

# Perspectives in Particle Physics

What we do (not) know  
What else is there?  
How to discover it?

*John Ellis*

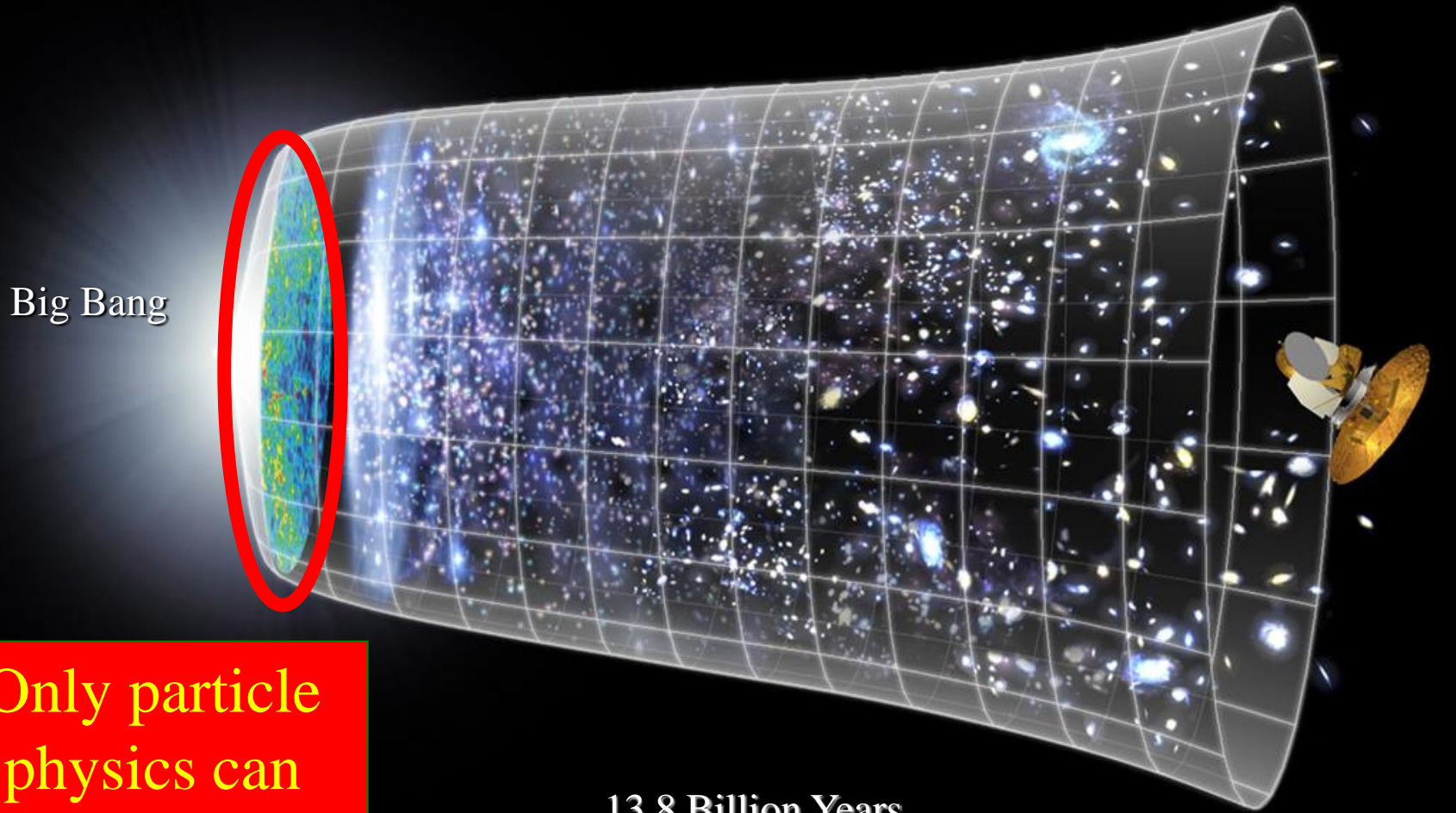
**KING'S**  
*College*  
**LONDON**

“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



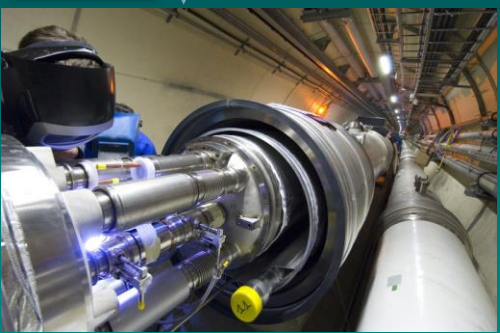
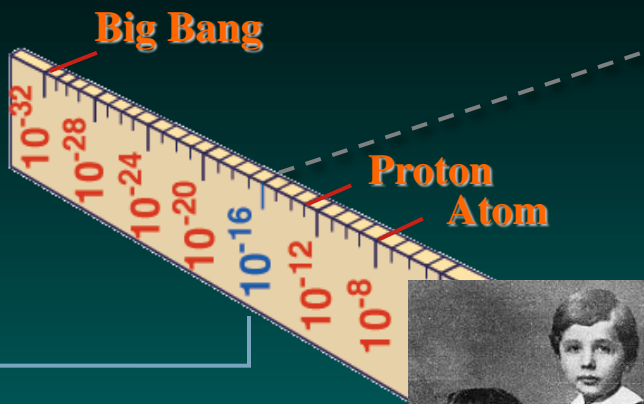
Big Bang

Today

13.8 Billion Years

$10^{28}$  cm

Only particle physics can tell us what happened here

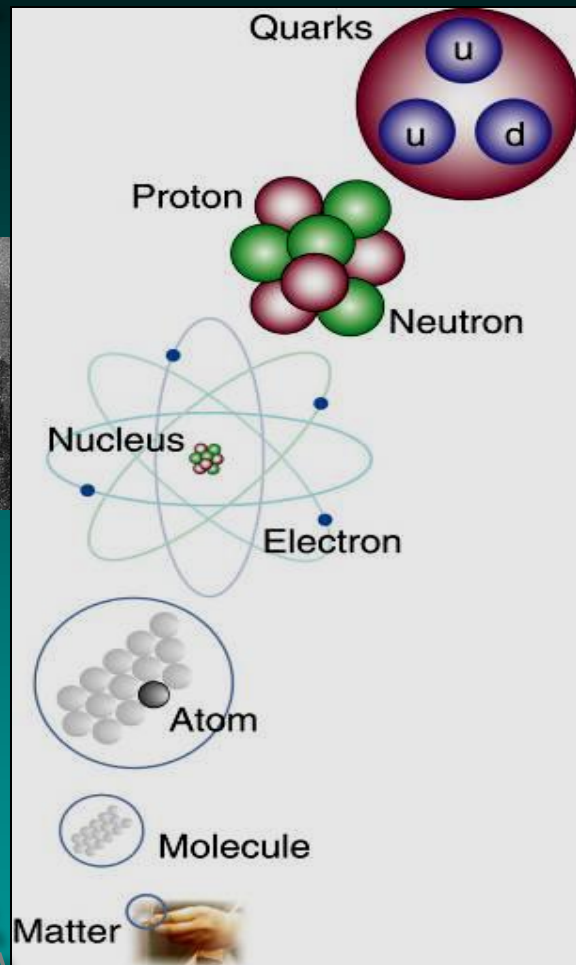


LHC

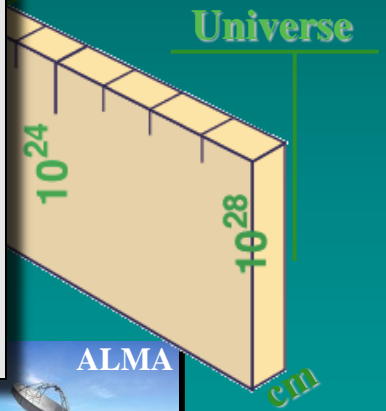
Super-Microscope



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



Radius of Galaxies

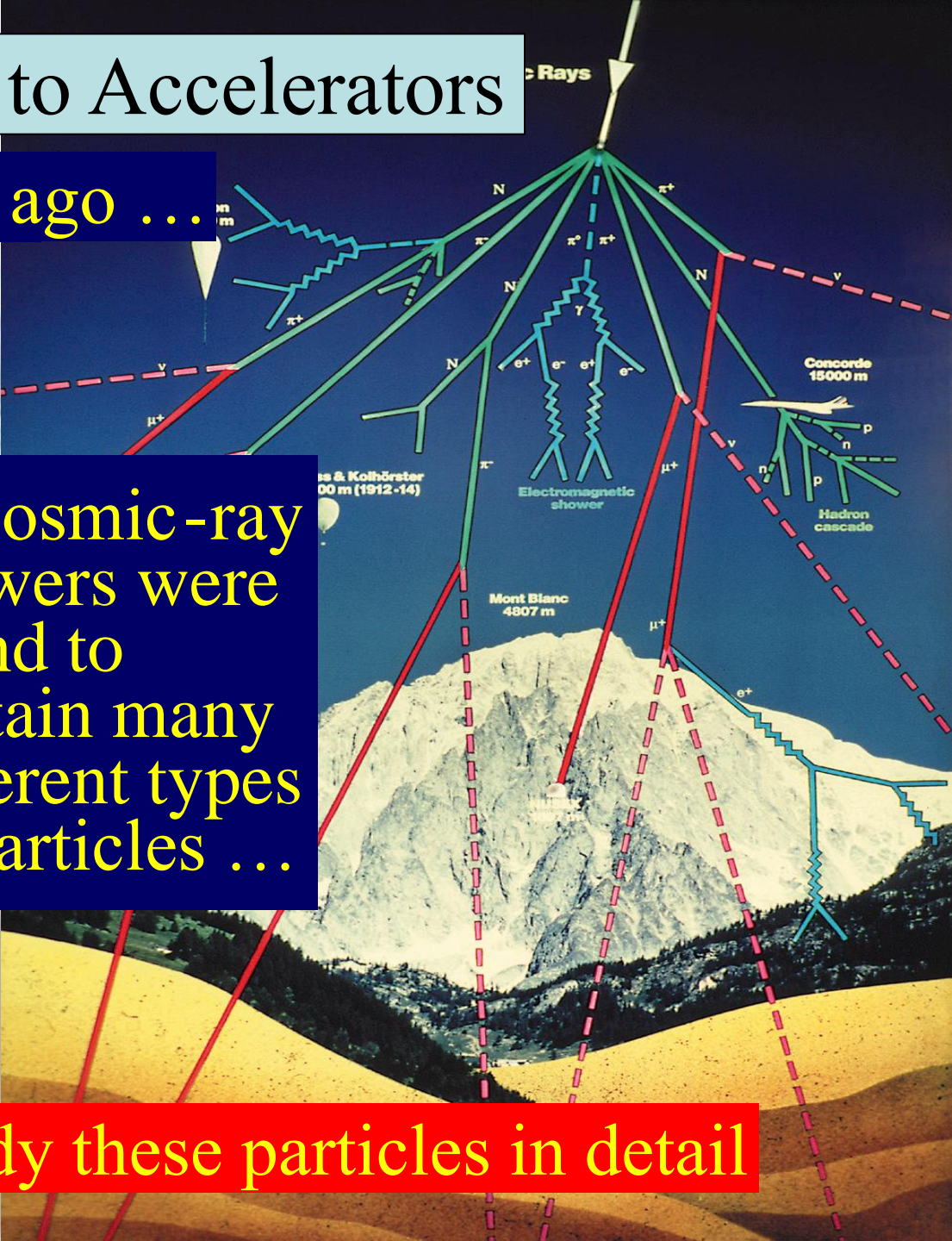


# From Cosmic Rays to Accelerators

Discovered a century ago ...

