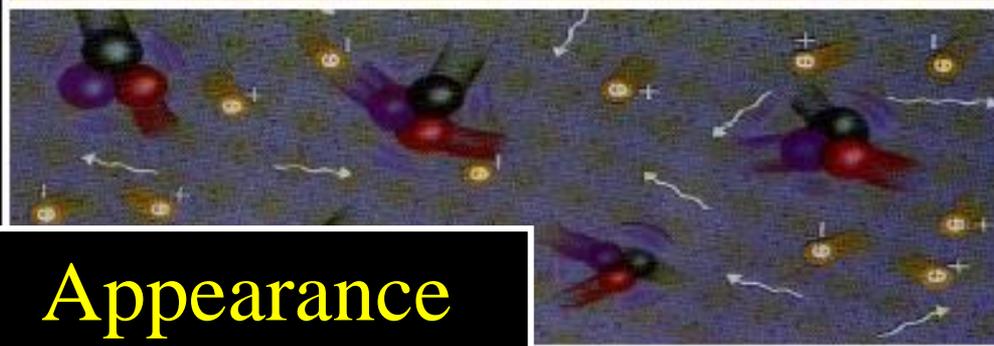
Formation
of atoms

3
minutes



Formation
of nuclei

1 micro-
second



Formation
of protons
& neutrons

1 pico-
second

Appearance
of dark matter?



Appearance
of mass?

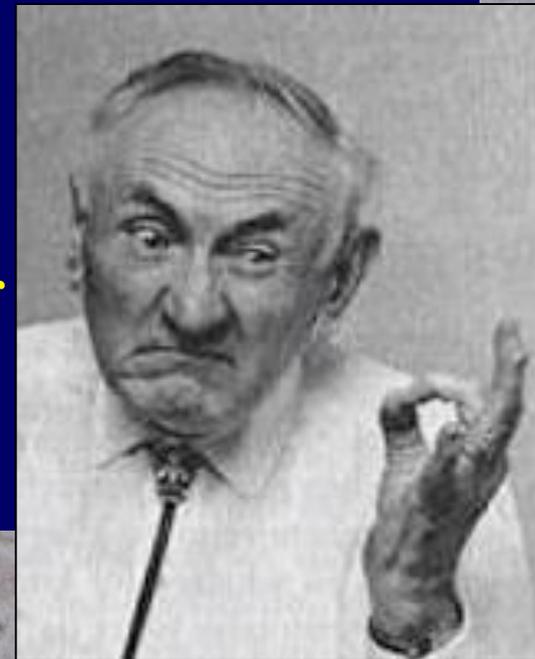
Appearance
of matter?



BANG!

The Dark Matter Hypothesis

- Motivated by Fritz Zwicky's observations of the Coma galaxy cluster
- The galaxies move too quickly
- The observations require a stronger gravitational field than provided by the visible matter
- **Dark matter?**



