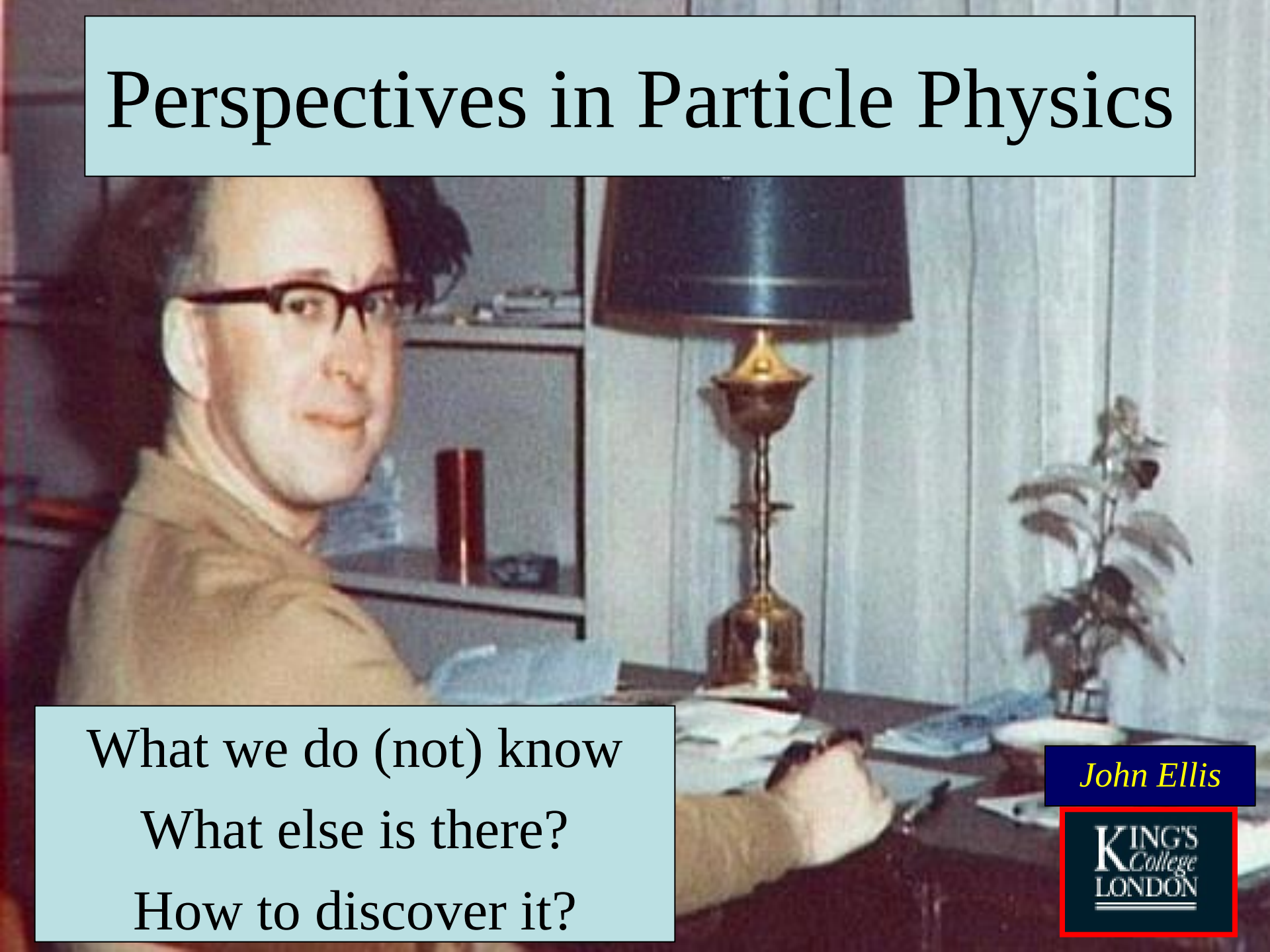
Perspectives in Particle Physics



What we do (not) know

What else is there?

How to discover it?

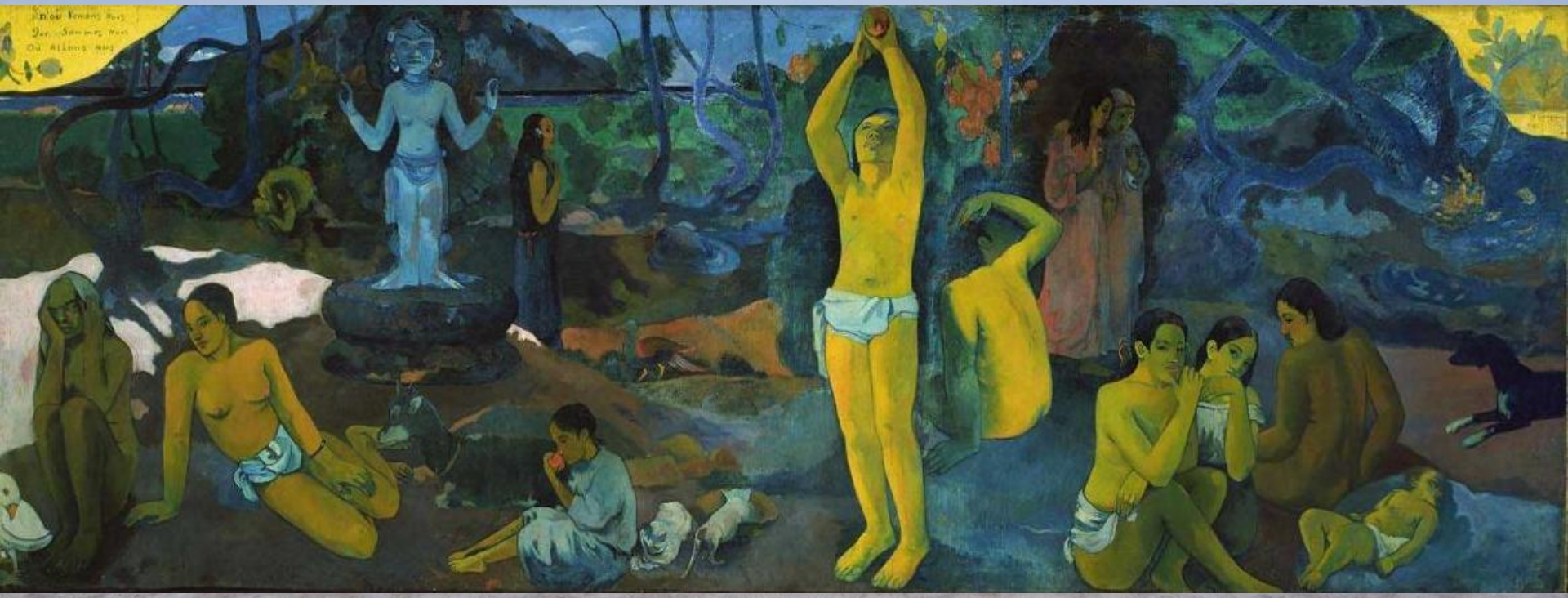
John Ellis

KING'S College LONDON

“Where do we come from?

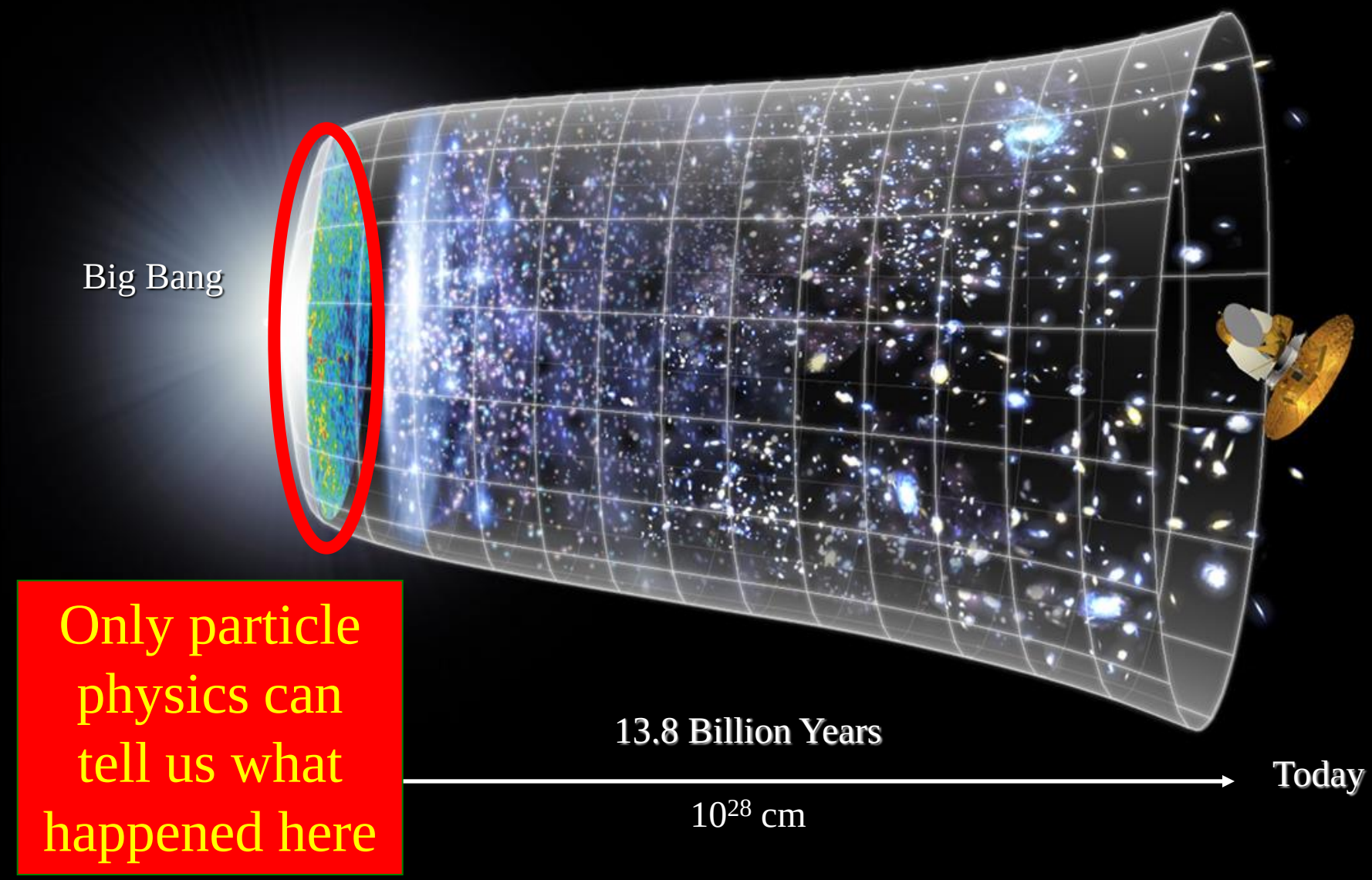
What are we?

Where are we going?”



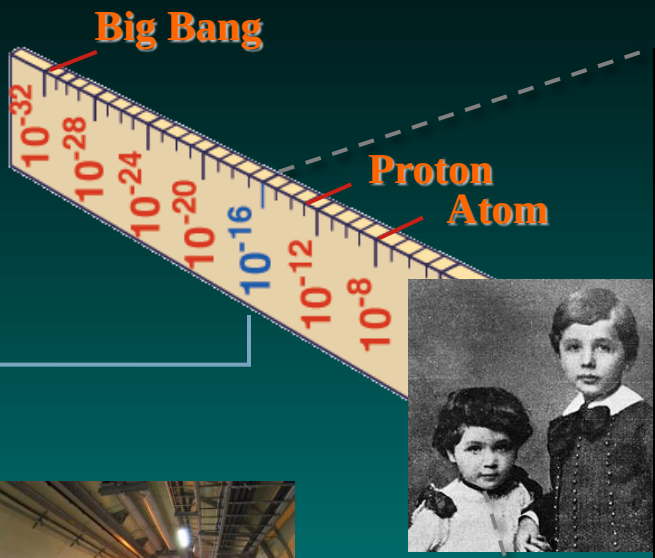
The aim of particle physics, CERN & the LHC:
What is the Universe made of?

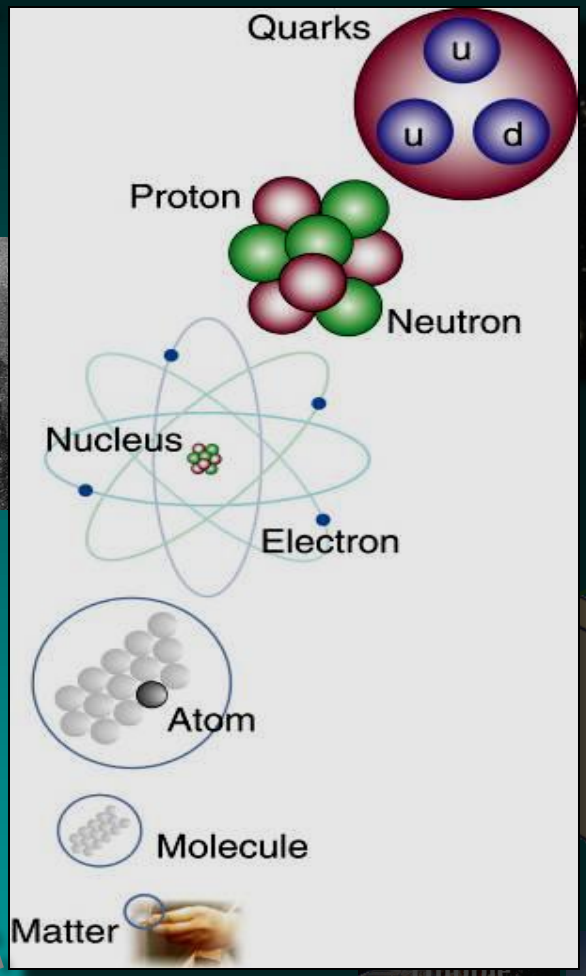
Evolution of the Universe



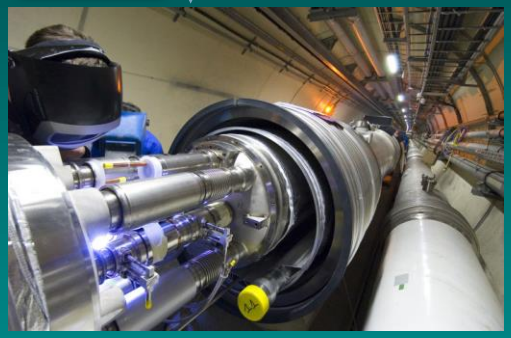
Only particle physics can tell us what happened here