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

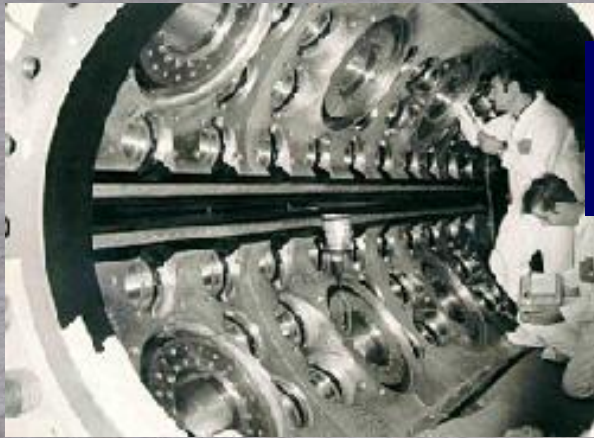
Accelerators study these particles in detail



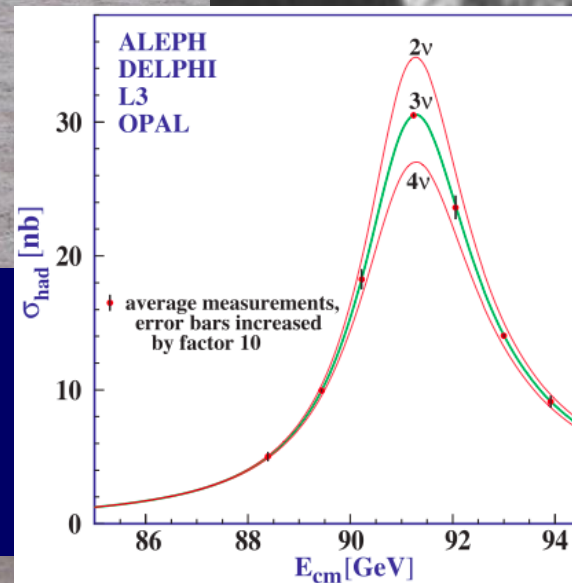
# The 'Standard Model' of Particle Physics

Proposed by Abdus Salam,  
Glashow and Weinberg

First evidence from  
CERN experiment



Perfect agreement between  
theory and experiments  
in all laboratories



# The 'Standard Model'

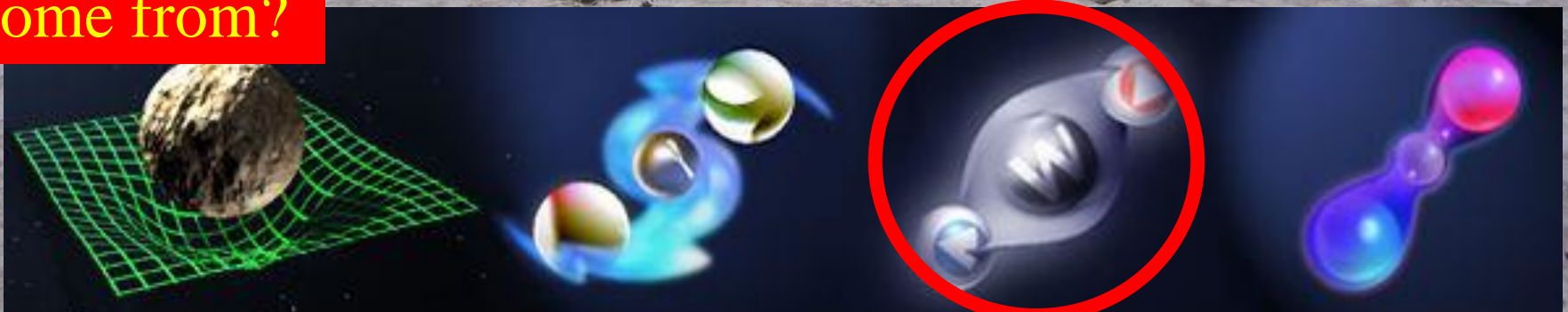
= Cosmic DNA

## The matter particles



Where does mass come from?

## The fundamental interactions



Gravitation

electromagnetism

weak nuclear force

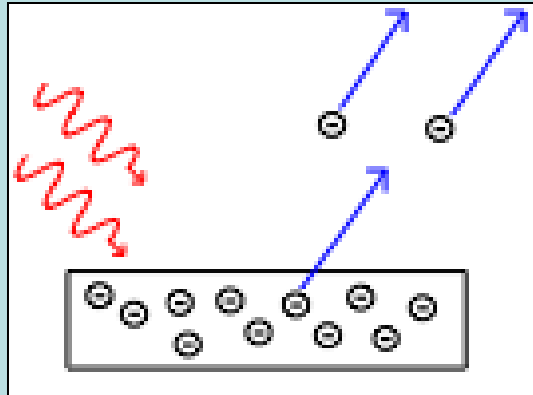
strong nuclear force

# Photon: the Particle of Light

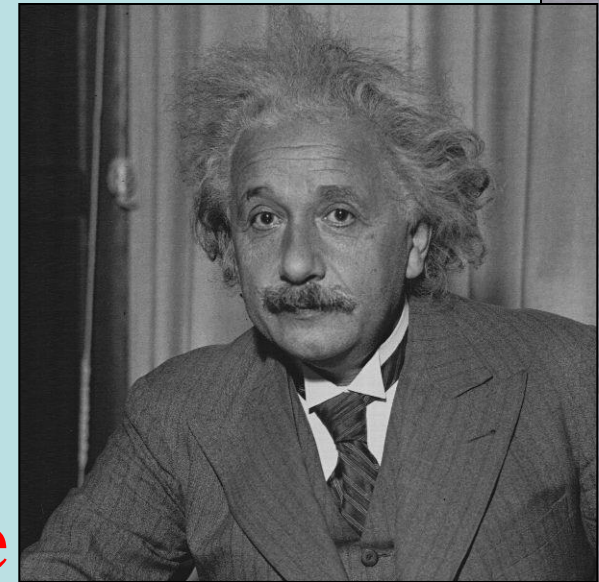
- Quantum hypothesis introduced by Planck:

$$E = hf$$

- Physical reality postulated by Einstein to explain photoelectric effect



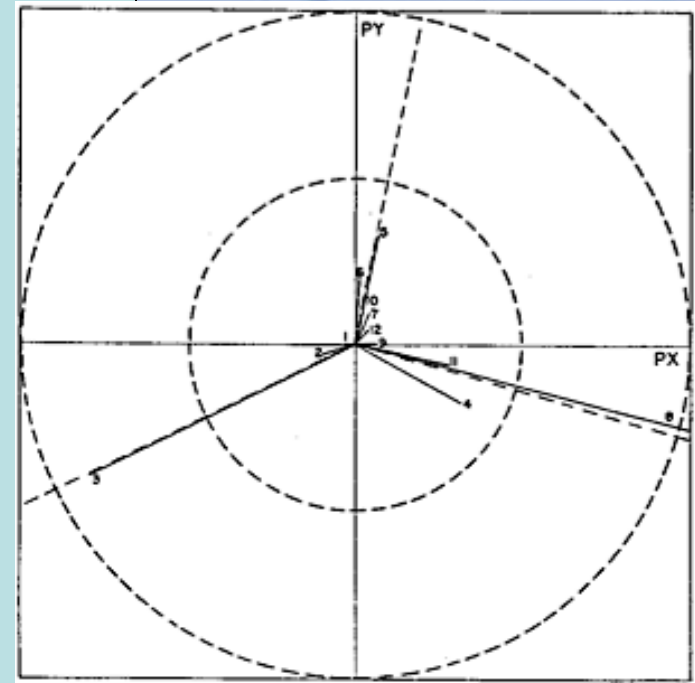
- **Motivation for his Nobel Prize**





# 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**

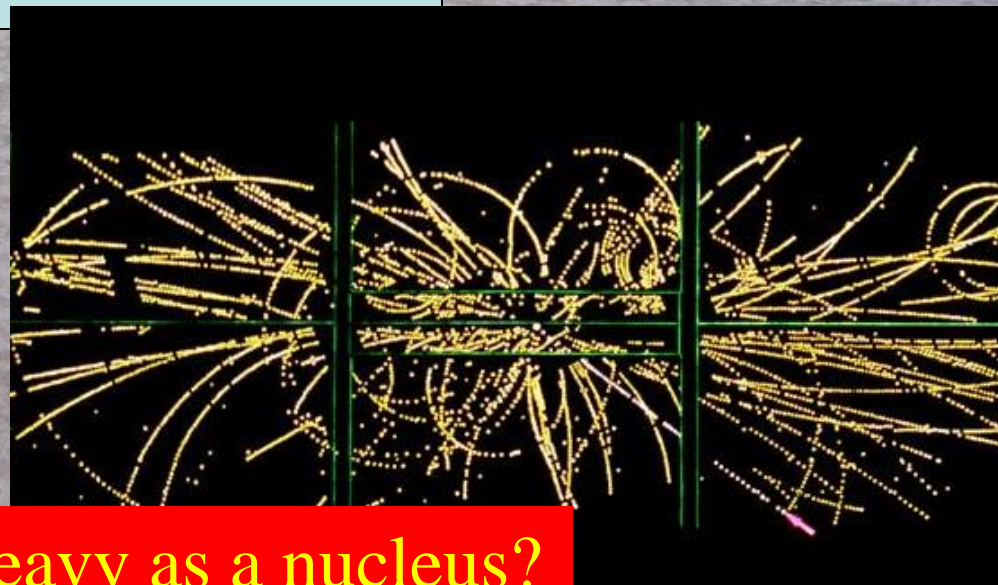
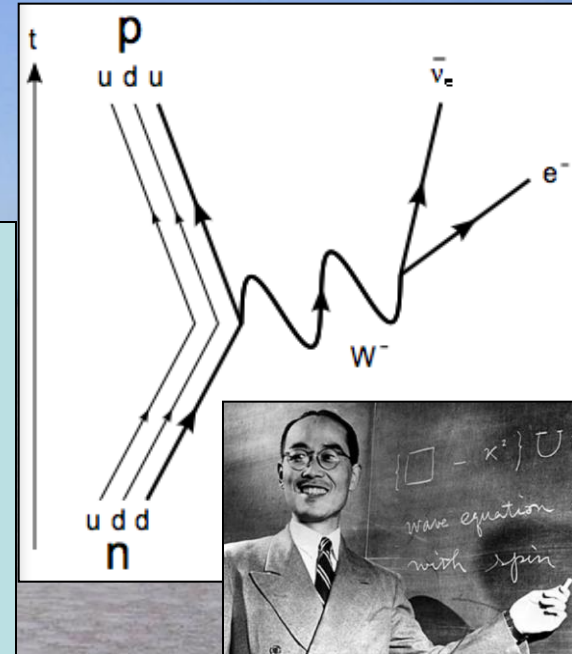
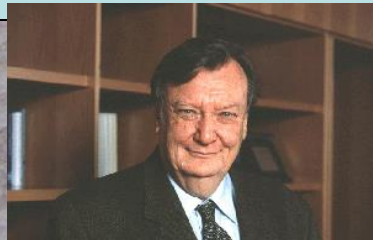


# Weak Interactions

Radioactivity due to weak interactions  
( $\beta$  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 Universe?
- 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)



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# The (NG)AEB **H**GHKMP 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 LETTERS

**BROKEN SYMMETRIES AND THE MASSES OF GAUGE VECTOR MESONS\***

**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,<sup>†</sup> C. R. Hagen,<sup>‡</sup> 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*