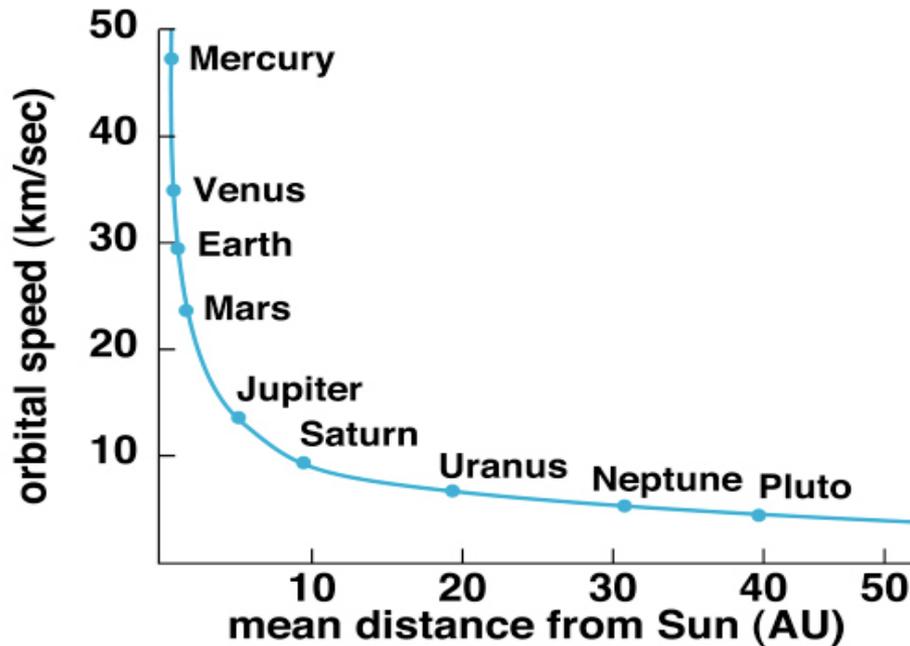
The Rotation Curves of Galaxies

- Measured by Vera Rubin
- The stars also orbit ‘too quickly’
- Her observations also required a stronger gravitational field than provided by the visible matter
- **Further strong evidence for dark matter**