/Users/johne/Desktop/YoungEinsteins.png



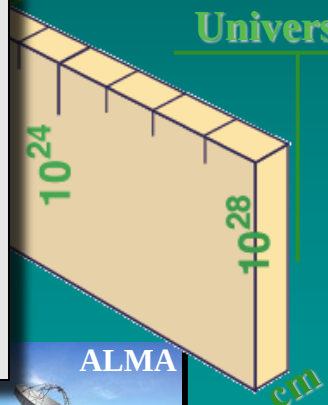


CERN



LHC

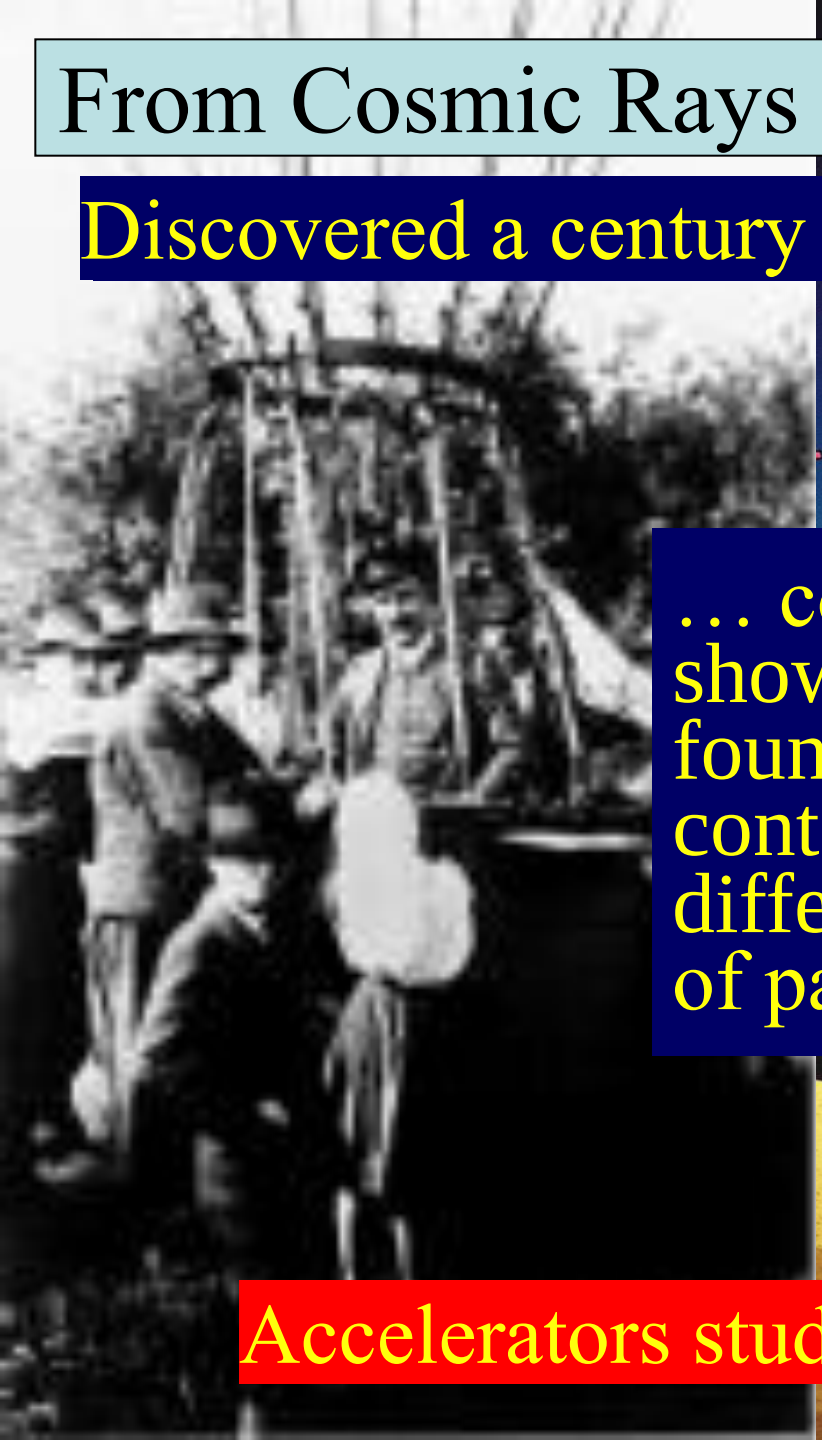
Super-Microscope

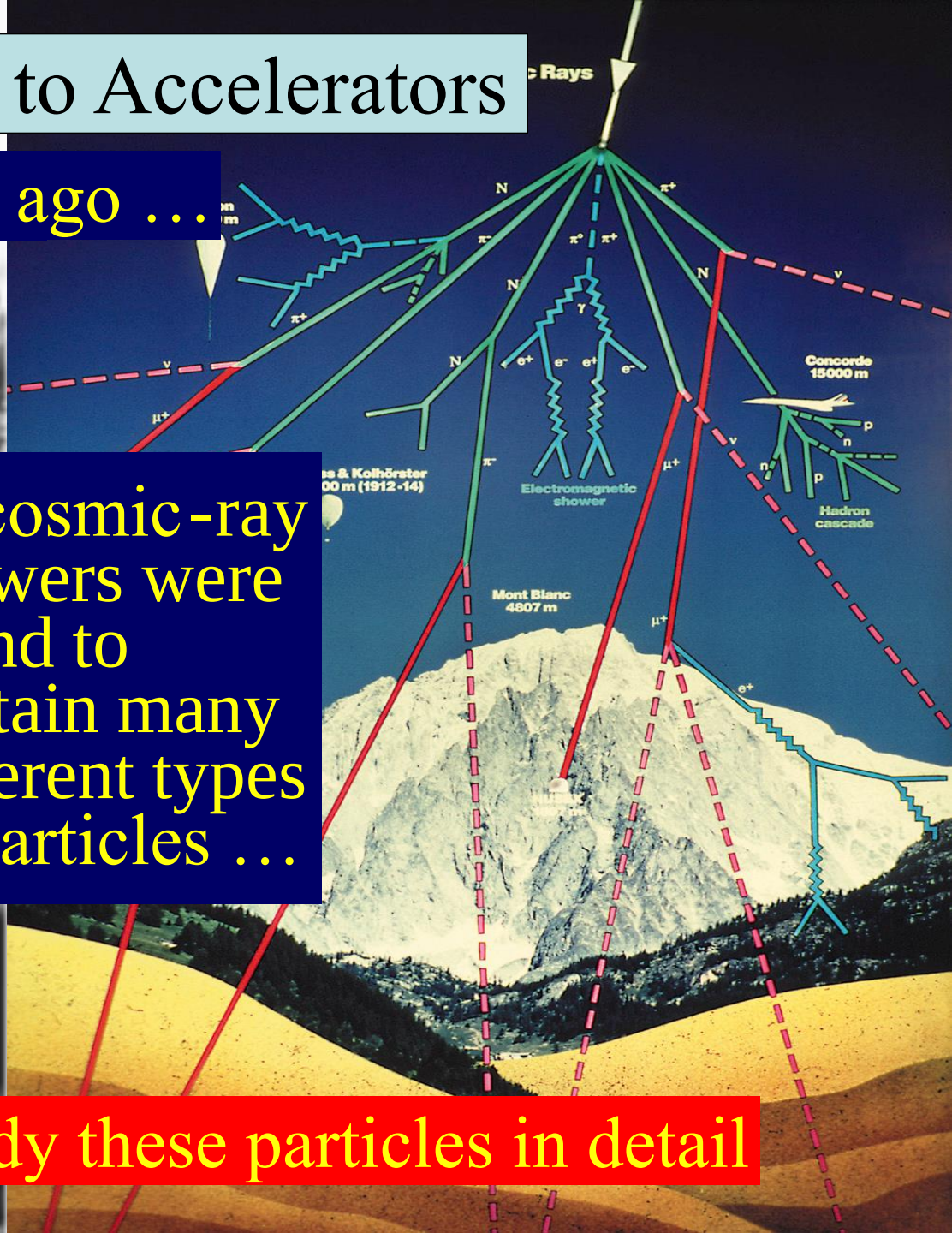


Study physics laws of first moments after Big Bang
increasing Symbiosis between Particle Physics,
Astrophysics and Cosmology

From Cosmic Rays to Accelerators

Discovered a century ago …





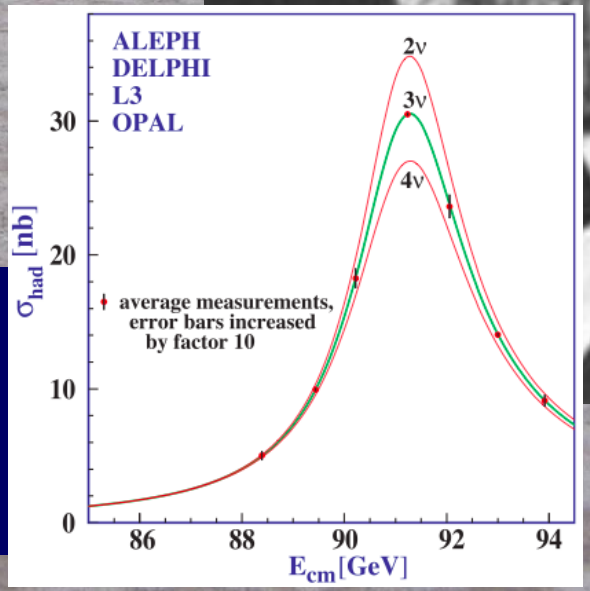
… cosmic-ray showers were found to contain many different types of particles …

Accelerators study these particles in detail

The ‘Standard Model’ of Particle Physics

Proposed by Abdus Salam, Glashow and Weinberg

First evidence from CERN experiment

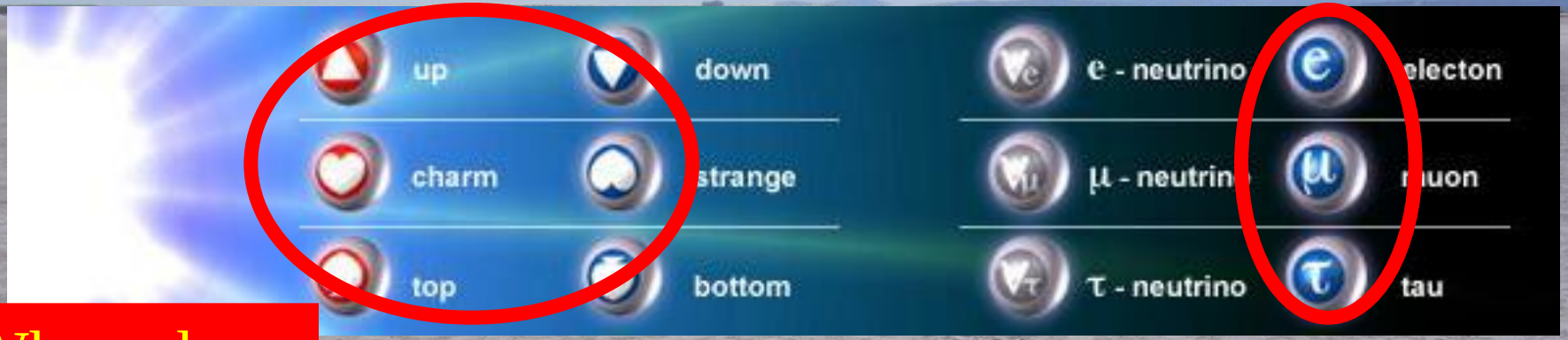


Perfect agreement between theory and experiments in all laboratories

The ‘Standard Model’

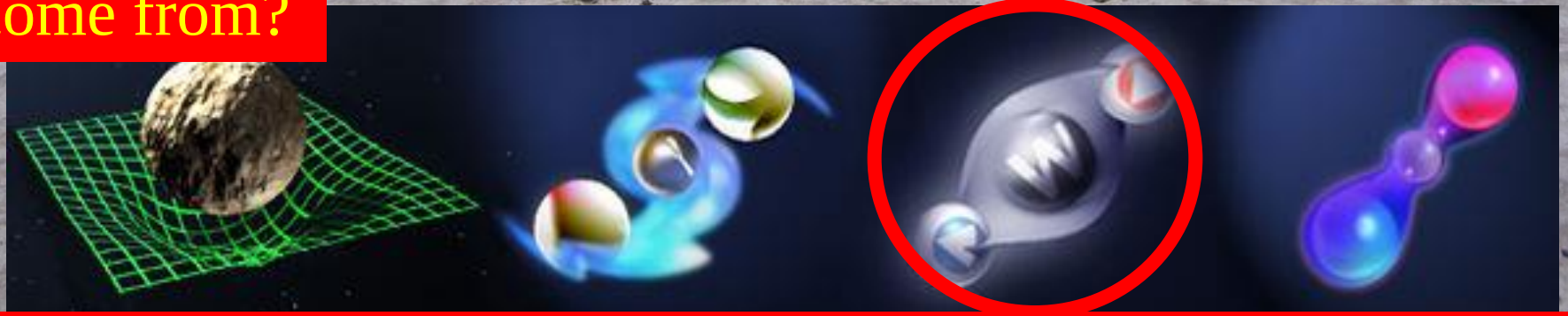
= Cosmic DNA

The matter particles



Where does mass come from?

The fundamental interactions



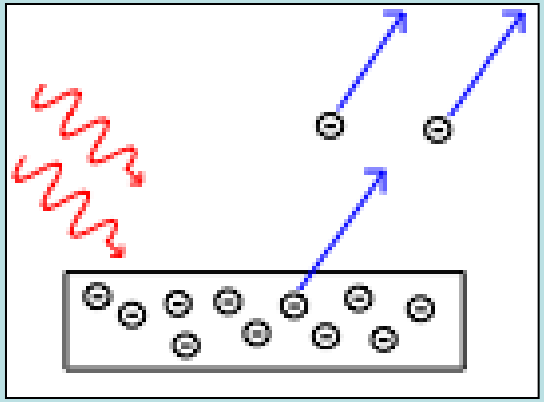
Gravitation electromagnetism weak nuclear force strong nuclear force

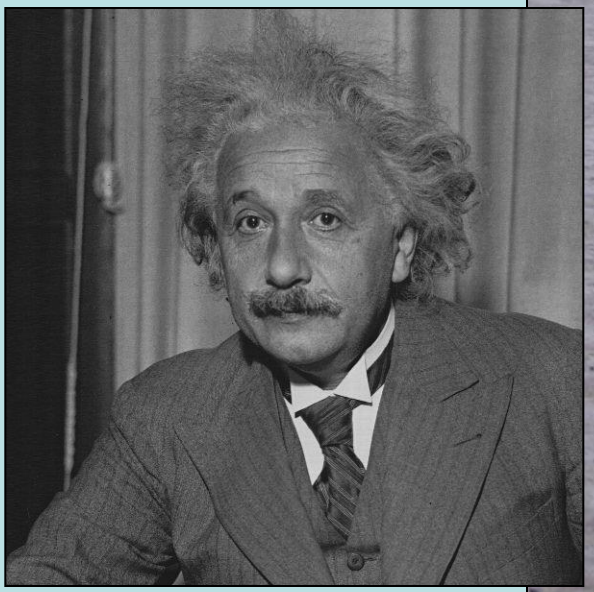
Photon: the Particle of Light

- Quantum hypothesis introduced by Planck:

$$E = hf$$

- Physical reality postulated by Einstein to explain photoelectric effect

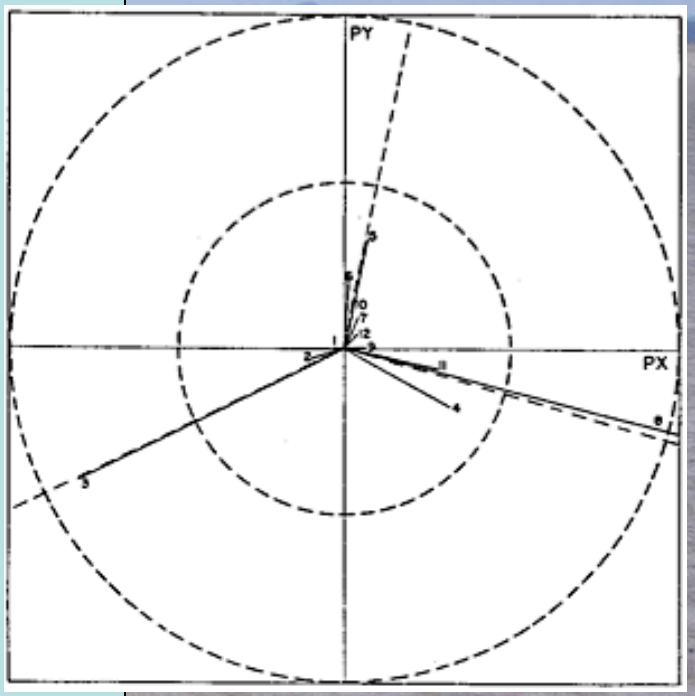




- **Motivation for his Nobel Prize**

Strong Nuclear Forces

- Modelled after Maxwell's theory
- Carried by 'gluon' particles
- Massless like the photon
- Discovered in 1979
- Using method suggested by JE, Mary Gaillard, Graham Ross in 1976
- **Second force particle discovered**