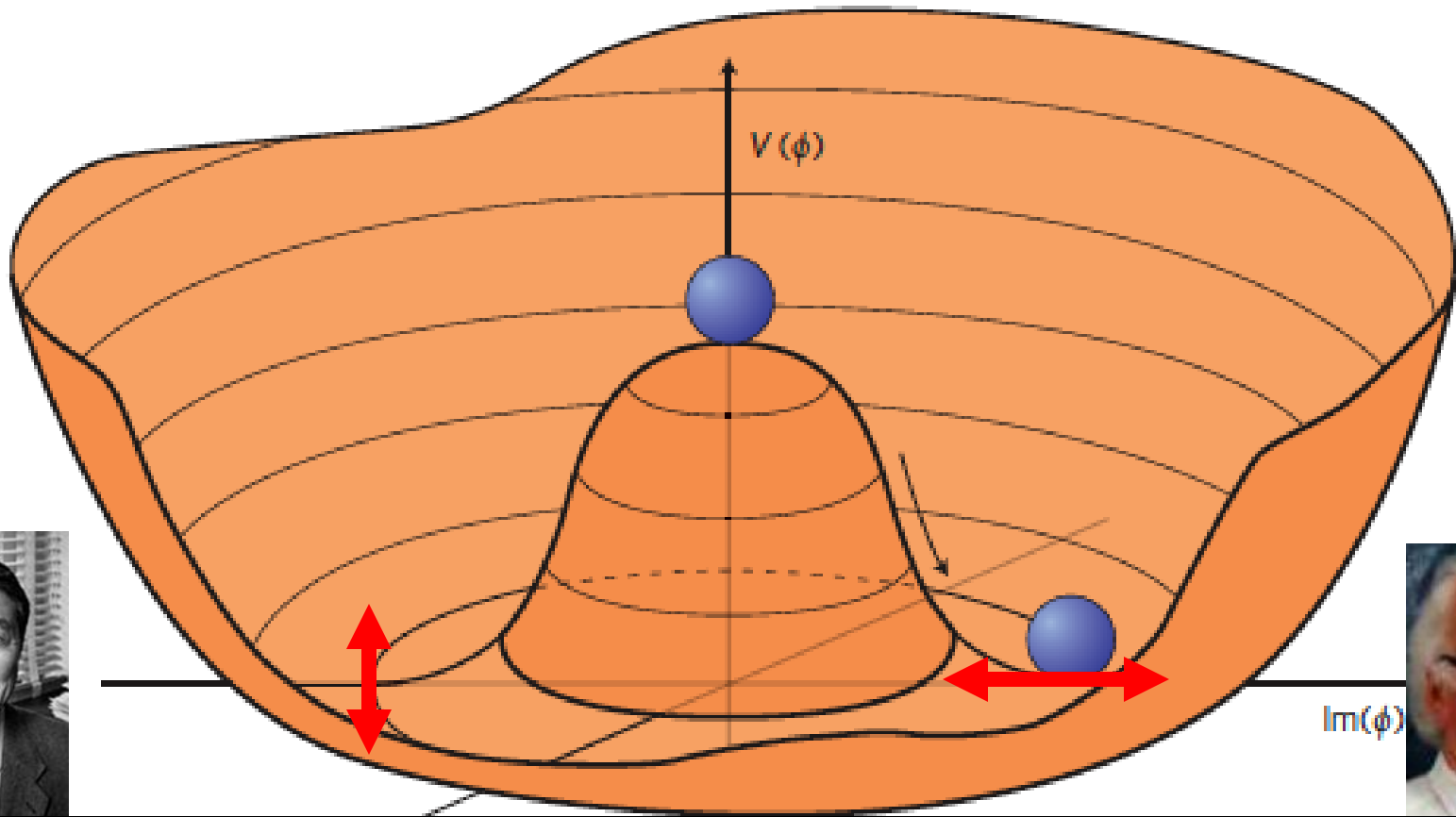
A. A. MIGDAL and A. M. YAKOVLEV

Submitted to JETP editor November 30, 1965; resubmitted February 16, 1966

J. Exp. Theor. Phys. (USSR) 51: 195-198 (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

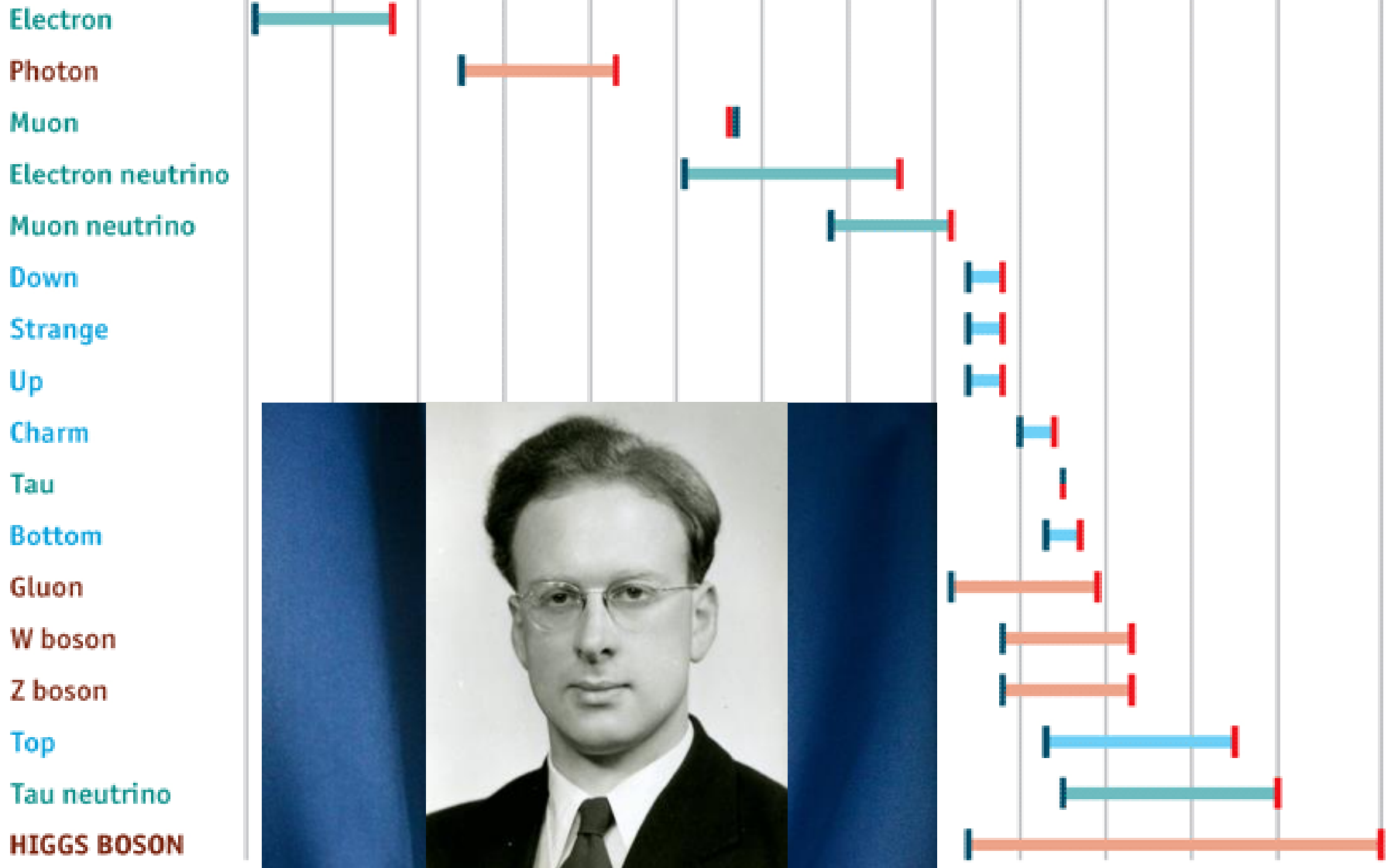
# Nambu **EB, H, GHK** and Higgs



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

DEUTSCHES ELEKTRONEN-SYNCHROTRON **DESY**

DESY 84-071  
August 1984  
CERN-TH.3943/84

NEW PARTICLES AND THEIR EXPERIMENTAL SIGNATURES

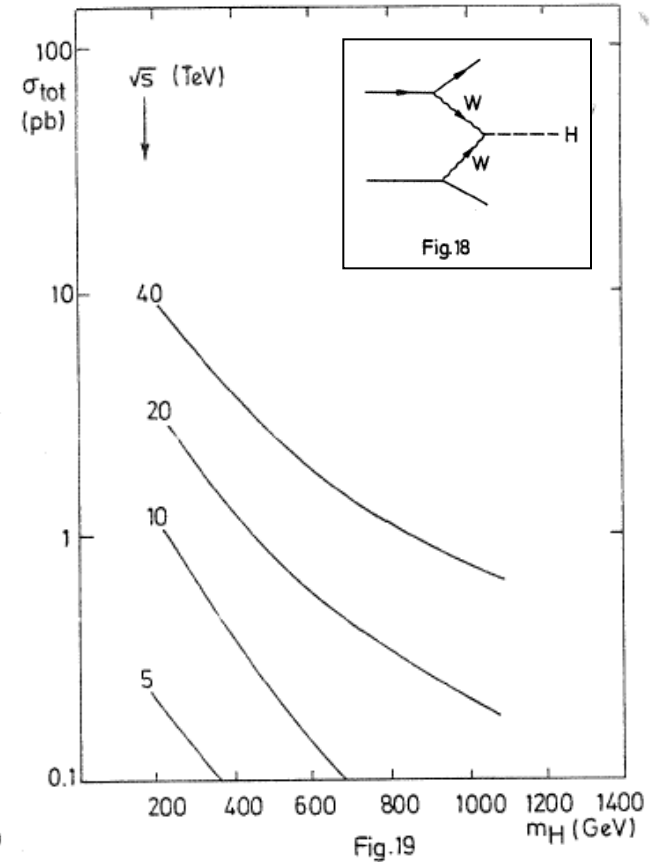
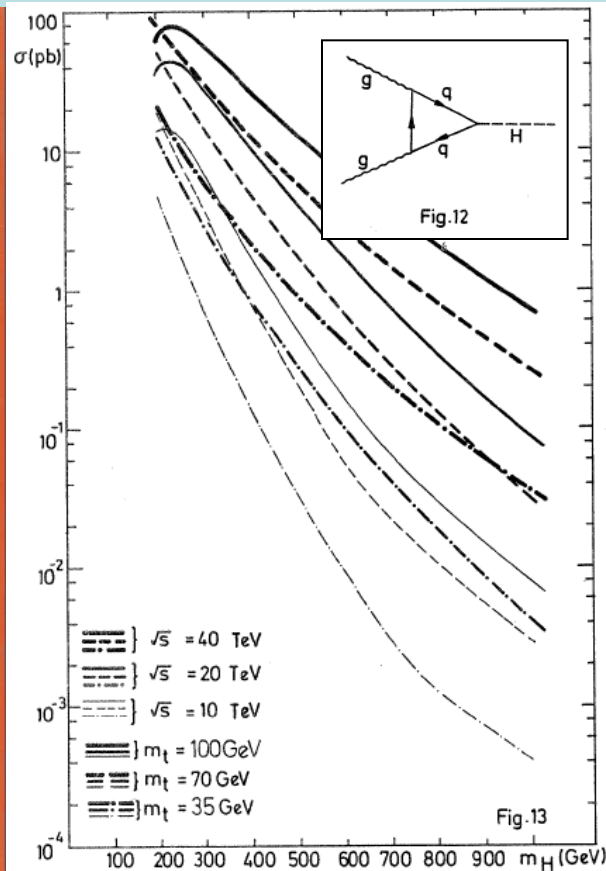
by

J. Ellis and G. Gelmini  
CERN, Geneva

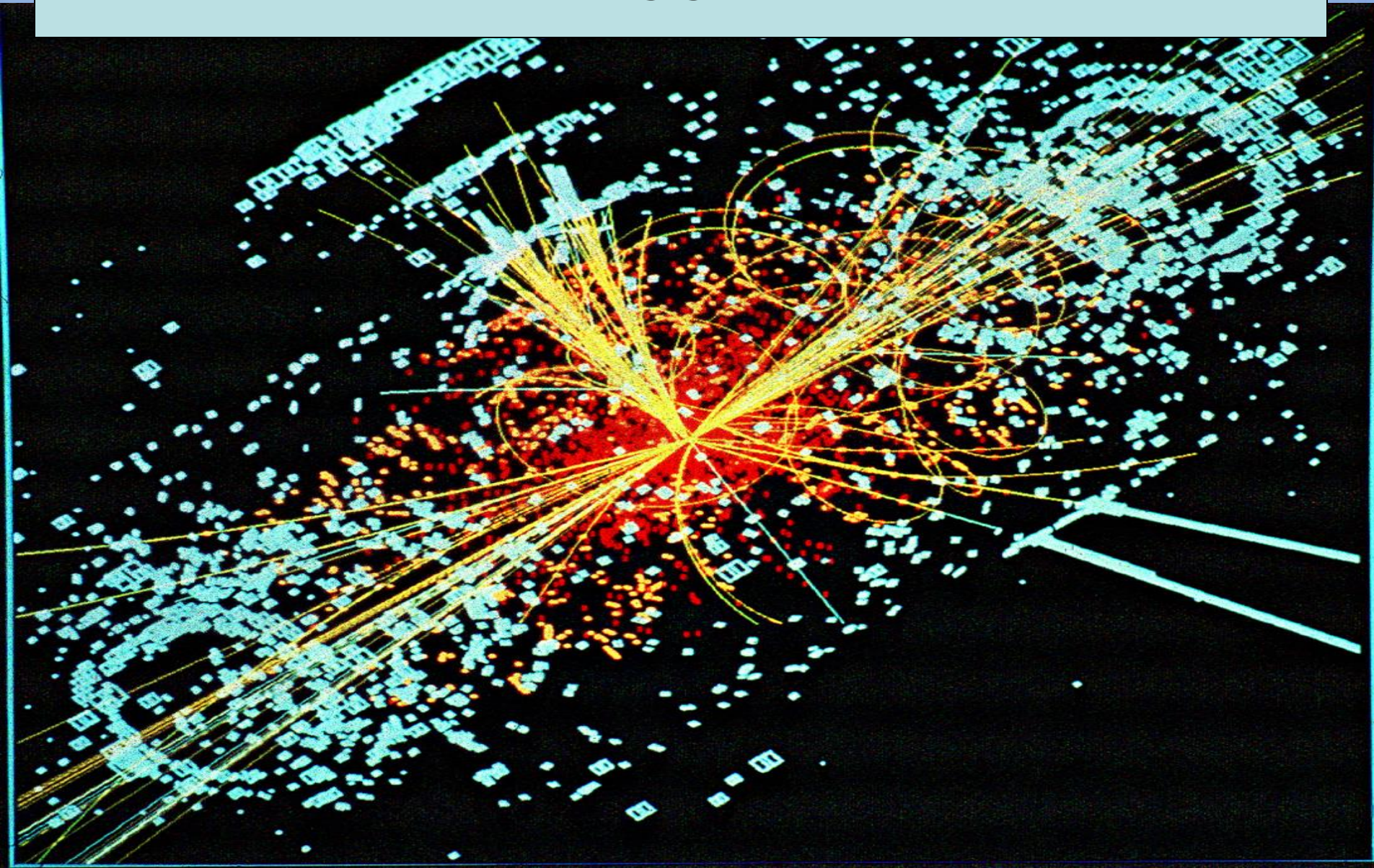
H. Kowalski  
Deutsches Elektronen-Synchrotron DESY, Hamburg