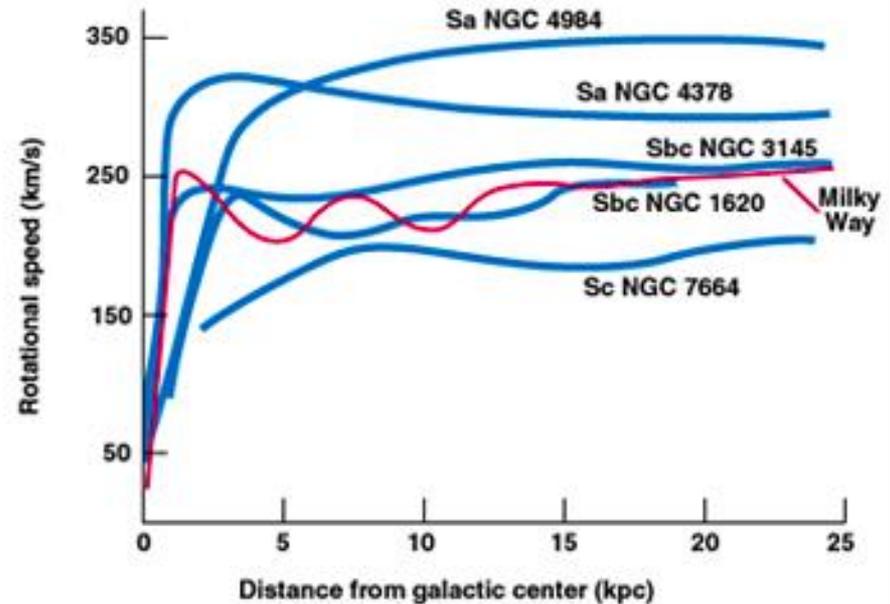
Rotation Curves

- In the Solar System



- The velocities decrease with distance from Sun
- Mass lumped at centre

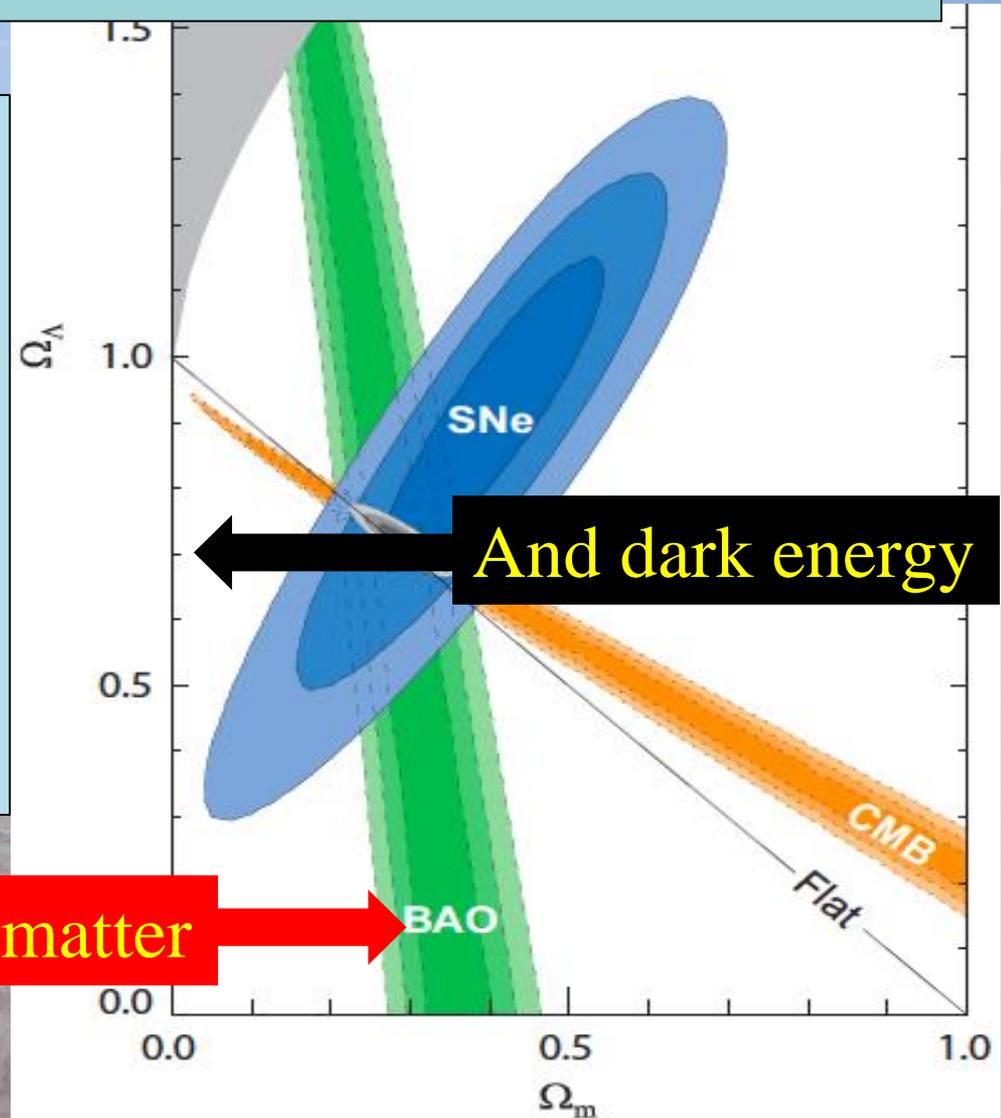
- In galaxies



- The velocities do not decrease with distance
- Dark matter spread out

The Content of the Universe

- According to
 - **Microwave background**
 - **Supernovae**
 - **Structures**
(galaxies, clusters, ...)
in the Universe



There is dark matter

Dark Energy

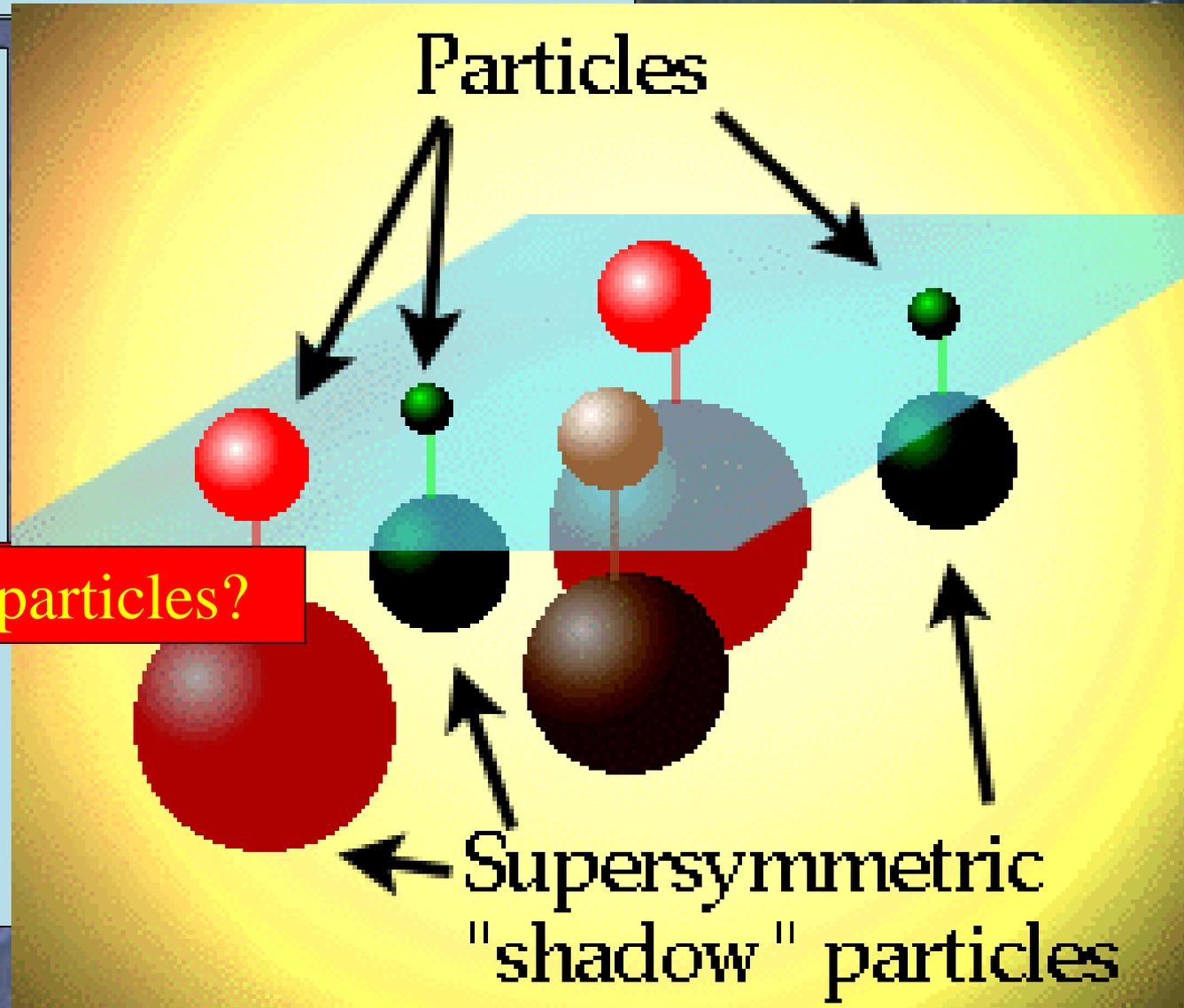
- Energy density spread throughout space
- Not clustered like matter in galaxies, etc.
- Apparently \sim constant for billions of years
- Expect in many theories of fundamental physics
- Mystery is why it is so small