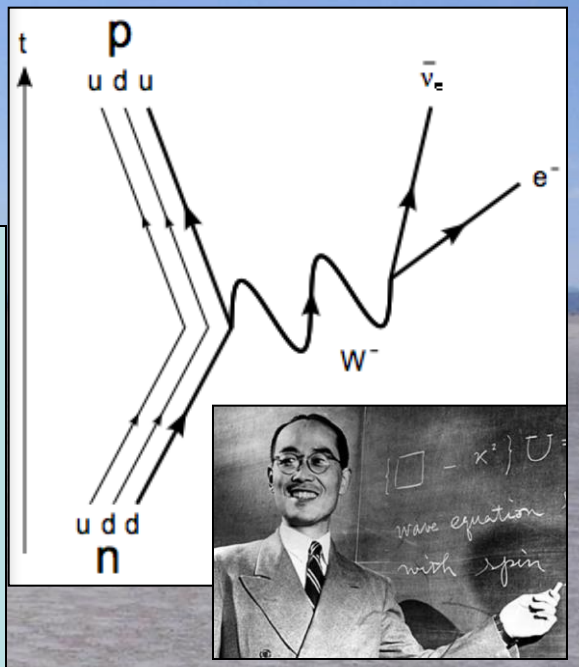
Weak Interactions

Radioactivity due to weak interactions

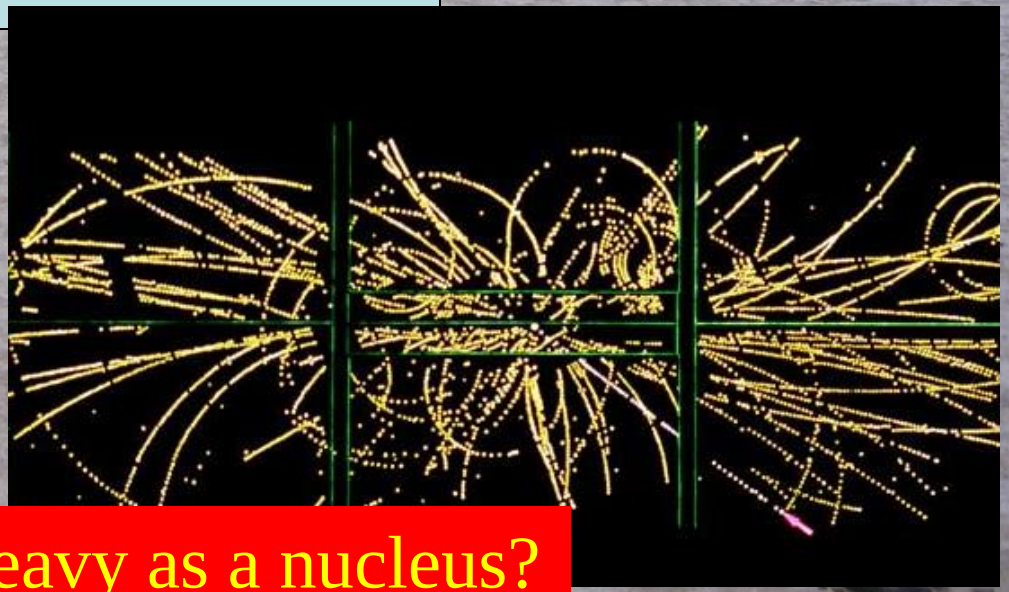
(β decay)

W boson - carrier of weak interaction

postulated by Yukawa



Discovered at CERN in 1983 by Carlo Rubbia et al

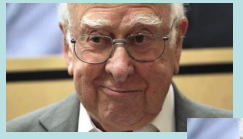


Why is it as heavy as a nucleus?

Gauguin's Questions in the Language of Particle Physics

- What is matter made of?
- Why do things weigh?
- What is the origin of matter?
- What is the dark matter that fills the Univer
- How does the Universe evolve?
- Why is the Universe so big and old?
- Are there additional dimensions of space?




Our job is to ask - and answer - these questions

Why do Things Weigh?

Newton:

Weight proportional to Mass

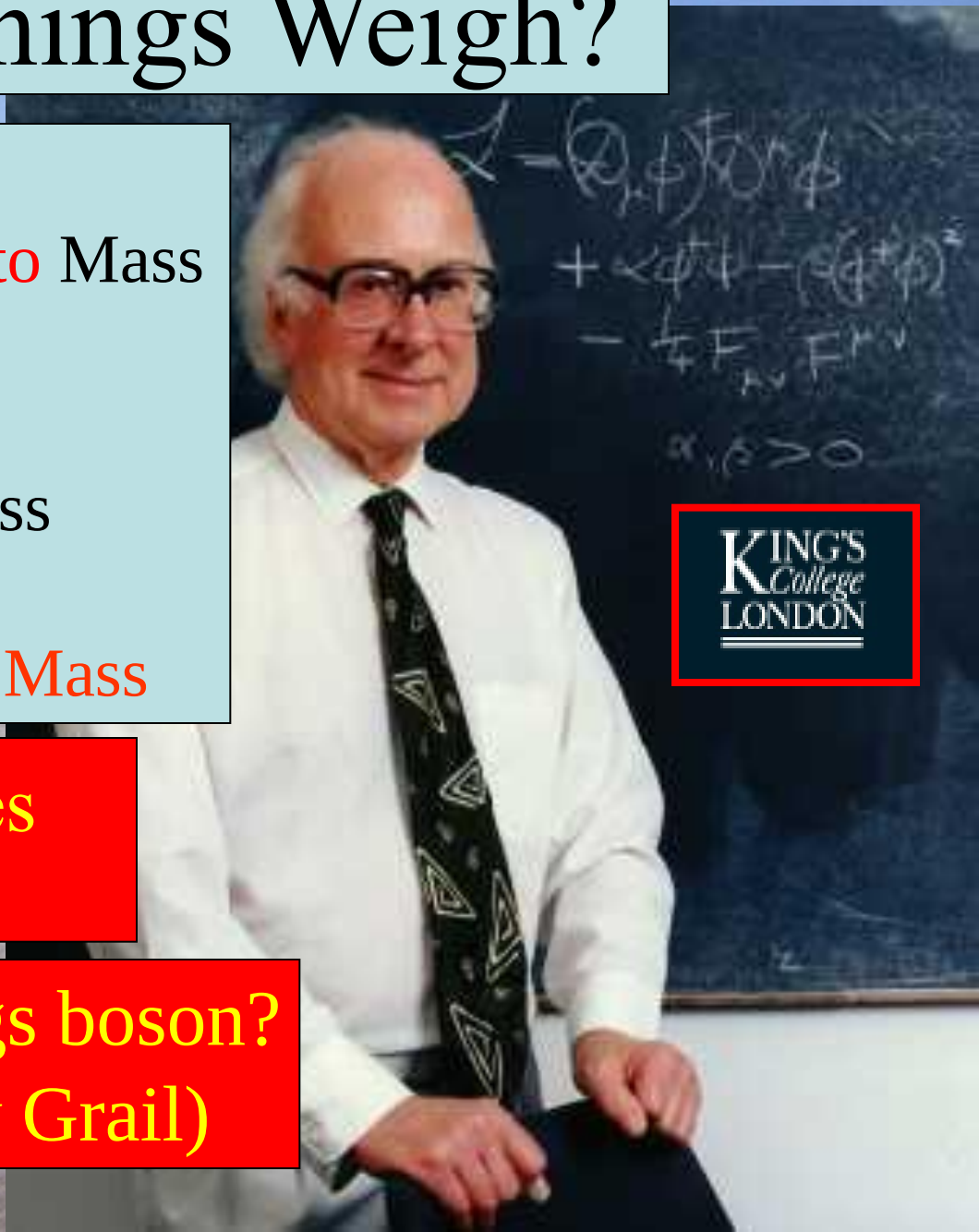
Einstein:

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)



The (NG)AEBHGHKMP Mechanism

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTE

BROKEN SYMMETRIES AND THE MASSES OF GA

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh,
(Received 31 August 1964)

The only one who mentioned a massive scalar boson

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

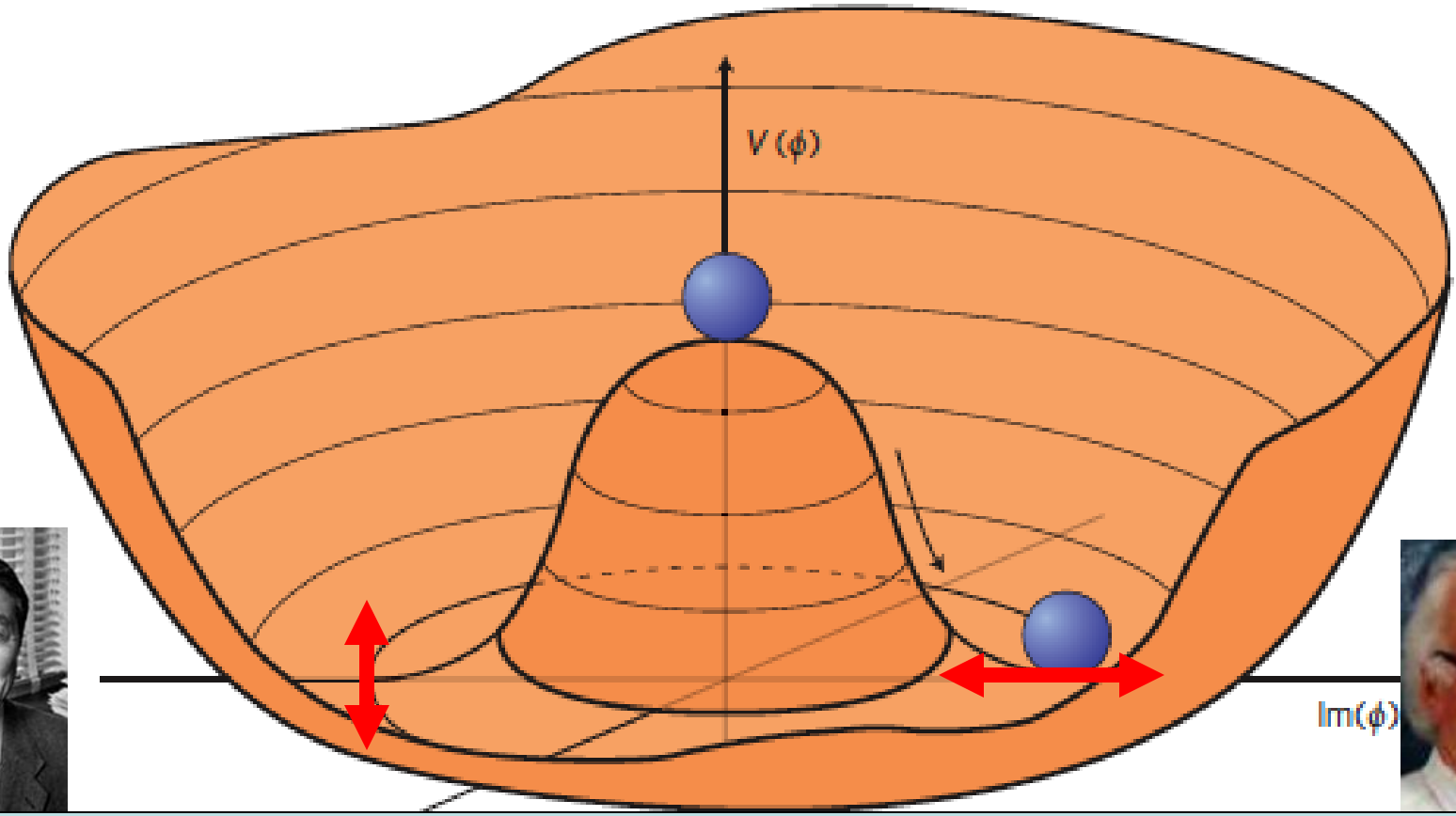
SPONTANEOUS BREAKDOWN OF STRONG INTERACTION SYMMETRY AND THE ABSENCE OF MASSLESS PARTICLES

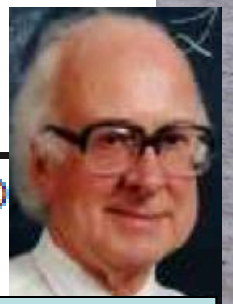
A. A. MIGDAL and A. M.

Submitted to JETP editor November 30, 1965; resubmitted February 16, 1966
J. Exptl. Theoret. Physics (U.S.S.R.) 51, 135-146 (July, 1966)

The occurrence of massless particles in the presence of spontaneous symmetry breakdown is discussed. By summing all Feynman diagrams, one obtains for the difference of the mass

Nambu **EB, H, GHK** **and Higgs**

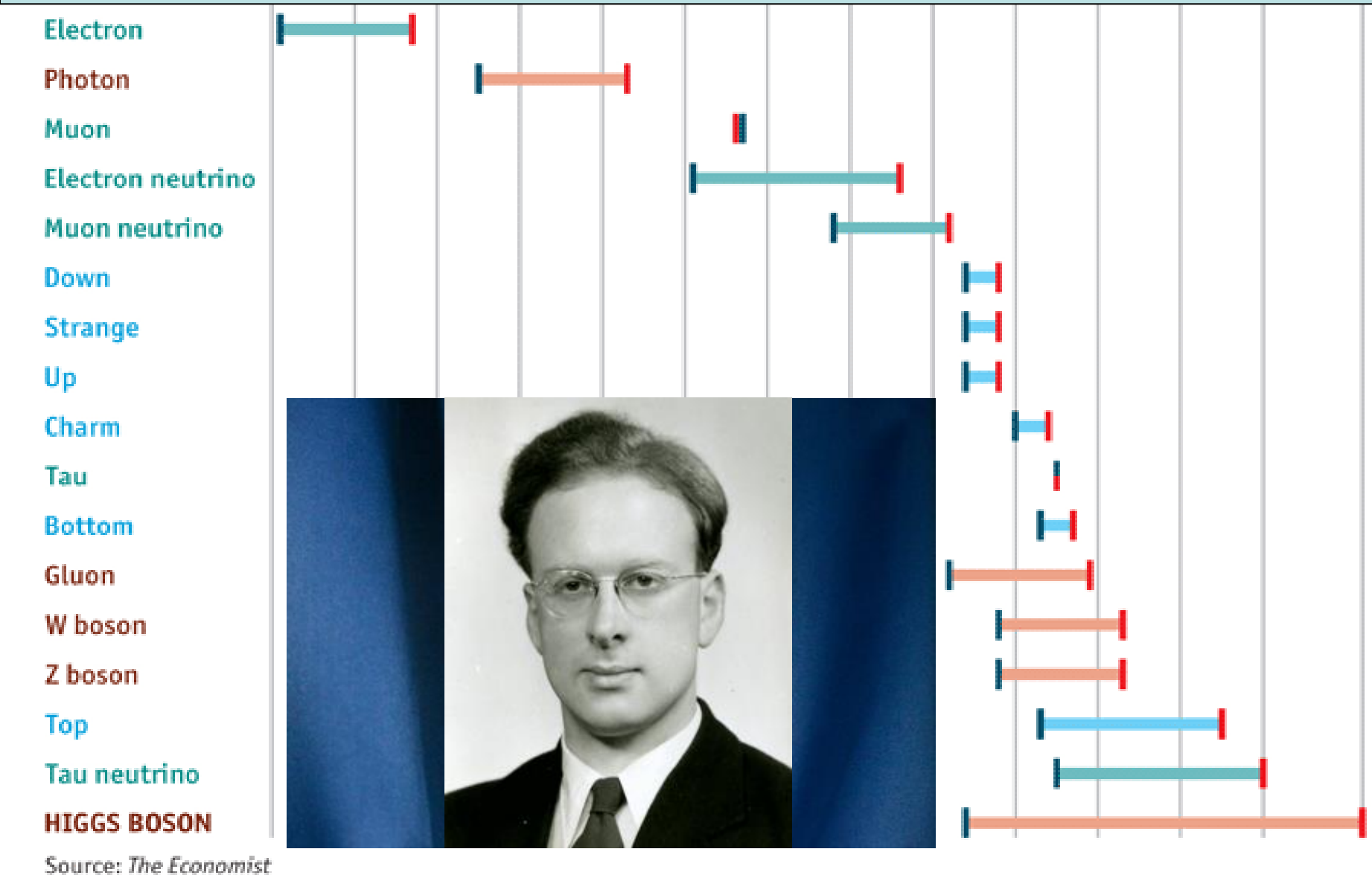




Spontaneous symmetry breaking: massless Nambu-Goldstone boson **'eaten' by massless gauge boson**