ISSN 0418-9833

NOTKESTRASSE 85 · 2 HAMBURG 52



# 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*

**007**

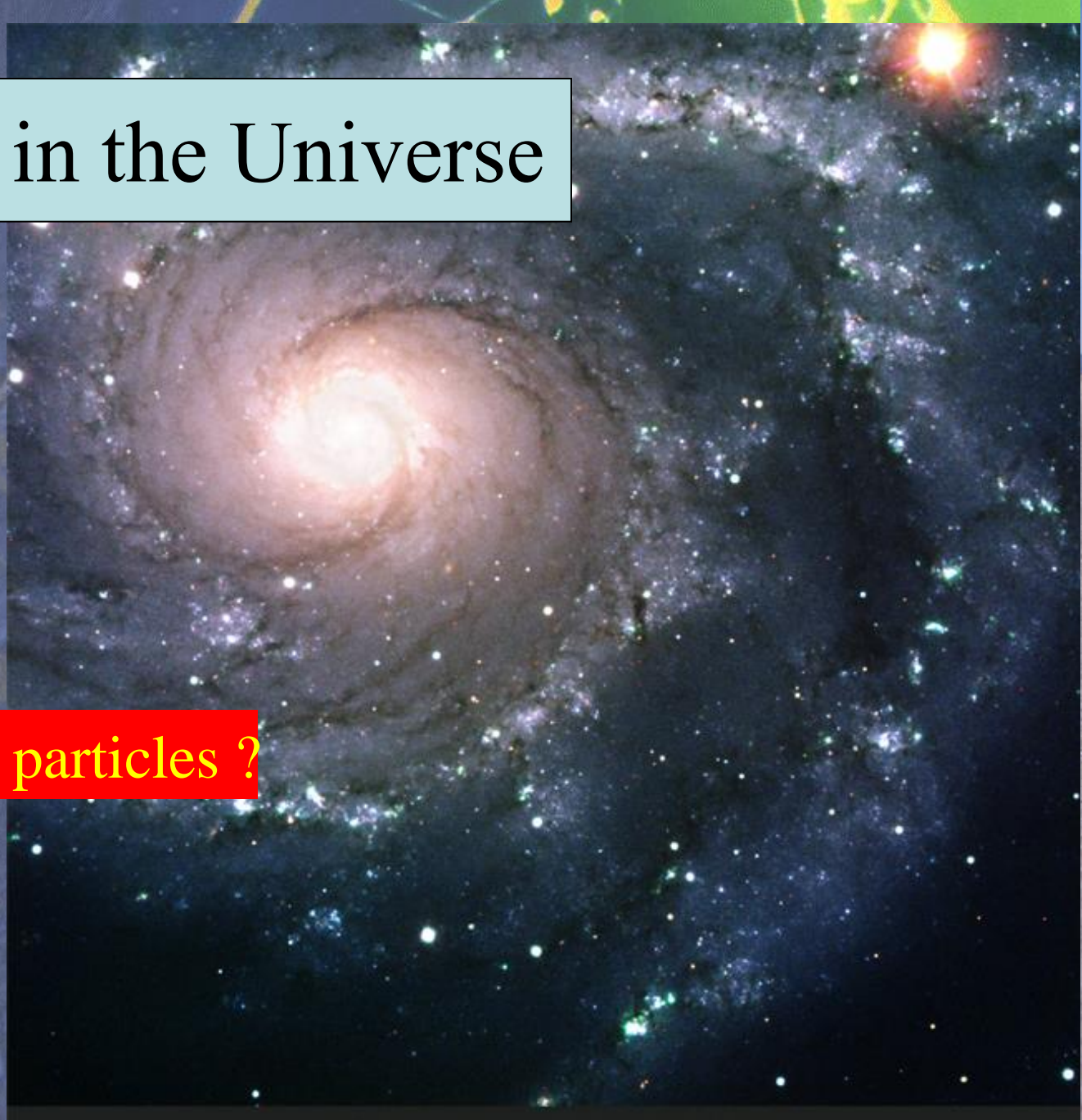
ALBERT R. BROCCOLI'S SON PRODUCTIONS PRESENTS PIERCE BROSNAN IN IAN FLEMING'S JAMES BOND 007™  
"THE WORLD IS NOT ENOUGH" SOPHIE MARQUEAU ROBERT CARVILLE DENISE RICHARDS TORRE COUTRANI AND JOHN DENCH  
DESIGN LINDY HEARMING COSTUME DESIGNER DAVID ARNOLD EDITOR JIM CLARK EXECUTIVE PRODUCERS ADRIAN BIDDLE AND PRODUCED BY PETER JARANT  
WRITTEN BY ANTHONY WAYE DIRECTED BY NEAL PURVIS & ROBERT WADDE PRODUCED BY NEAL PURVIS & ROBERT WADDE AND BRUCE FENSTER  
EXECUTIVE PRODUCERS MICHAEL E. WOLSON AND BARBARA BROCCOLI PRODUCED BY MICHAEL APPEL  
CASTING BY JUDITH GARBAGE COSTUME DESIGNER JUDITH GARBAGE EXECUTIVE PRODUCERS MICHAEL E. WOLSON AND BARBARA BROCCOLI PRODUCED BY MICHAEL APPEL

# Dark Matter in the Universe

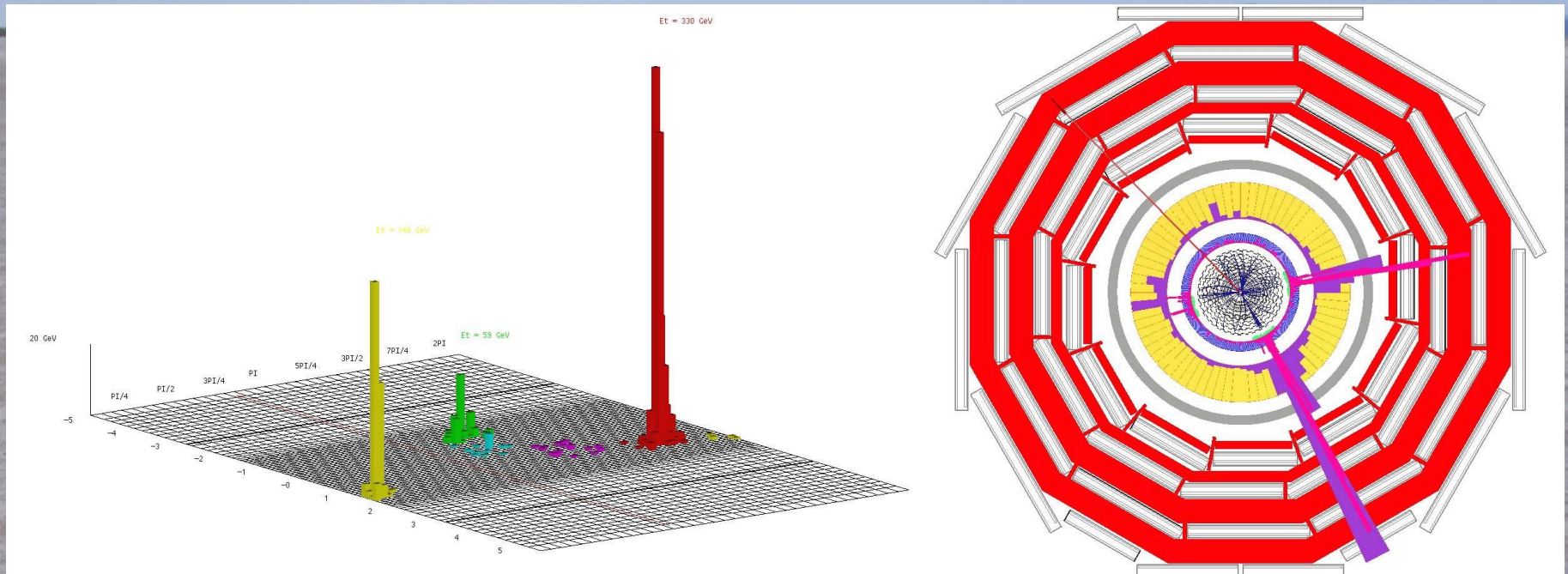
Astronomers say  
that most of the  
matter in the  
Universe is  
invisible  
Dark Matter

‘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

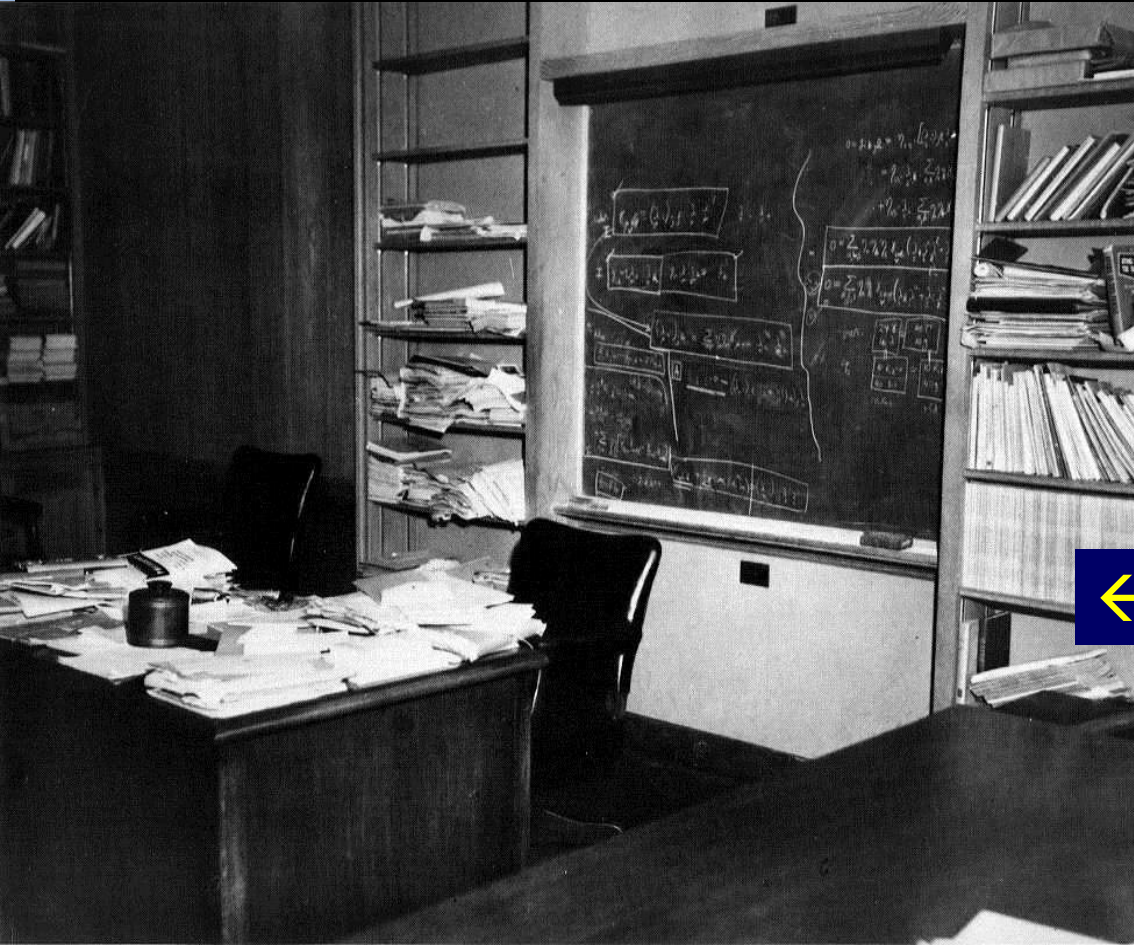


Matter and antimatter not quite equal and opposite: WHY?