Dark Matter in the Universe

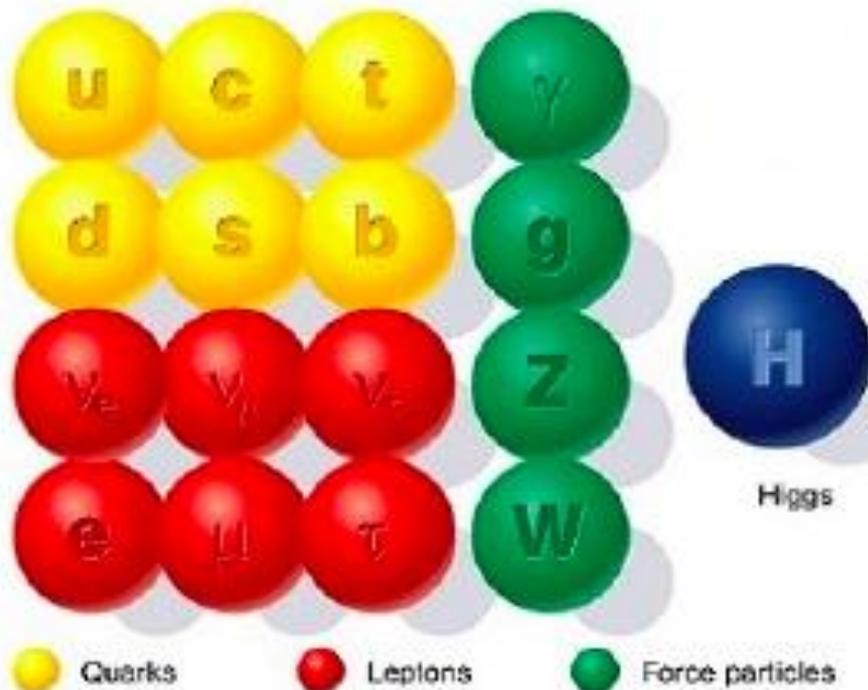
Astronomers say that most of the matter in the Universe is invisible Dark Matter

Supersymmetric particles?