Accompanied by massive particle

Standard Model Particles:
Years from Proposal to Discovery



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

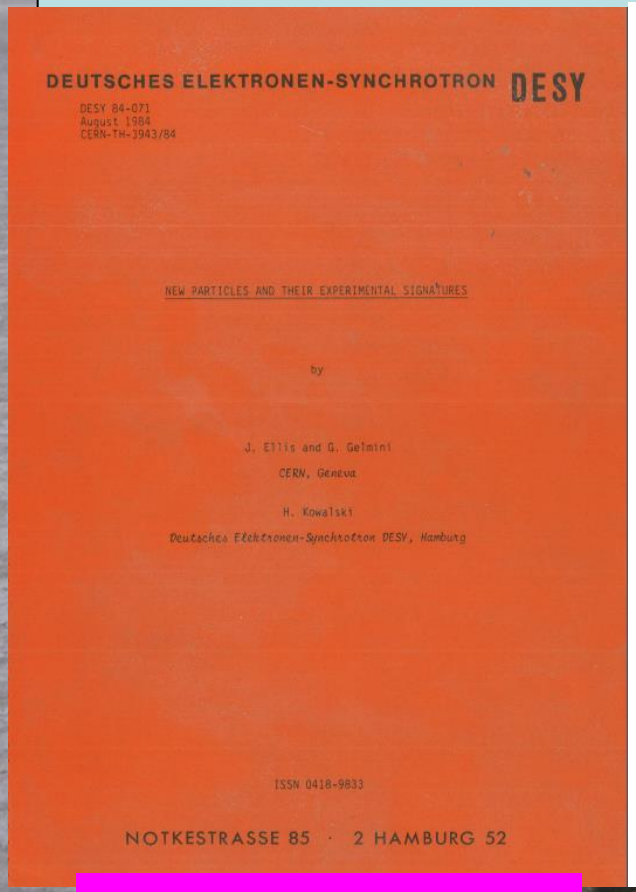
Received 7 November 1975

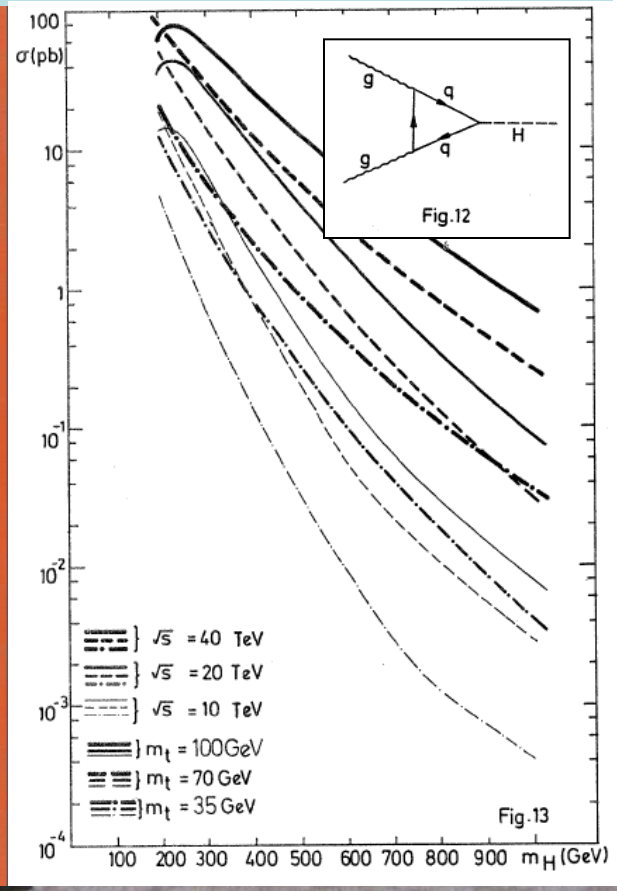
A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of

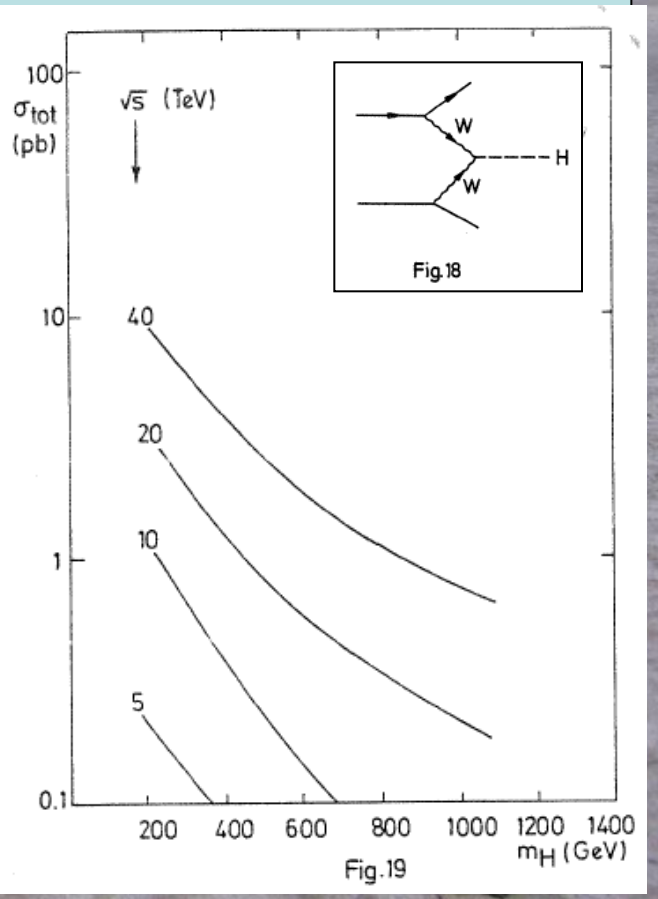
We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons 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.

A Preview of the Higgs Boson @ LHC

- Prepared for LHC Lausanne workshop 1984

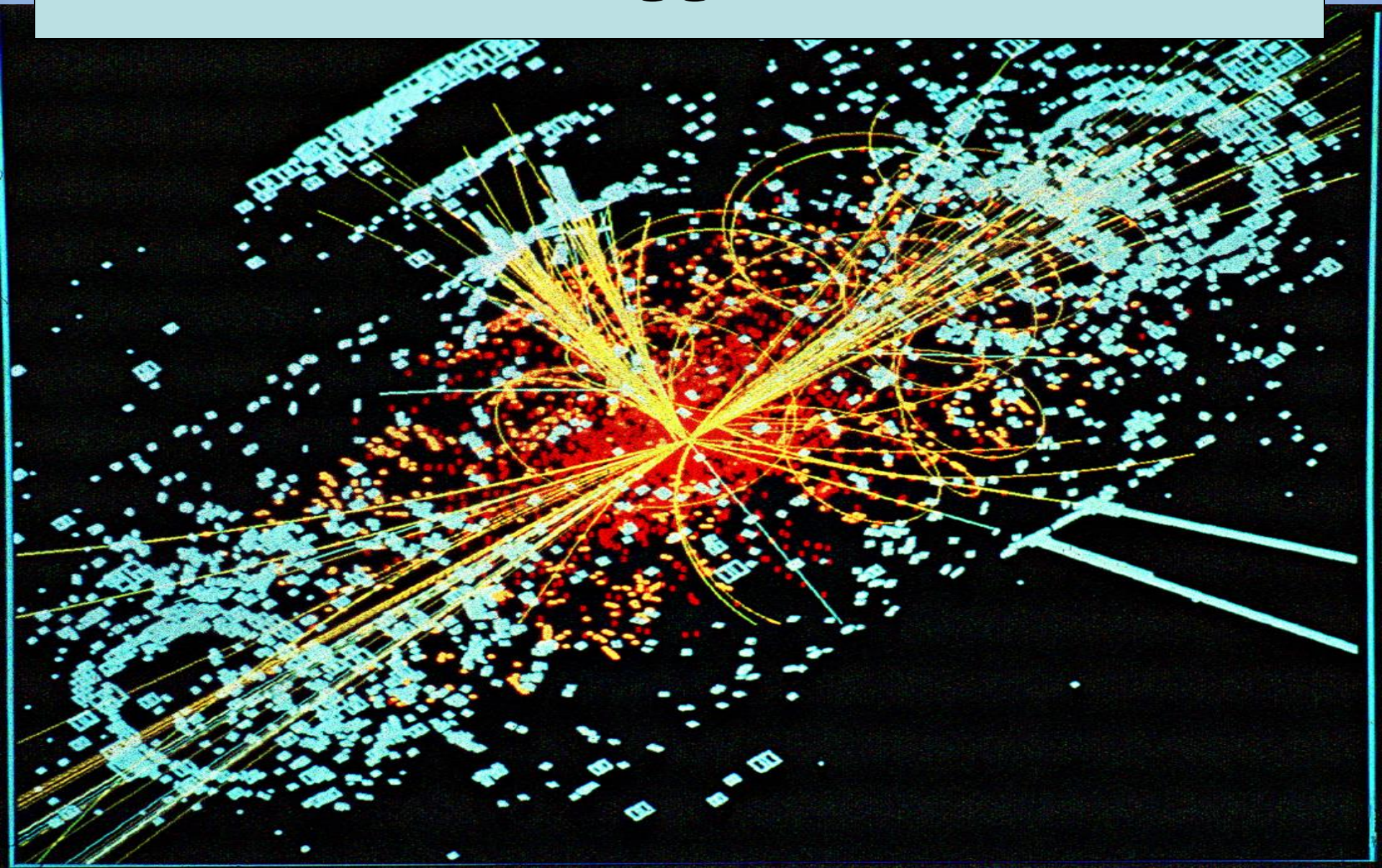


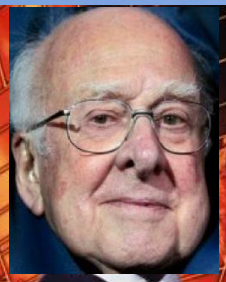




JE, Gelmini & Kowalski, 1984

A Simulated Higgs Event @ LHC





- « Empty » space is unstable
- Dark matter
- Origin of matter
- Masses of neutrinos
- Why is weak force so strong?
- Inflation
- Quantum gravity
- …

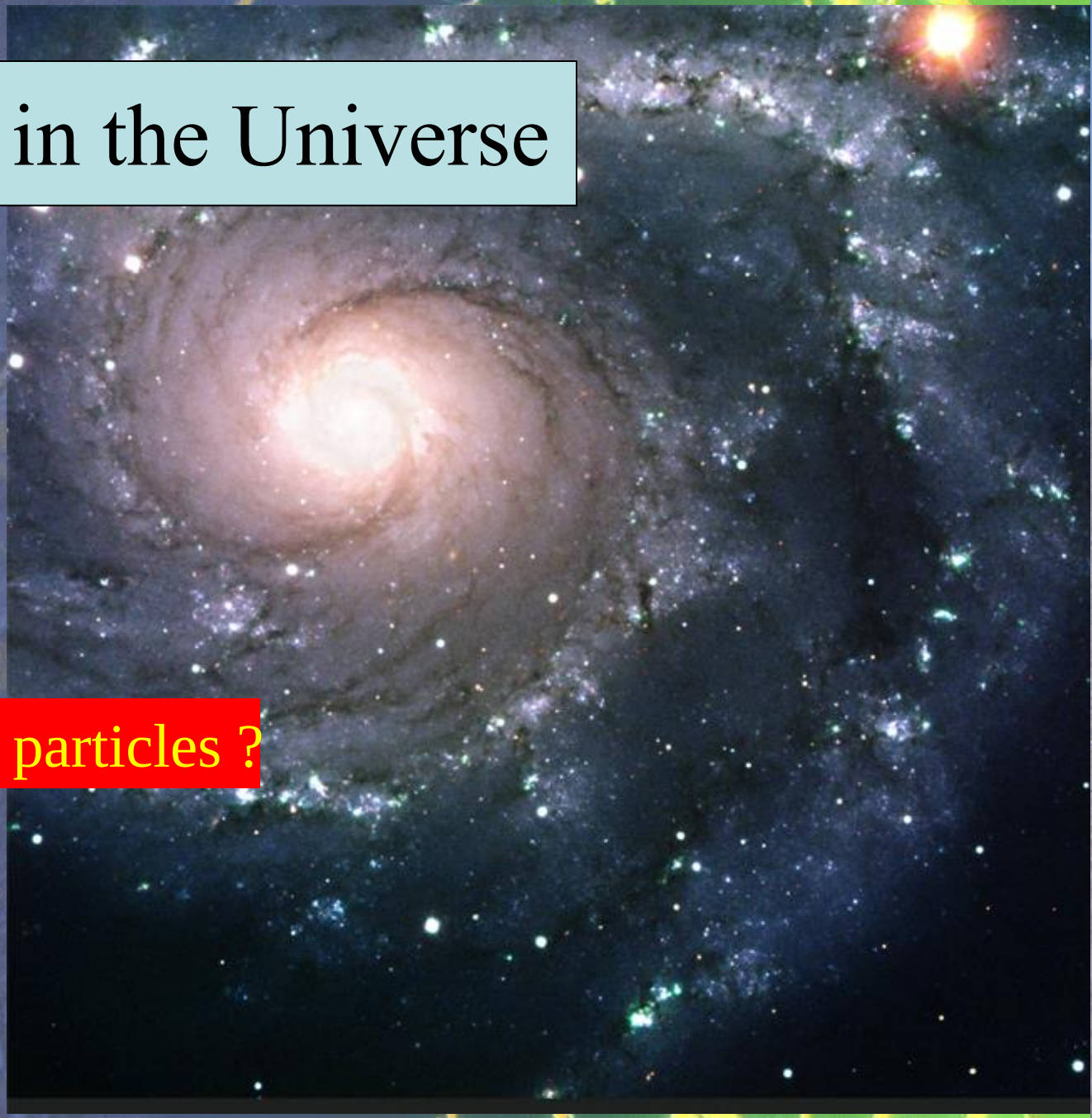
The *Standard Model* Is Not *Enough*

Dark Matter in the Universe

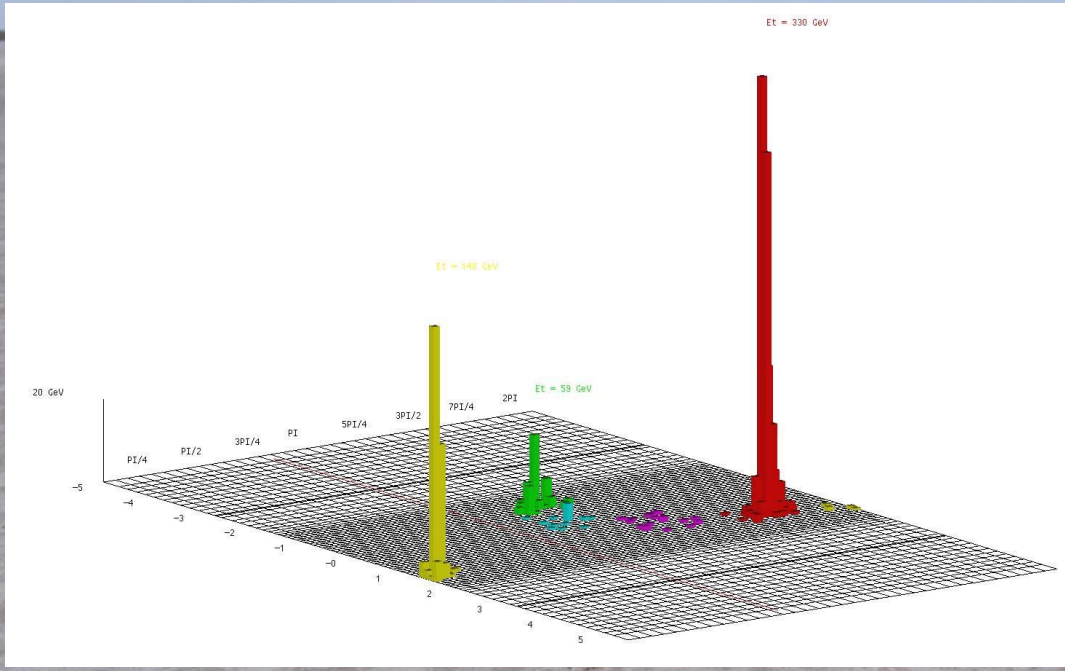
Astronomers say that most of the matter in the Universe is invisible
Dark Matter