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



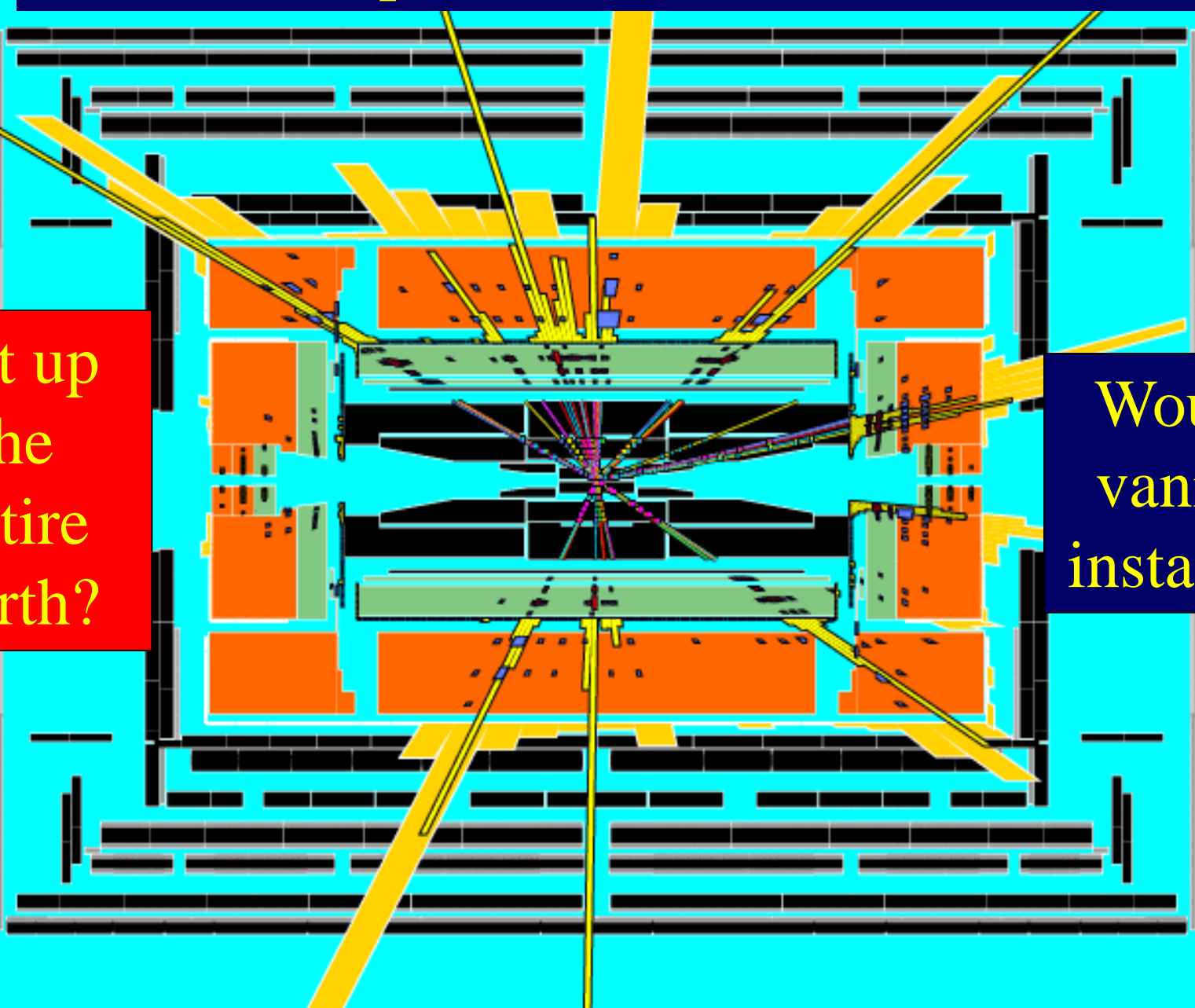
Unification via extra dimensions of space?



# Will LHC experiments create black holes?

Eat up  
the  
entire  
Earth?

Would  
vanish  
instantly



To answer these questions:

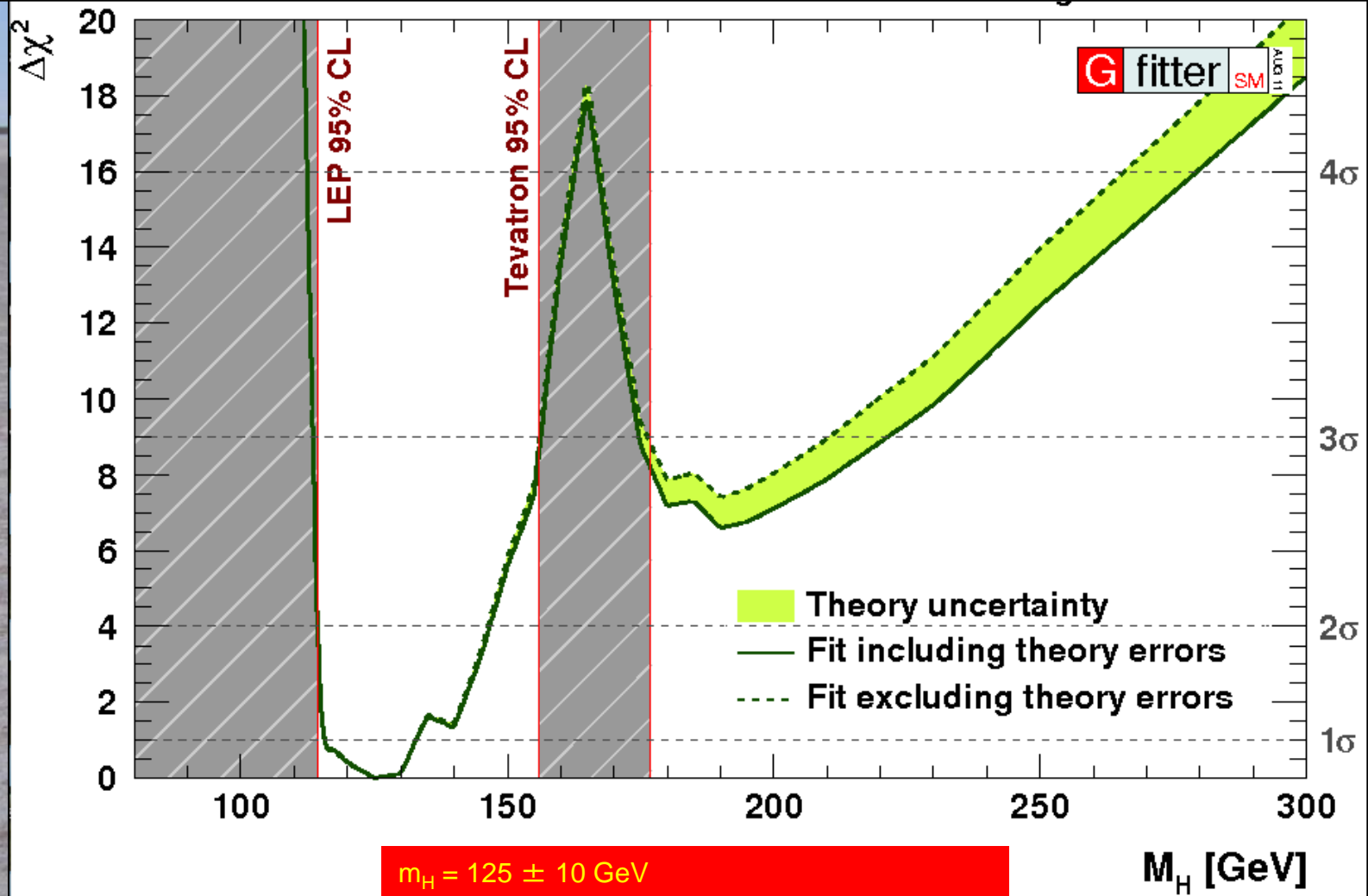
## The Large Hadron Collider (LHC)

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:

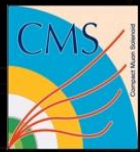
- Origin of mass
- Nature of Dark Matter
- Primordial Plasma
- Matter vs Antimatter

# 2011: Combining Information from Previous Direct Searches and Indirect Data

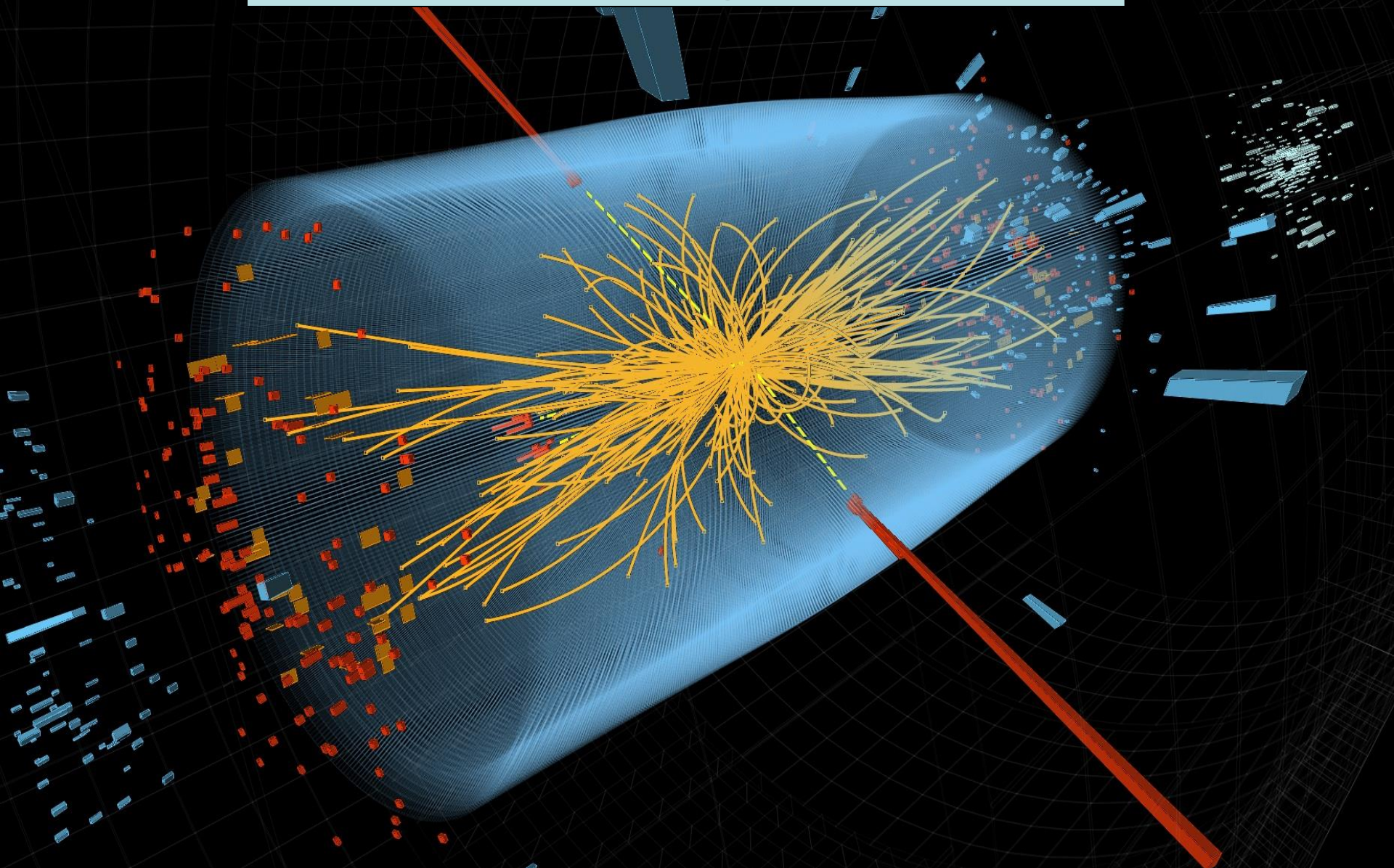


$m_H = 125 \pm 10$  GeV

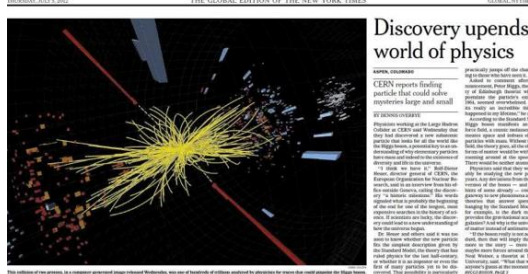
Gfitter collaboration



# Interesting Events



July 4th 2012
The discovery of a new particle



Discovery upends world of physics

CERN reports finding particle that could solve mysteries large and small



新素粒子検出 年内に結論
ヒッグス粒子発見か

ヒッグス粒子検出 年内に結論
新素粒子検出 年内に結論

Le Monde newspaper snippet with headline 'Science: la matière dévoilée' and '7.2 milliards de plus dès 2012'.