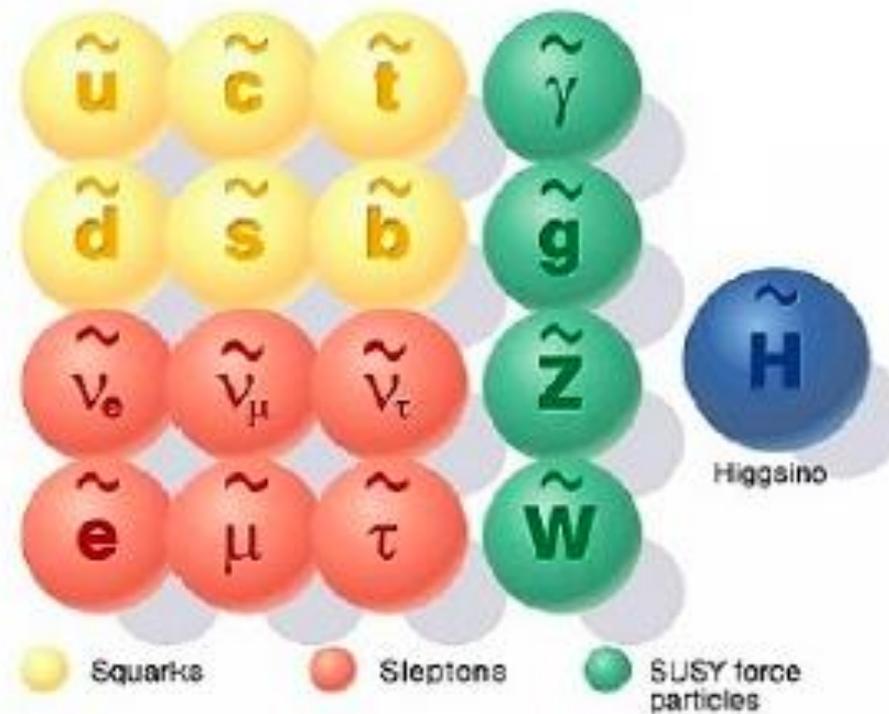
Searching for them at the LHC



Minimal Supersymmetric Extension of the Standard Model

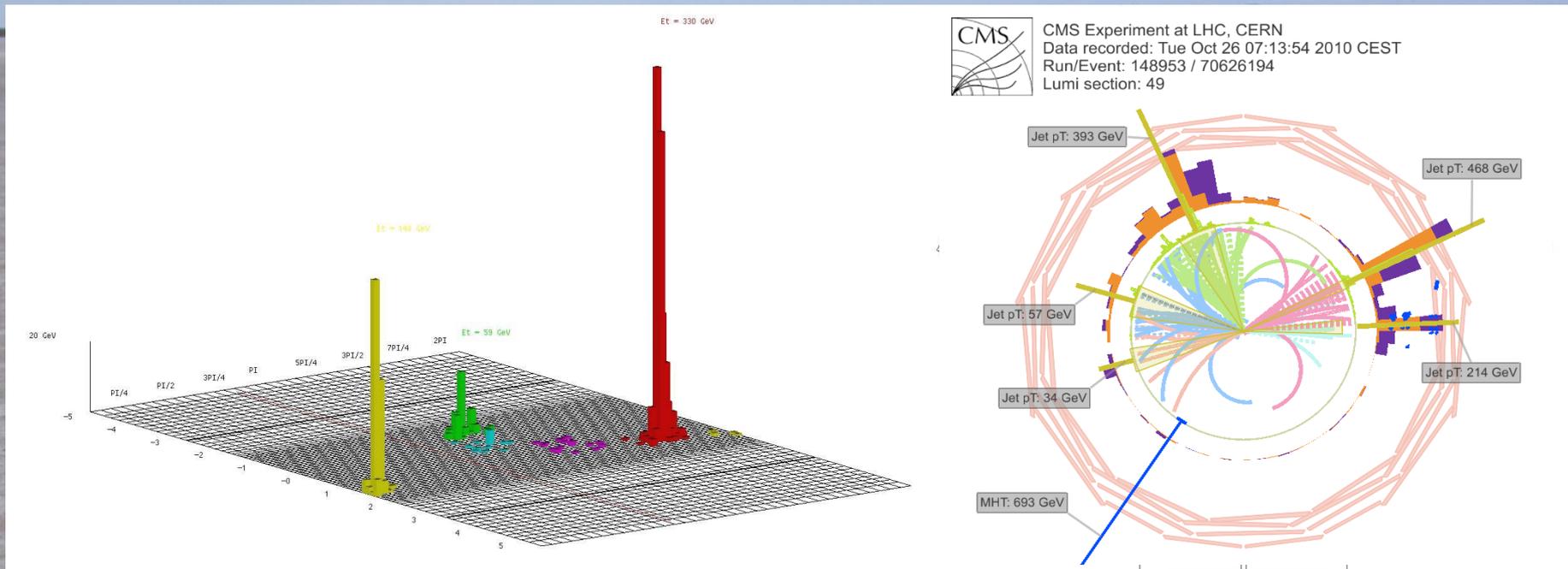


Standard particles



SUSY particles

Looking for Dark Matter @ LHC



Missing transverse energy
carried away by dark matter particles

General Interest in Antimatter Physics



Physicists cannot make enough for
Star Trek or Dan Brown!