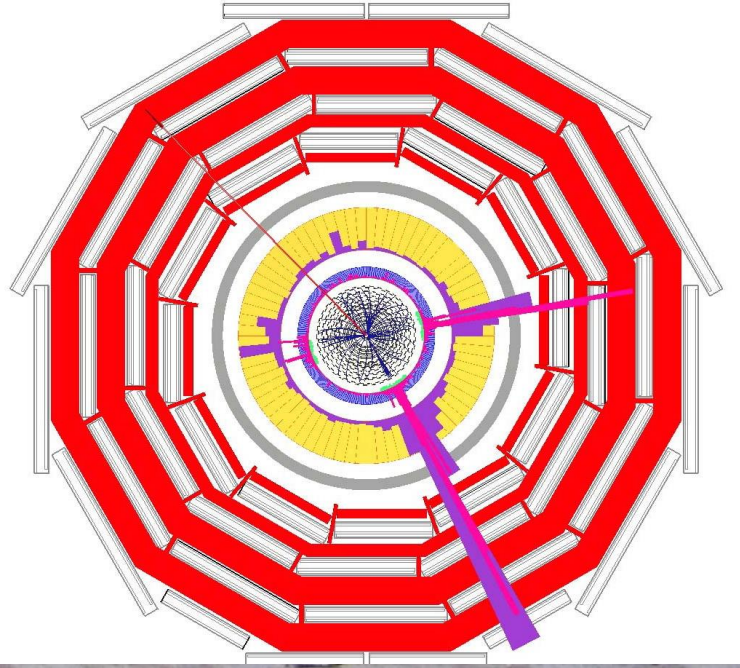
‘Supersymmetric’ particles ?

We shall look for them with the LHC



Classic Dark Matter Signature





Missing transverse energy
carried away by dark matter particles

General Interest in Antimatter Physics

Physicists cannot make enough for
Star Trek or Dan Brown!

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

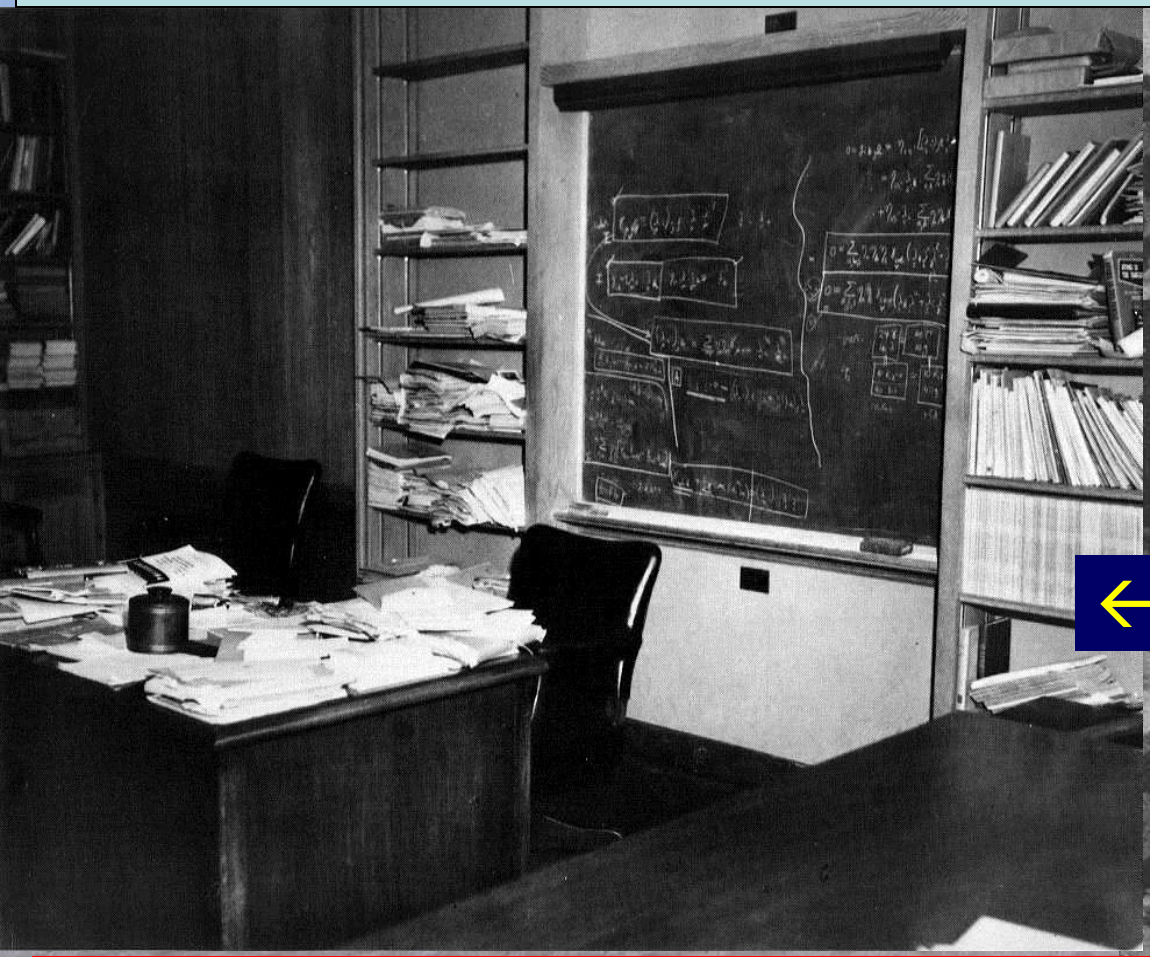
Used in PET scanners

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

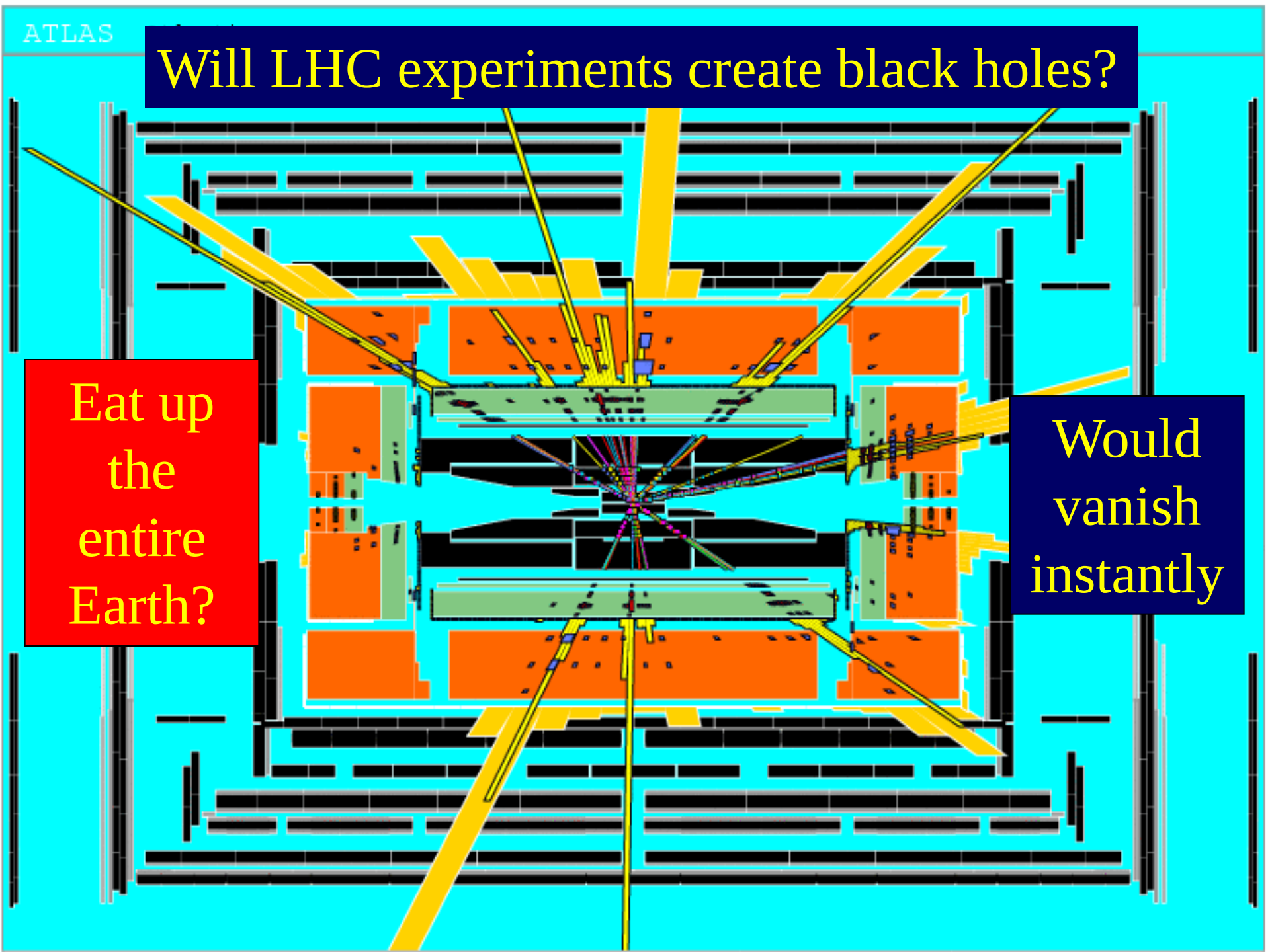
Unify the Fundamental Interactions: Einstein's Dream …



← … but he never succeeded

Unification via extra dimensions of space?

Will LHC experiments create black holes?

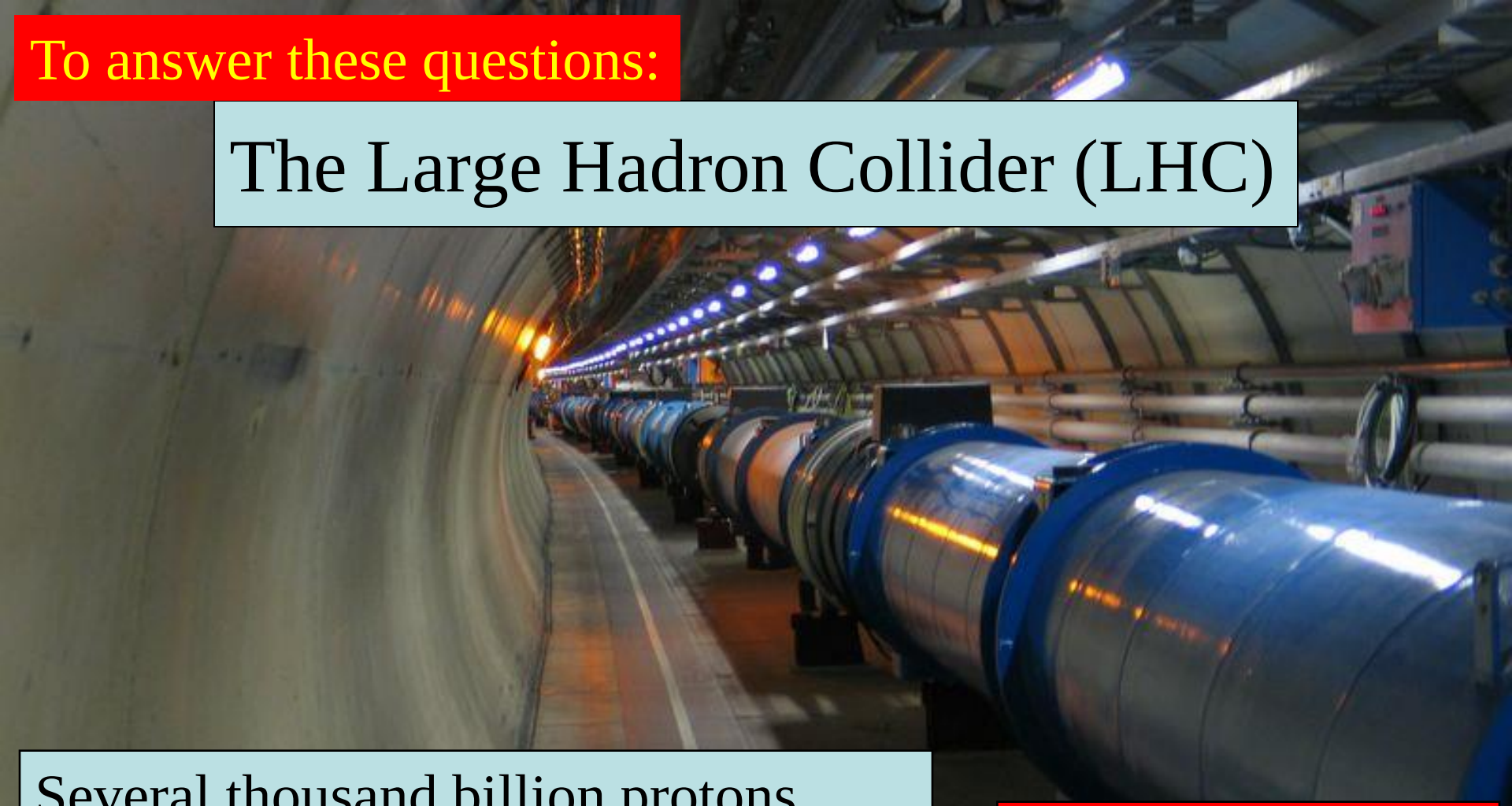


Eat up the entire Earth?