Portuguese newspaper snippet with headline 'Milhares de moradores de bairros sociais em risco de perderem RSI'.

Frankfurter Allgemeine newspaper snippet with headline 'Science: die Materie enthüllt' and 'DANGEROUS MOVE'.

MK newspaper snippet with headline 'ПОСЛЕДНИЙ КИРПИЧ В СТЕНУ МИРОЗДАНИЯ' and 'METRO СПУСКАЕТ НА ВОДУ'.

AD Algemeen Dagblad newspaper snippet with headline 'EINDELIJK BELIJK NA 48 JAAR' and 'Zieke Kaj en zijn moeder touch samen in de VS'.

Frankfurter Allgemeine newspaper snippet with headline 'Große Mehrheit im Bundestag' and 'Ukraine ist nie so groß wie Russland'.

The Hindu newspaper snippet with headline 'Elusive particle found, looks like Higgs boson'.

Corriere della Sera newspaper snippet with headline 'La particella che può svelare i segreti dell'universo'.

Gazeta Wyborcza newspaper snippet with headline 'Czastke Higgsa fizycy najpierw wymyślił, potem szukali 40 lat'.

The New York Times newspaper snippet with headline 'Physicists Find Elusive Particle Seen as Key to Universe'.

The Gazette newspaper snippet with headline 'falleda la partícula clave para a comprensión del universo'.

China Daily newspaper snippet with headline 'Big bang moment: Scientists may have found "God particle"'.

The Times of India newspaper snippet with headline 'Big bang moment: Scientists may have found "God particle"'.

Bangladesh newspaper snippet with headline 'বিশ্বজ্ঞানের "স্বপ্নের" দর্শন'.

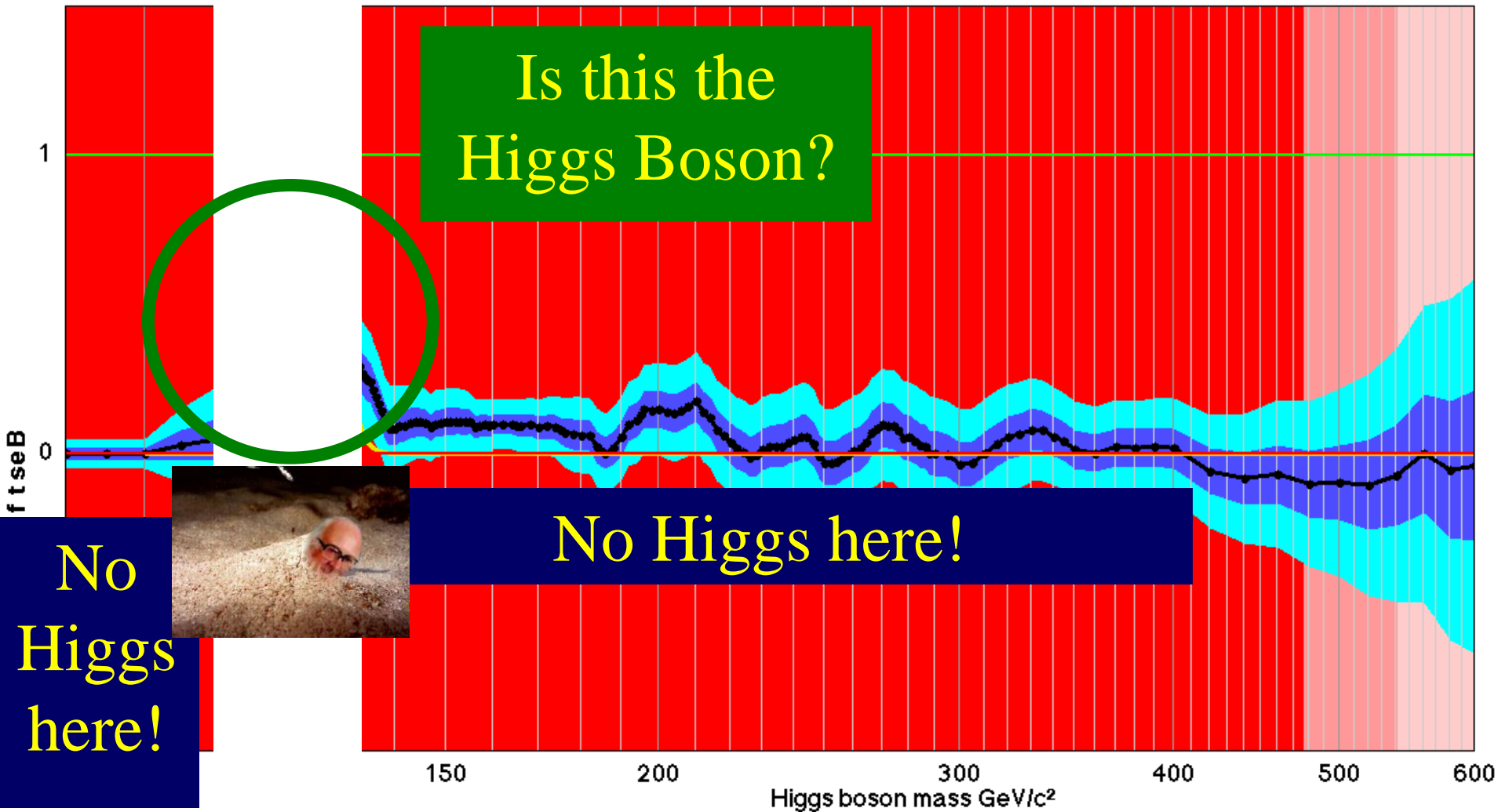
# Higgsdependence Day!