Where does the Matter come from?

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

Discovered in cosmic rays
Studied using accelerators
Used in medical diagnosis



Matter and antimatter not quite equal and opposite: WHY?

Is this why the Universe contains matter, not antimatter?

Will experiments reveal how matter was created?

How to Create the Matter in the Universe?

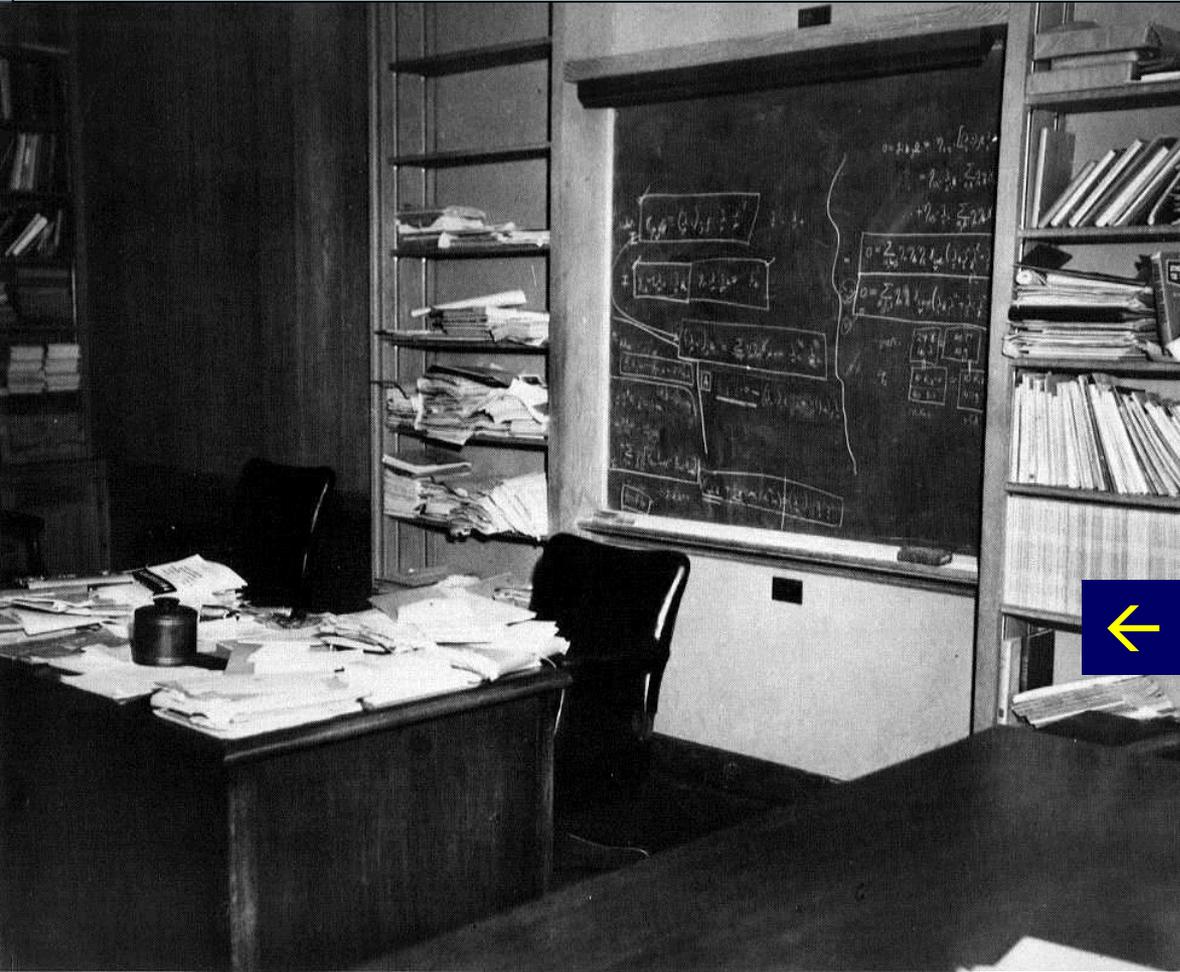
Sakharov

- Need a difference between matter and antimatter observed in the laboratory
- Need interactions able to create matter predicted by theories not yet seen by experiment
- Need the expansion of the Universe a role for the Higgs boson?