Would vanish instantly

To answer these questions:

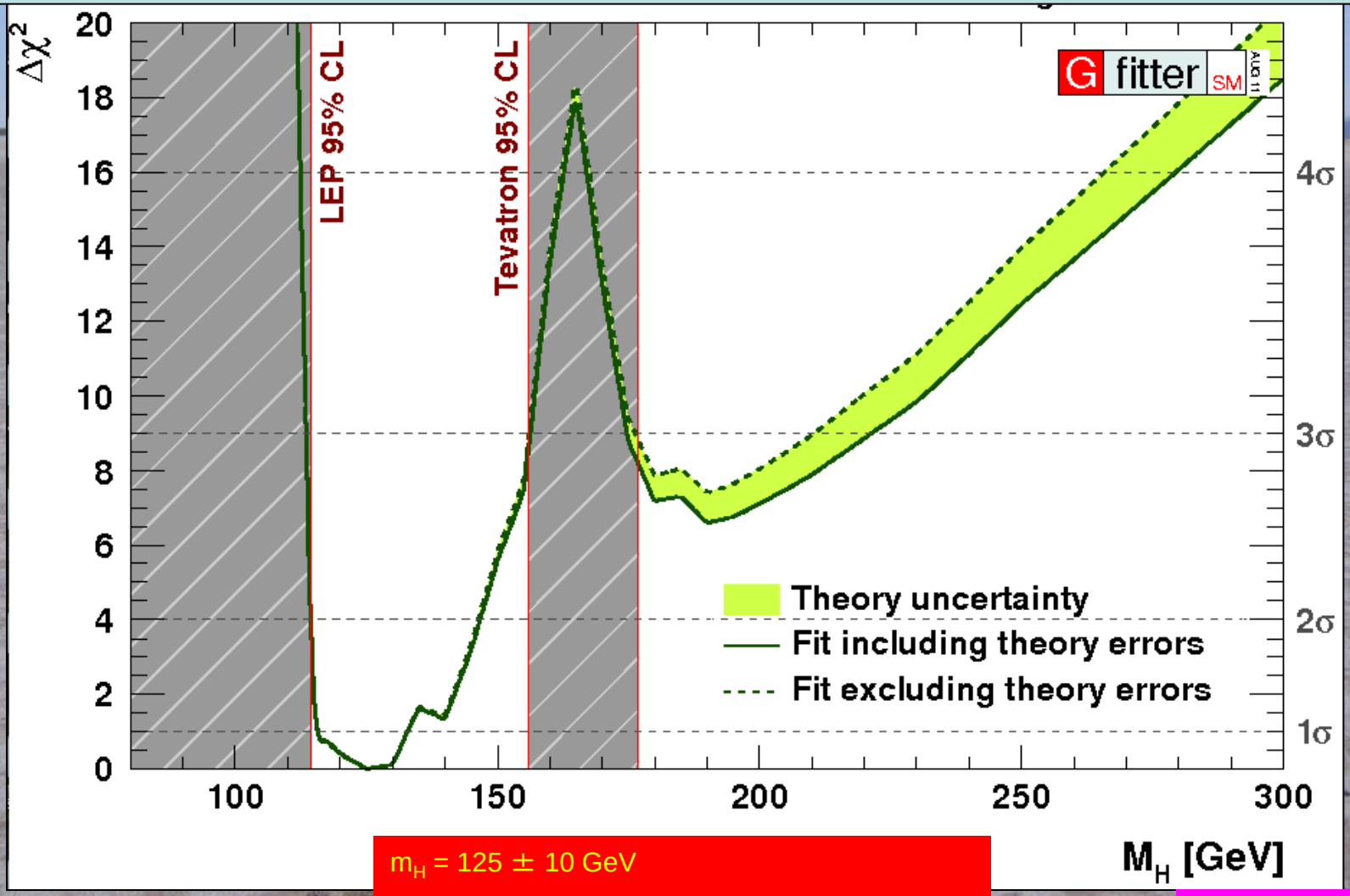
The Large Hadron Collider (LHC)



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

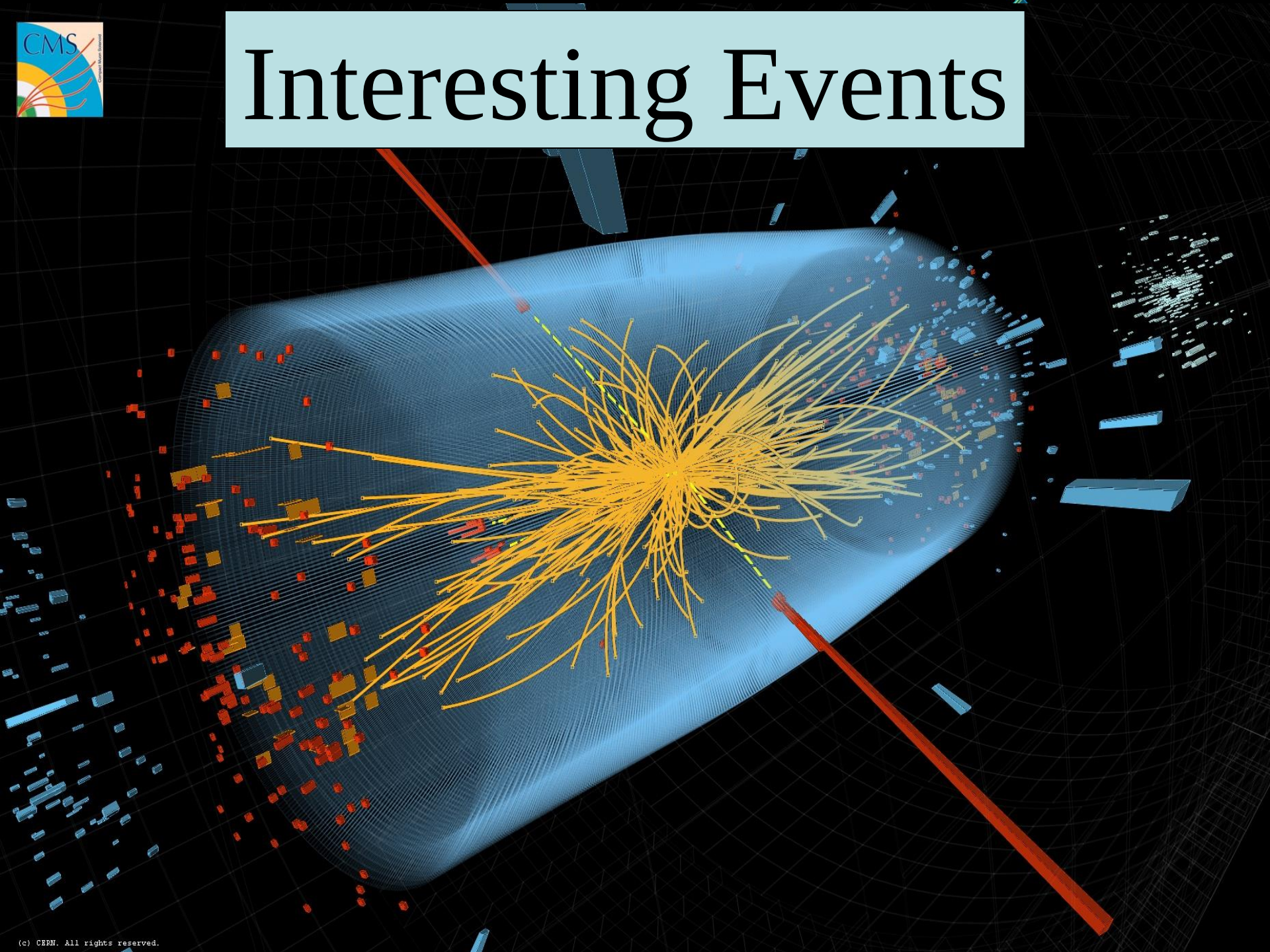
2011: Combining Information from Previous Direct Searches and Indirect Data



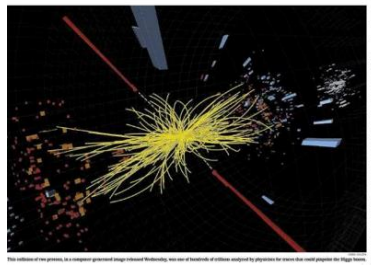
$m_H = 125 \pm 10$ GeV

Gfitter collaboration

Interesting Events

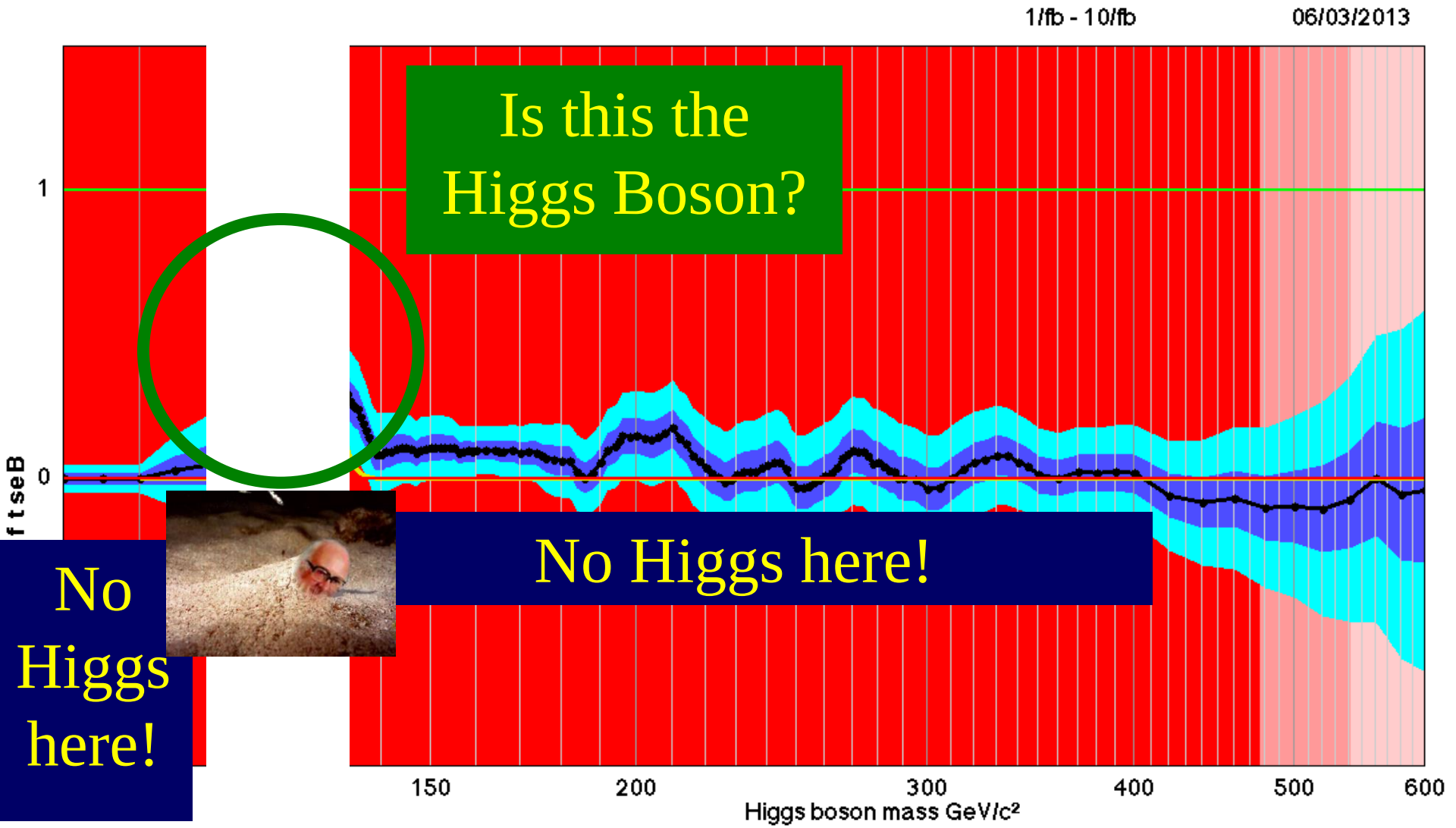


July 4th 2012
The discovery of a new particle

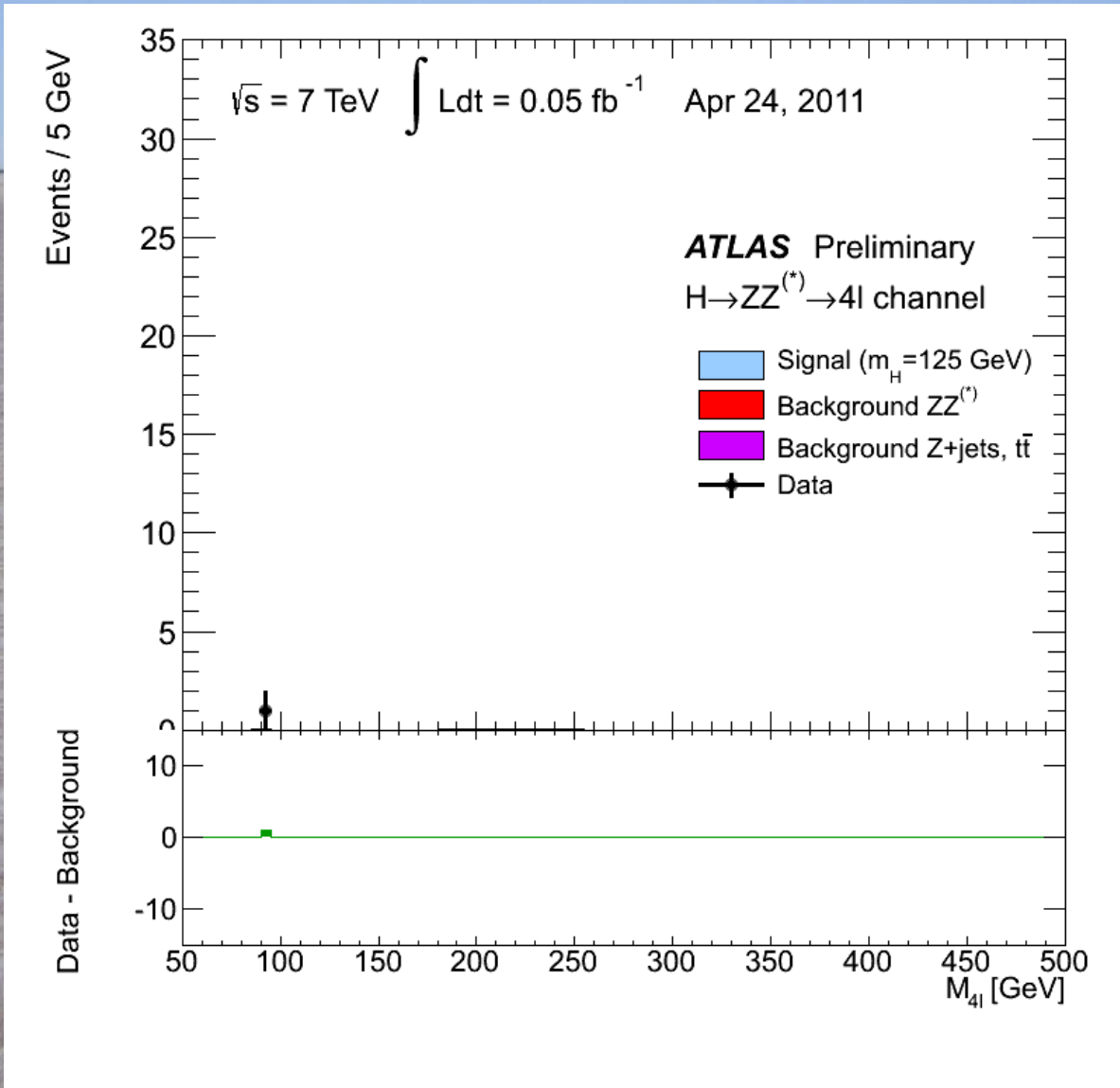


Higgsdependence Day!