Will we be able to calculate using laboratory data?



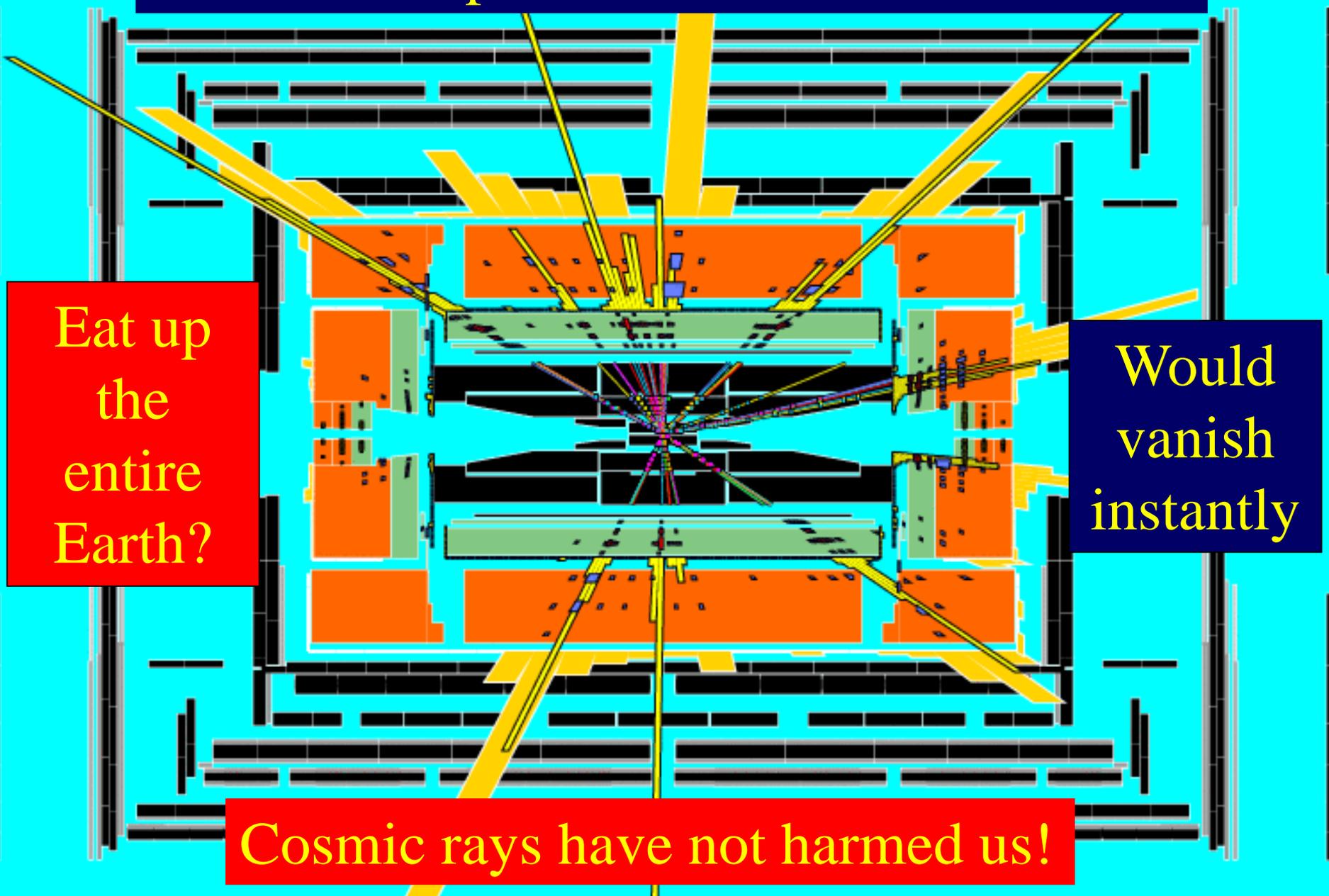
Unify Fundamental Interactions: Einstein's Dream ...



← ... but he never succeeded

Unification via extra dimensions of space?

Will LHC experiments create black holes?



Eat up
the
entire
Earth?

Would
vanish
instantly

Cosmic rays have not harmed us!

The Unification Trail