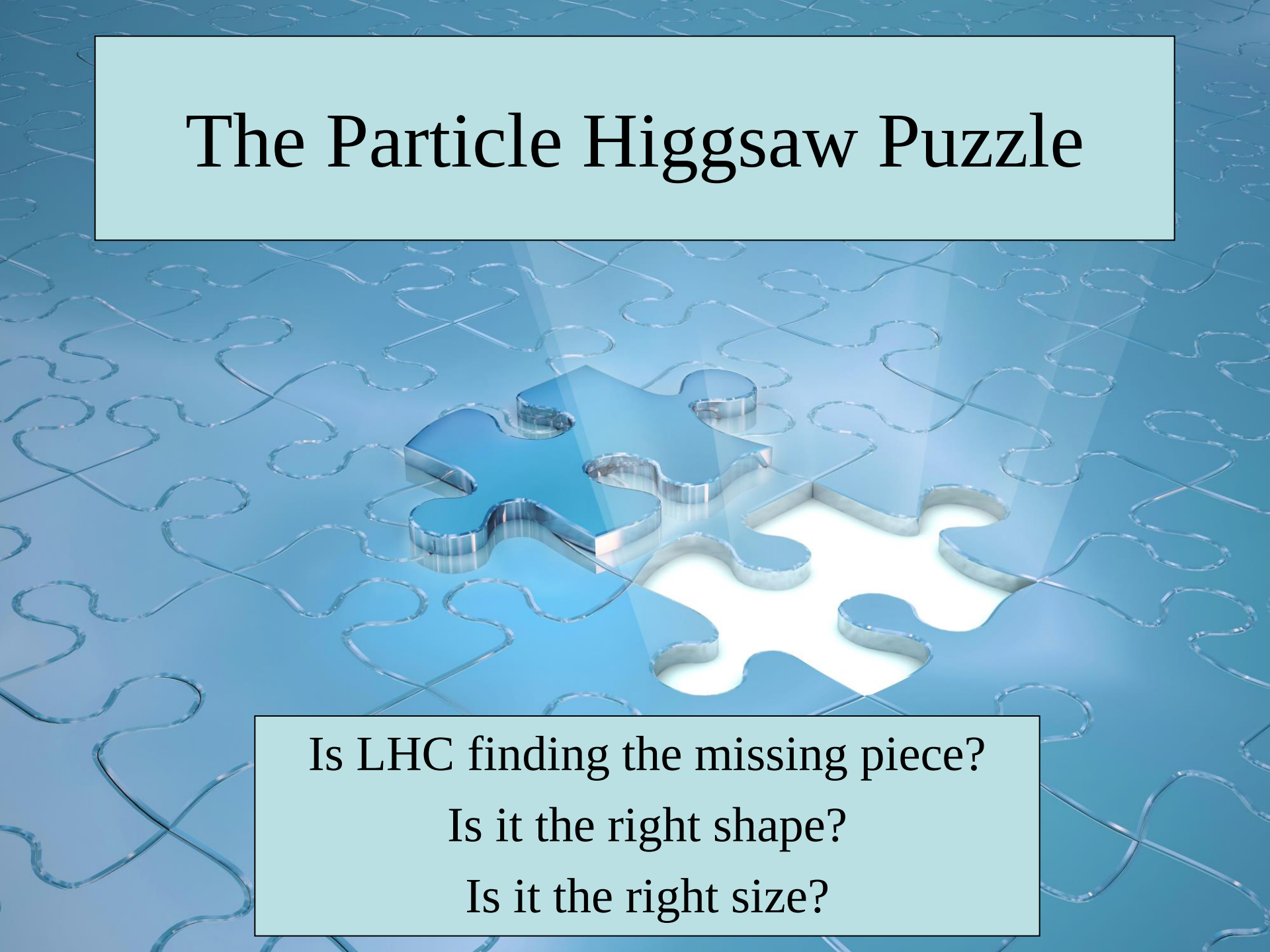
Unofficial Combination of Higgs Data



How the Higgs Signal has Grown



The Particle Higgsaw Puzzle

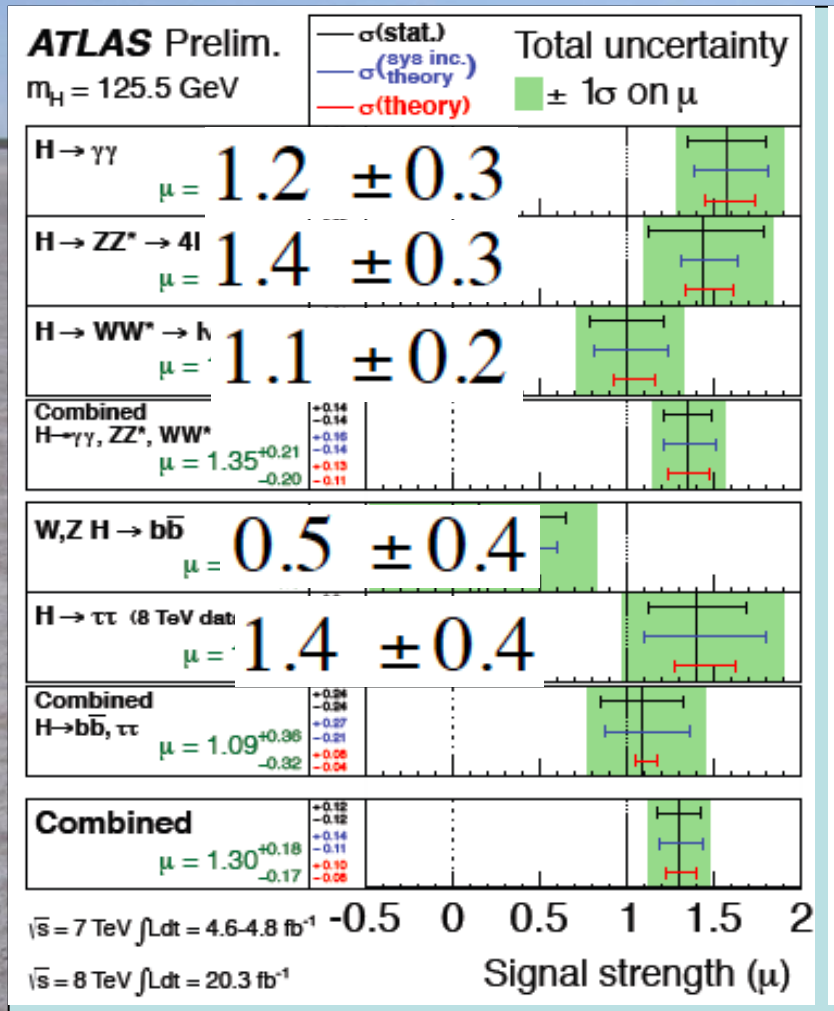


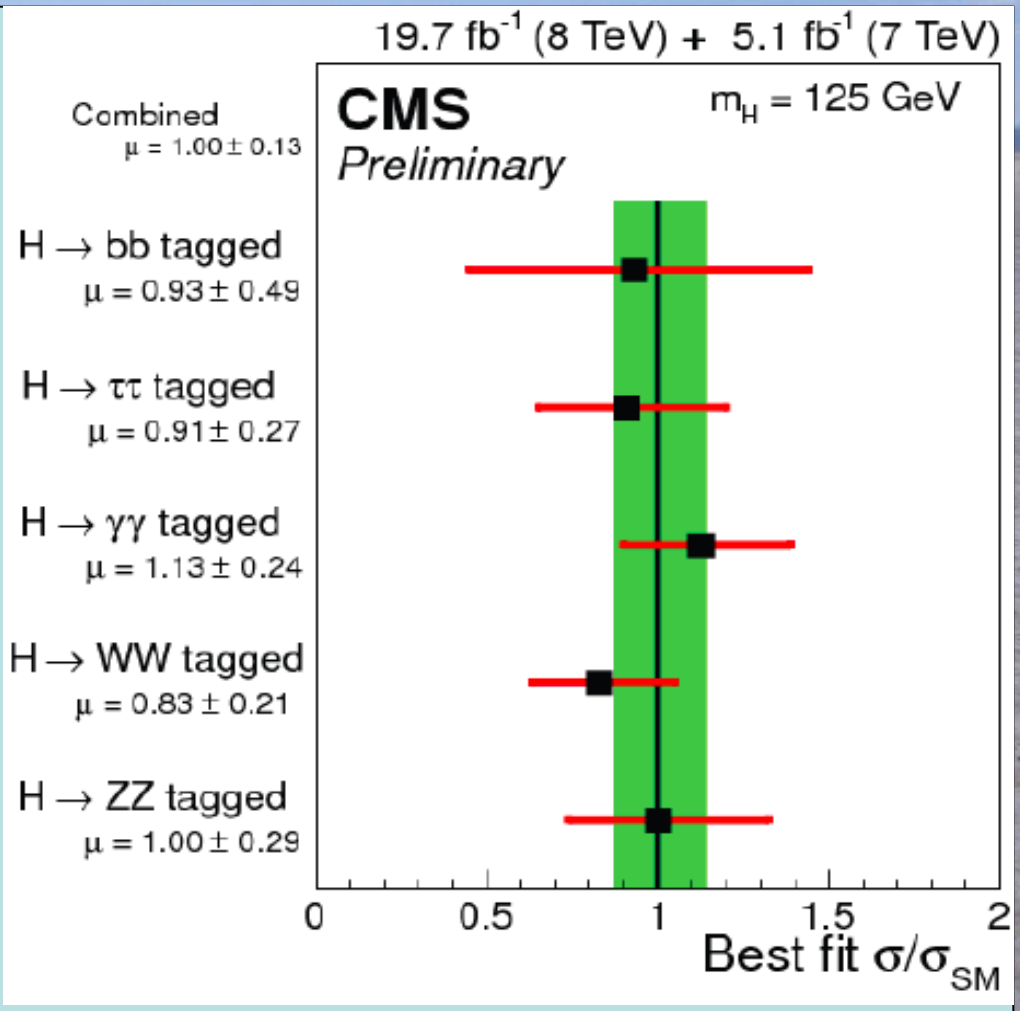
Is LHC finding the missing piece?

Is it the right shape?

Is it the right size?

Higgs Signal Strengths



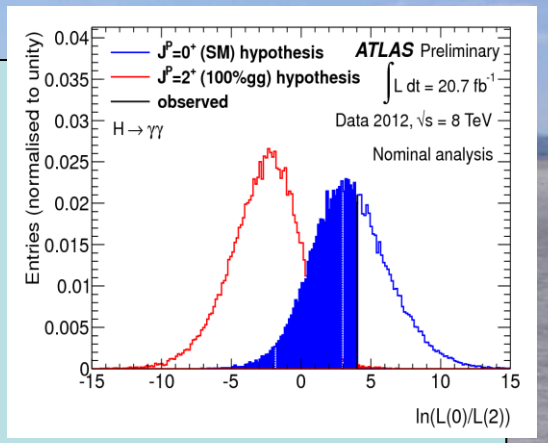


$\mu = 1.30 \pm 0.12\,(\text{stat}) \pm 0.10\,(\text{th}) \pm 0.09\,(\text{syst})$

$\sigma/\sigma_{\text{SM}} = 1.00 \pm 0.13 \left[\pm 0.09(\text{stat.})^{+0.08}_{-0.07}(\text{theo.}) \pm 0.07(\text{syst.})\right]$

Beyond any Reasonable Doubt

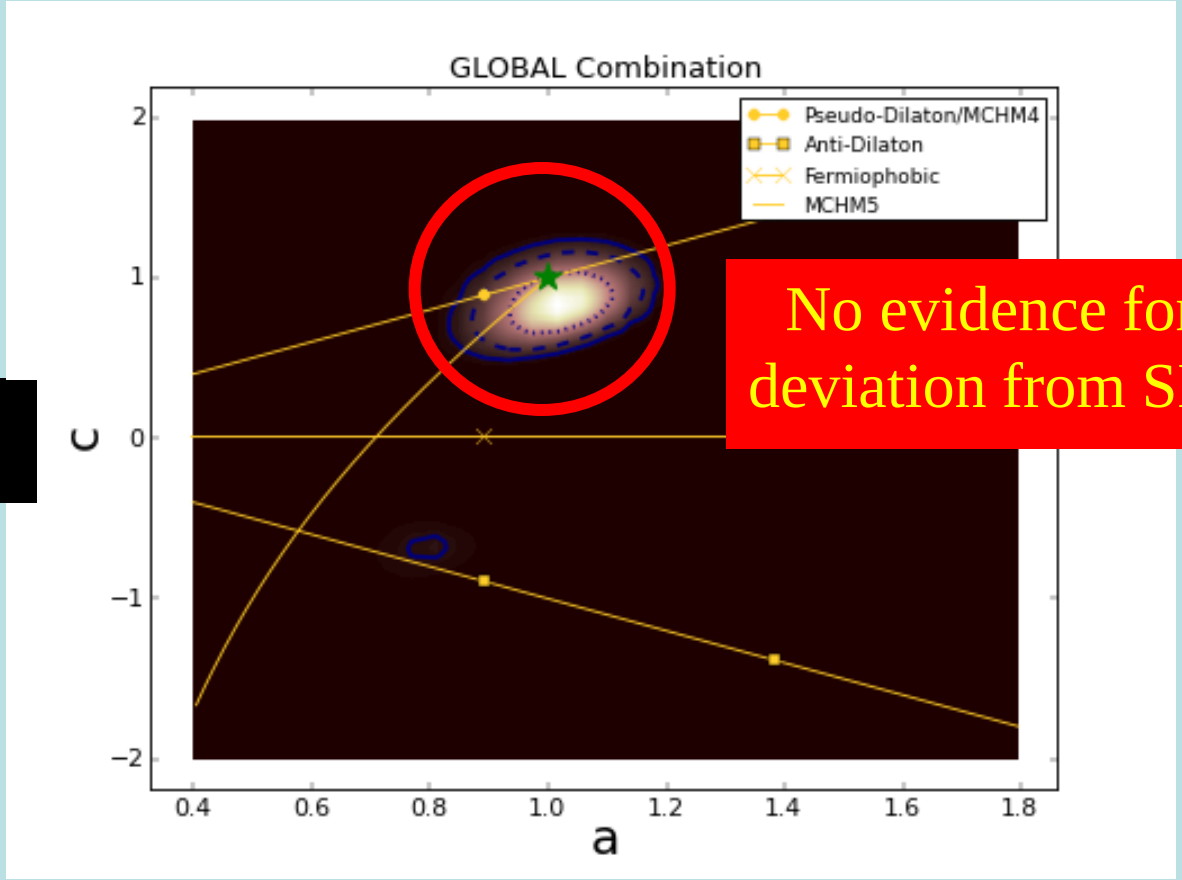
- Does it have spin 0 or 2?
  - **Spin 2 strongly disfavoured**
- Is it elementary or composite?
  - **No significant deviations from Standard Model**
- Does it couple to particle masses?
  - ***Prima facie* evidence that it does**



Global Analysis of Higgs-like Models

- Rescale couplings: to bosons by a, to fermions by c

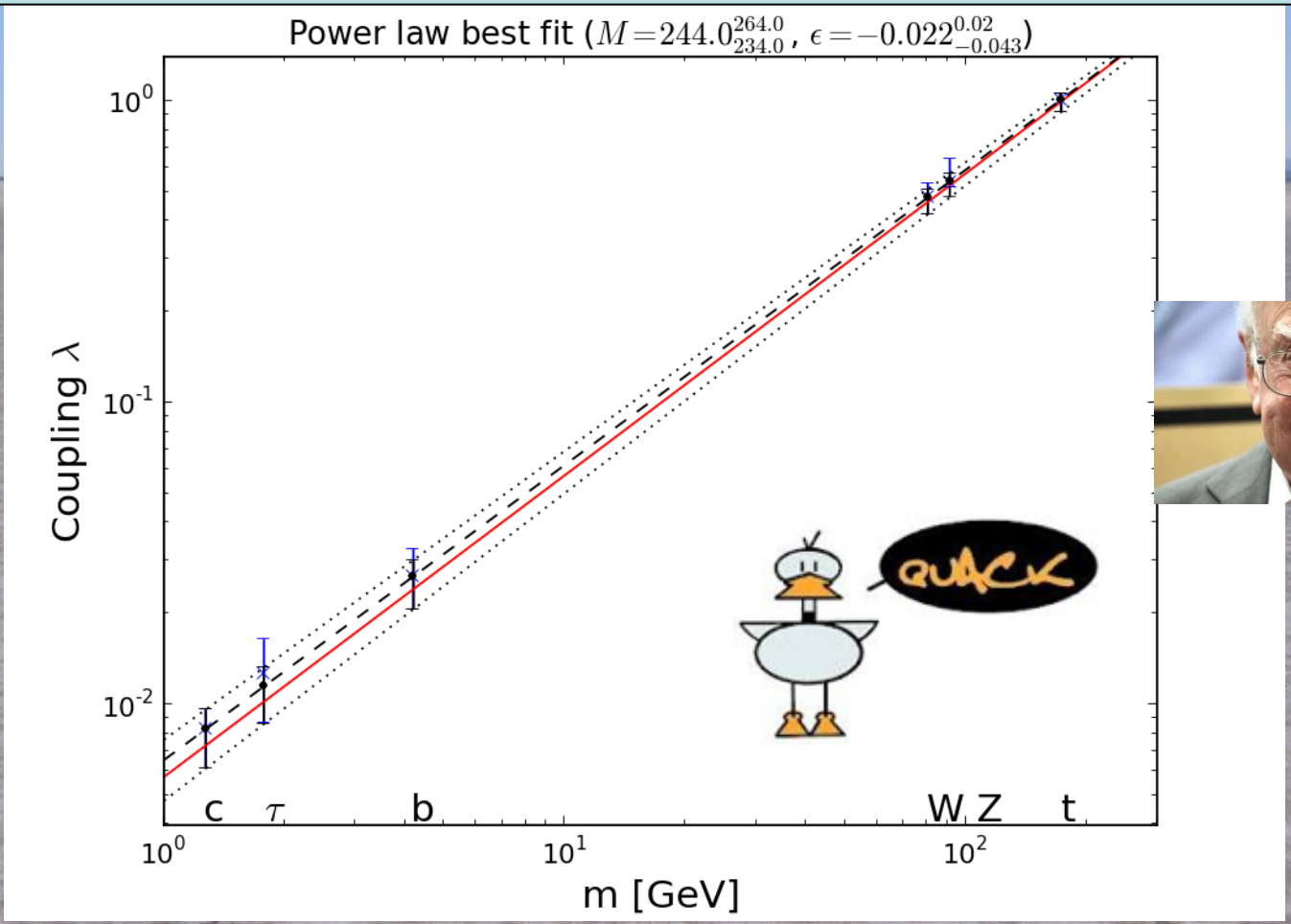
Global



- Standard Model: $a = c = 1$

JE & Tevong You, arXiv:1303.3879

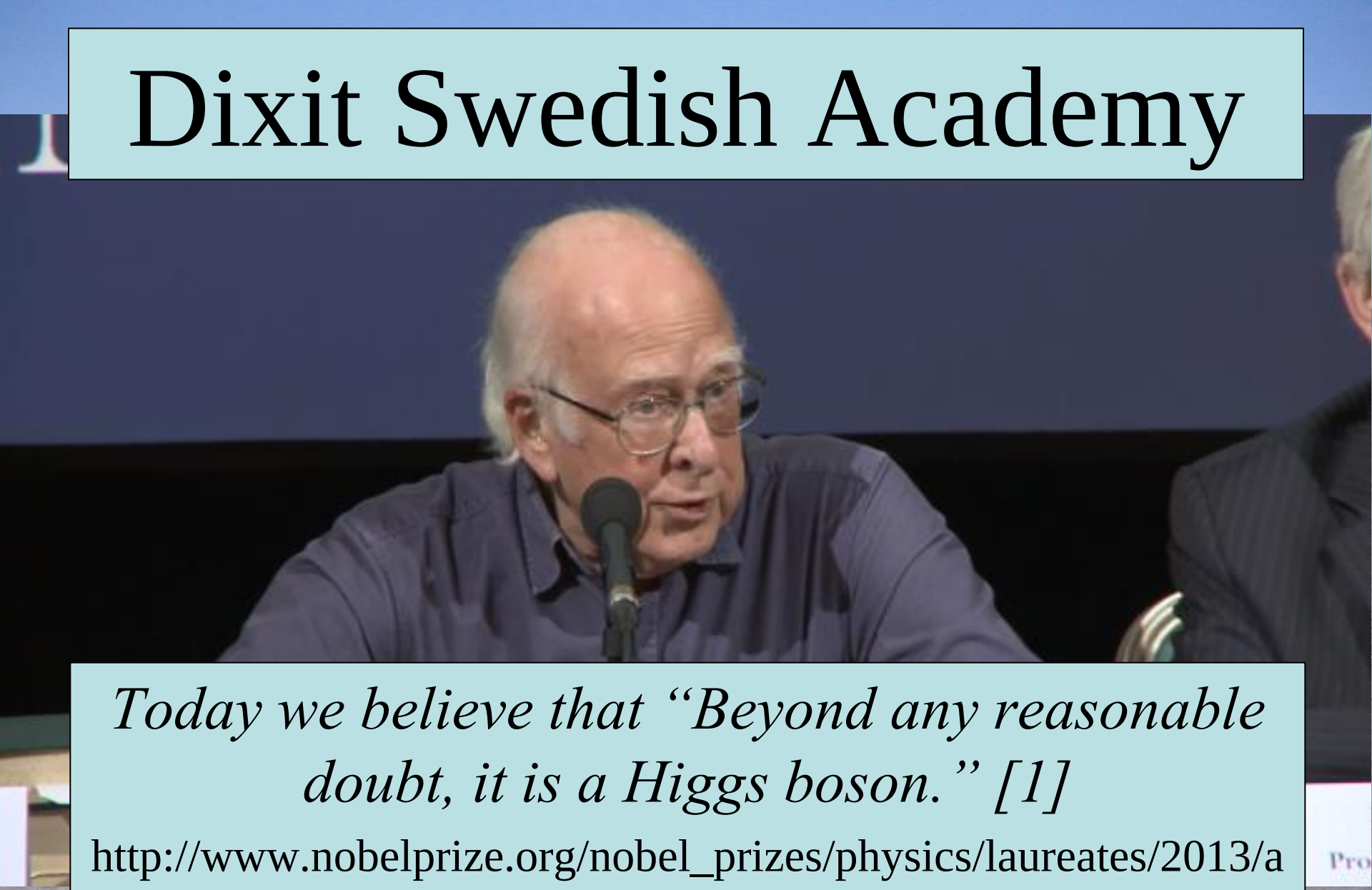
It Walks and Quacks like a Higgs



So far, it looks like a (bog) Standard Model Higgs Boson

JE & Tevong You, arXiv:1303.3879

Dixit Swedish Academy

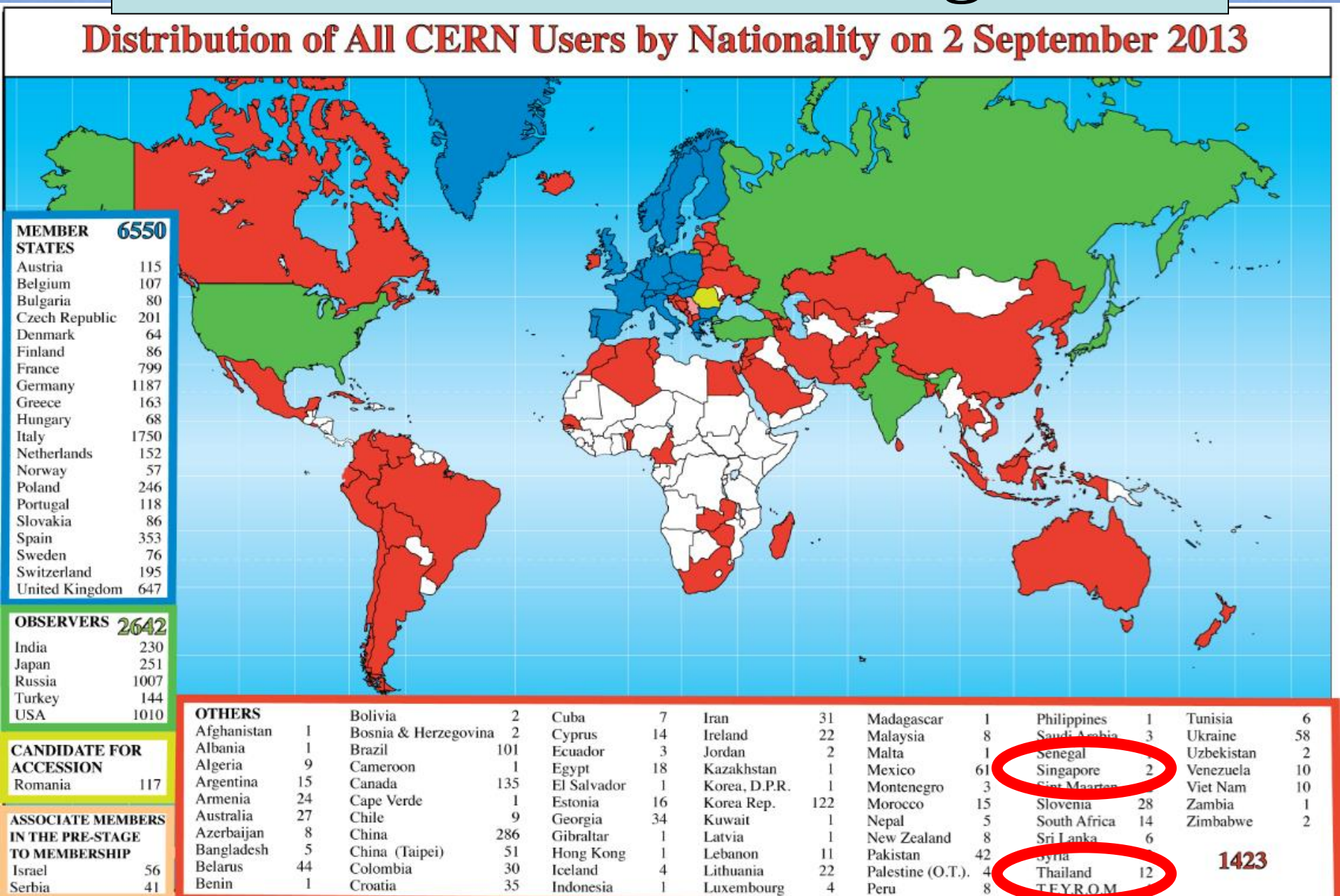


Today we believe that "Beyond any reasonable doubt, it is a Higgs boson." [1]

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

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

Science is ever more global



Without Higgs …

… 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

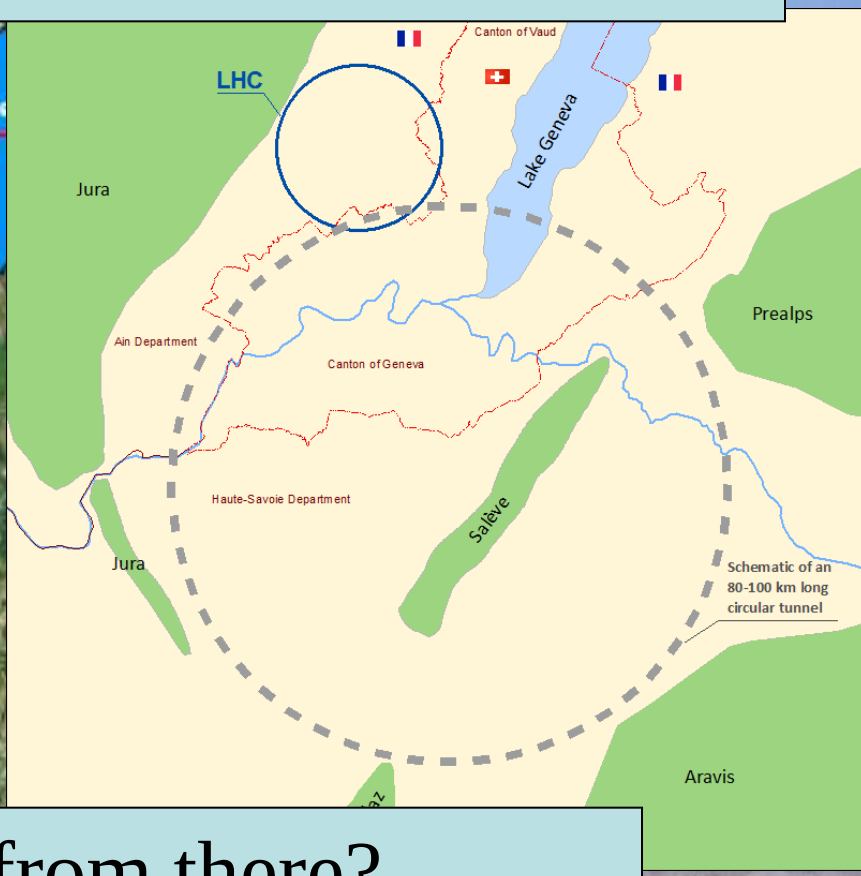
Its existence is a big deal!

What else is there?

Supersymmetry

- Successful prediction for Higgs mass
  - Should be < 130 GeV in simple models
- Successful predictions for Higgs couplings
  - Should be within few % of SM values
- Could explain the dark matter
- Naturalness, GUTs, string, … (???)

Next Steps at the High-Energy Frontier?



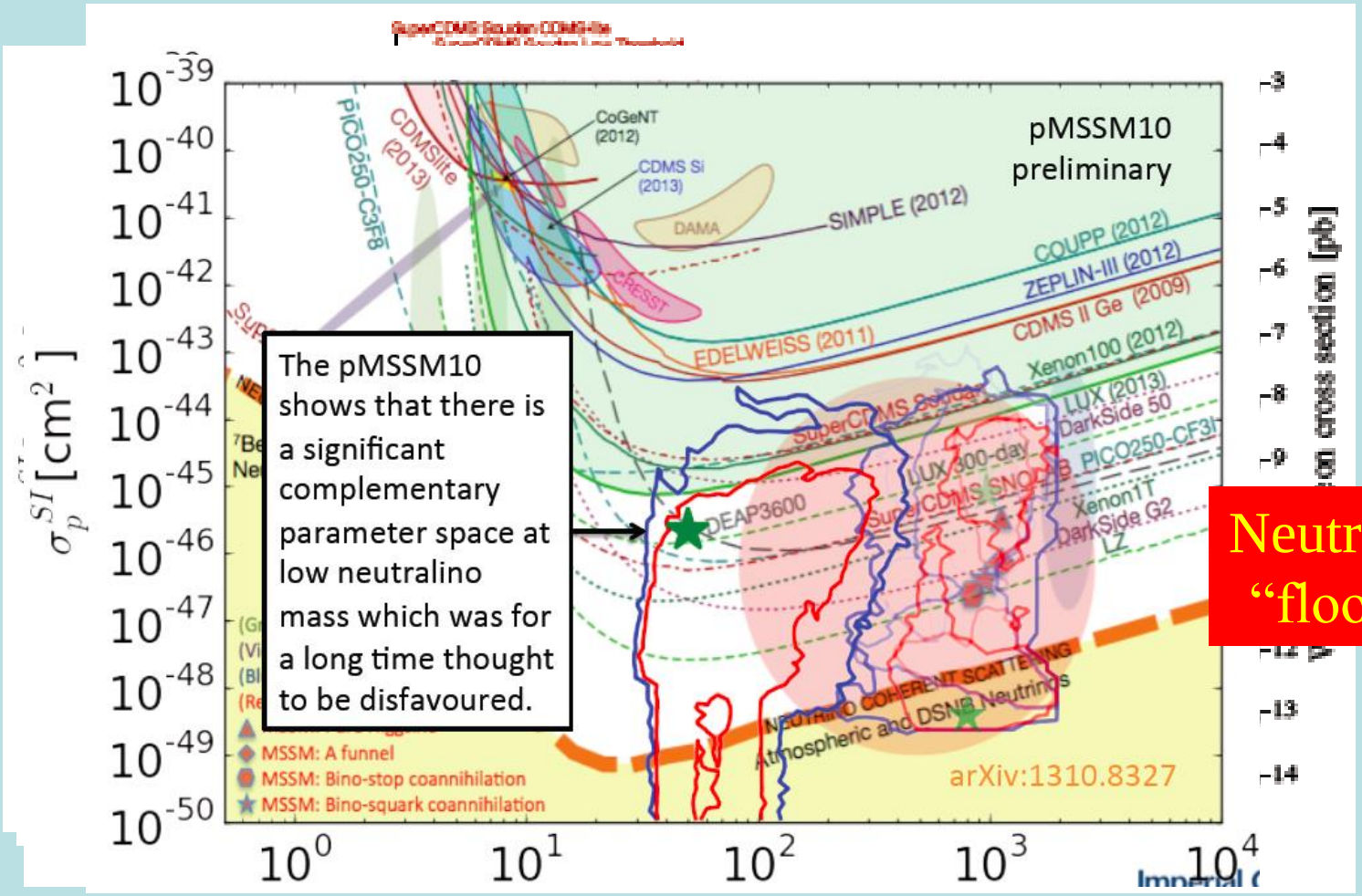
Where do we go from there?

50km linear e^+e^- collider?

100km circumference pp, e^+e^- collider?

Direct Dark Matter Searches

- Compilation of present and future sensitivities




The LHC is the world's most powerful microscope …
… and also a telescope