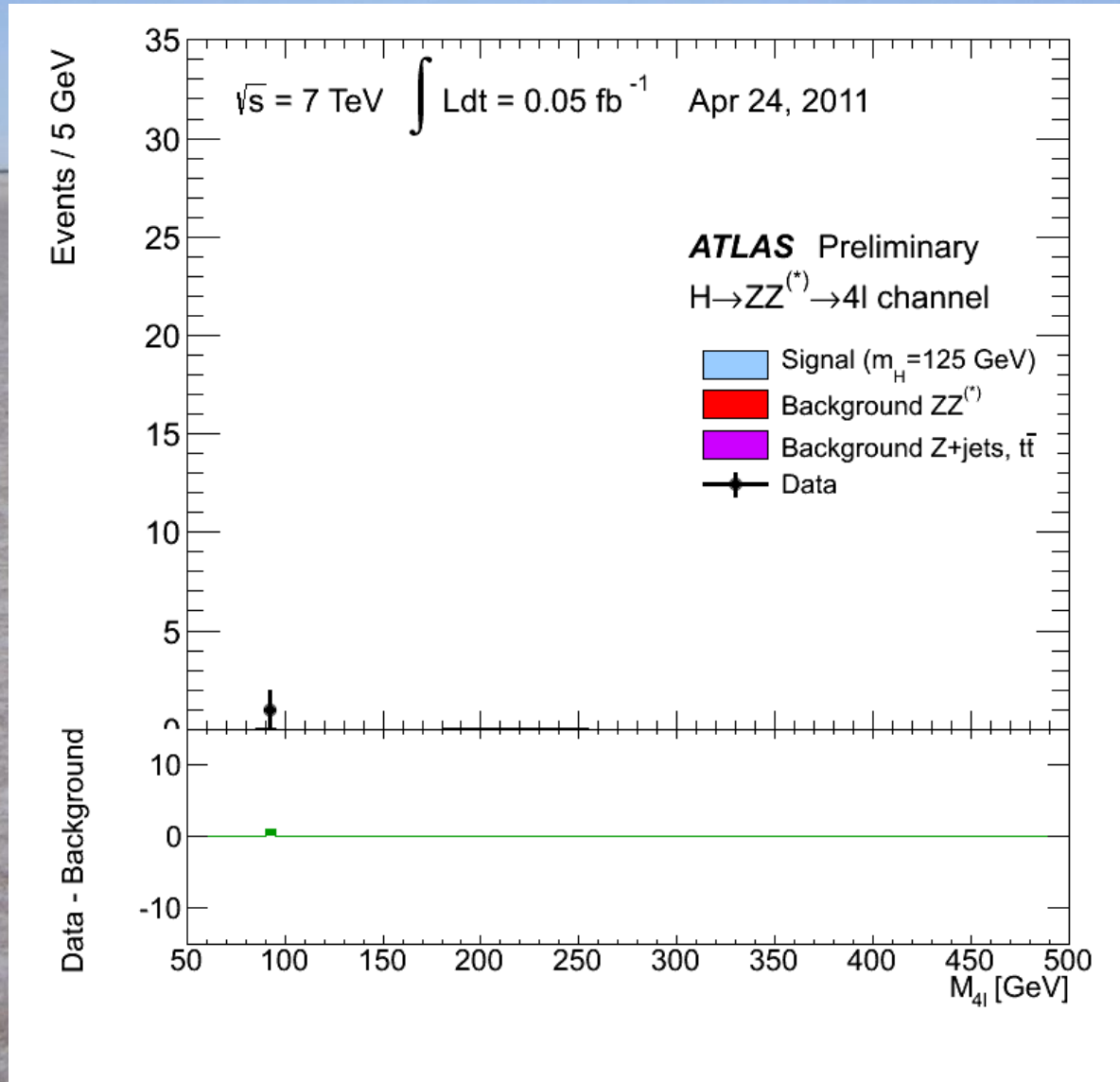
# Unofficial Combination of Higgs Data

1/fb - 10/fb

06/03/2013



# How the Higgs Signal has Grown





# The Particle Higgsaw Puzzle

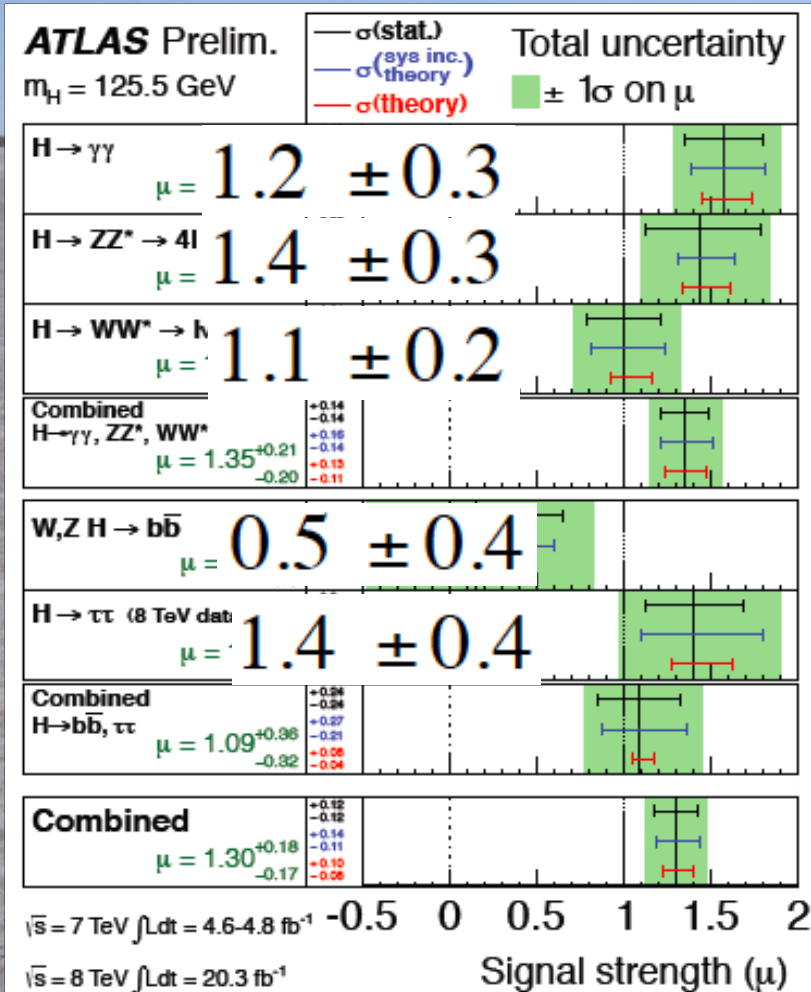
A 3D rendering of a blue puzzle piece being placed into a larger puzzle on a blue background with a wavy pattern. The puzzle piece is in the center, and the background is a grid of puzzle pieces. The lighting is dramatic, with a bright spot on the piece being placed.

Is LHC finding the missing piece?

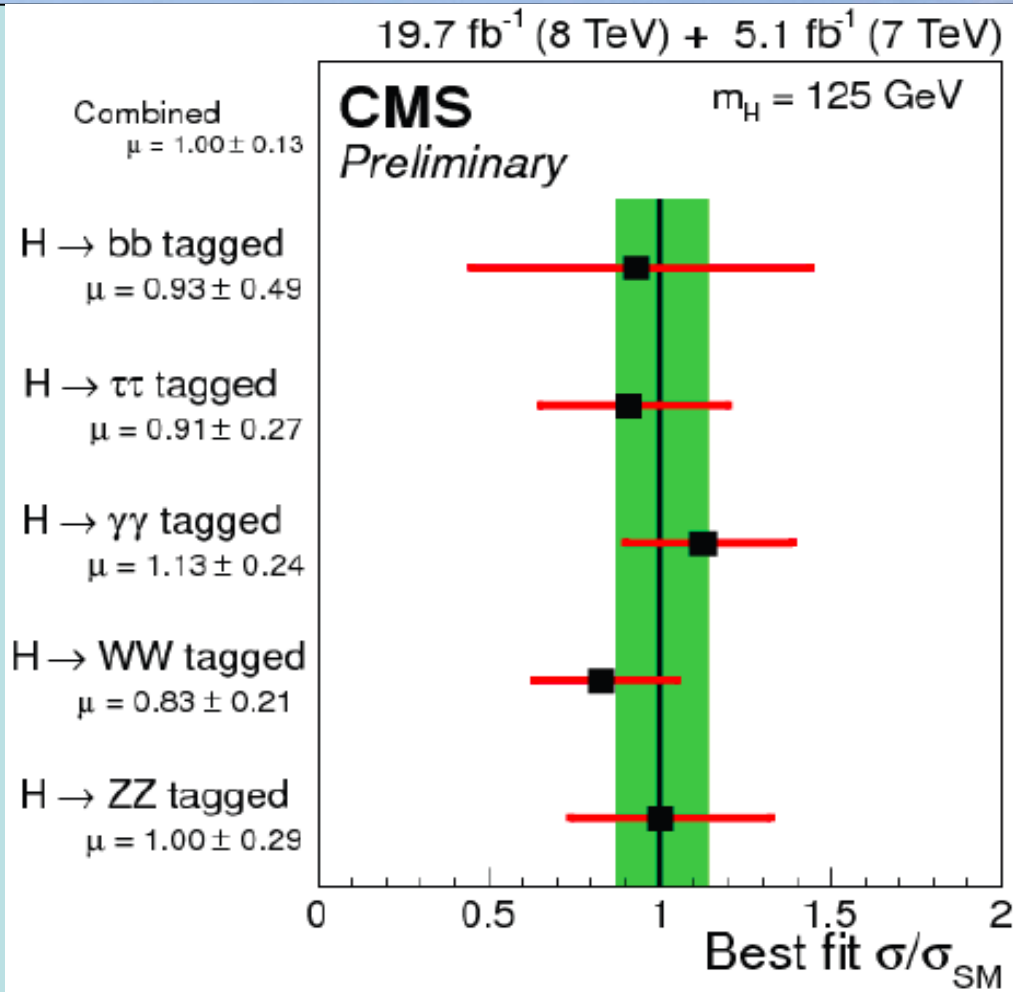
Is it the right shape?

Is it the right size?

# Higgs Signal Strengths



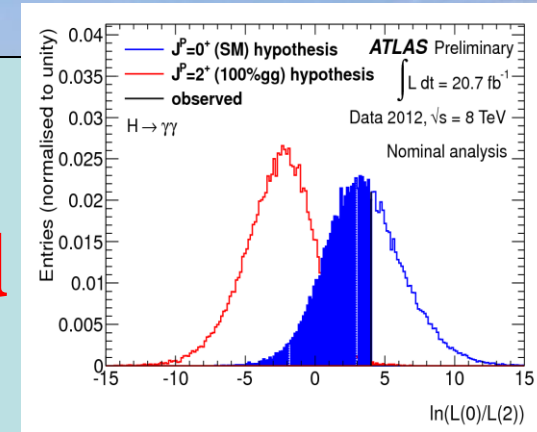
$$\mu = 1.30 \pm 0.12 \text{ (stat)} \pm 0.10 \text{ (th)} \pm 0.09 \text{ (syst)}$$



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

# Beyond any Reasonable Doubt

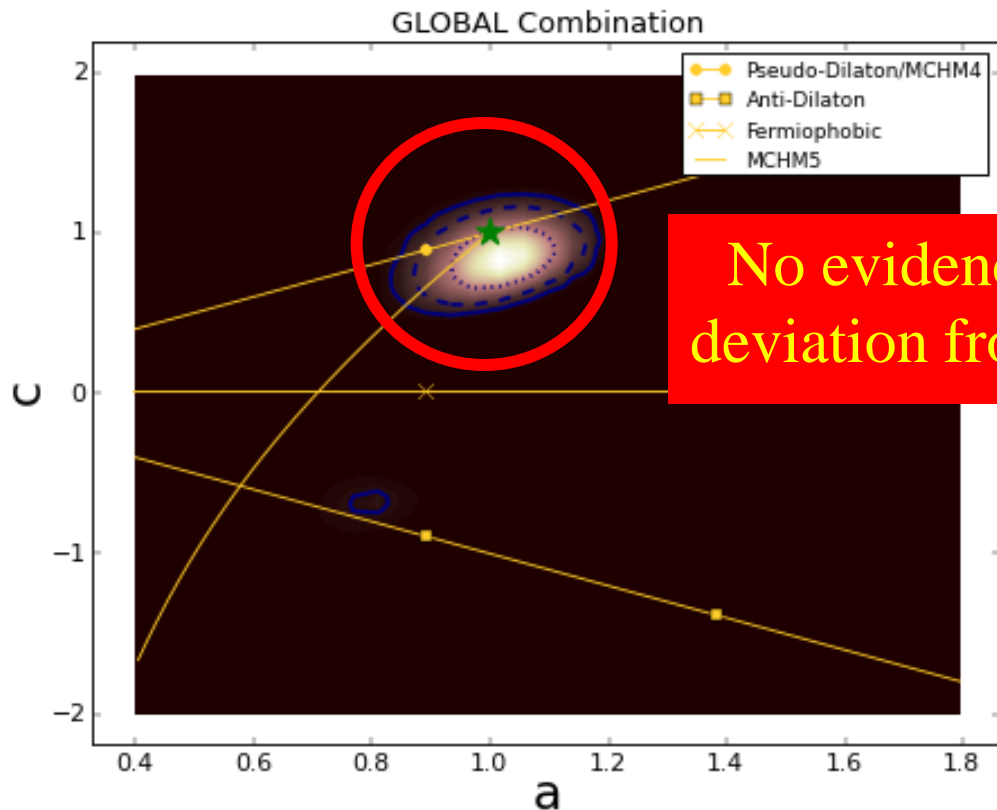
- Does it have spin 0 or 2?
  - **Spin 2 strongly disfavoured**
- Is it elementary or composite?
  - **No significant deviations from Standard Model**
- Does it couple to particle masses?
  - ***Prima facie* evidence that it does**



# Global Analysis of Higgs-like Models

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

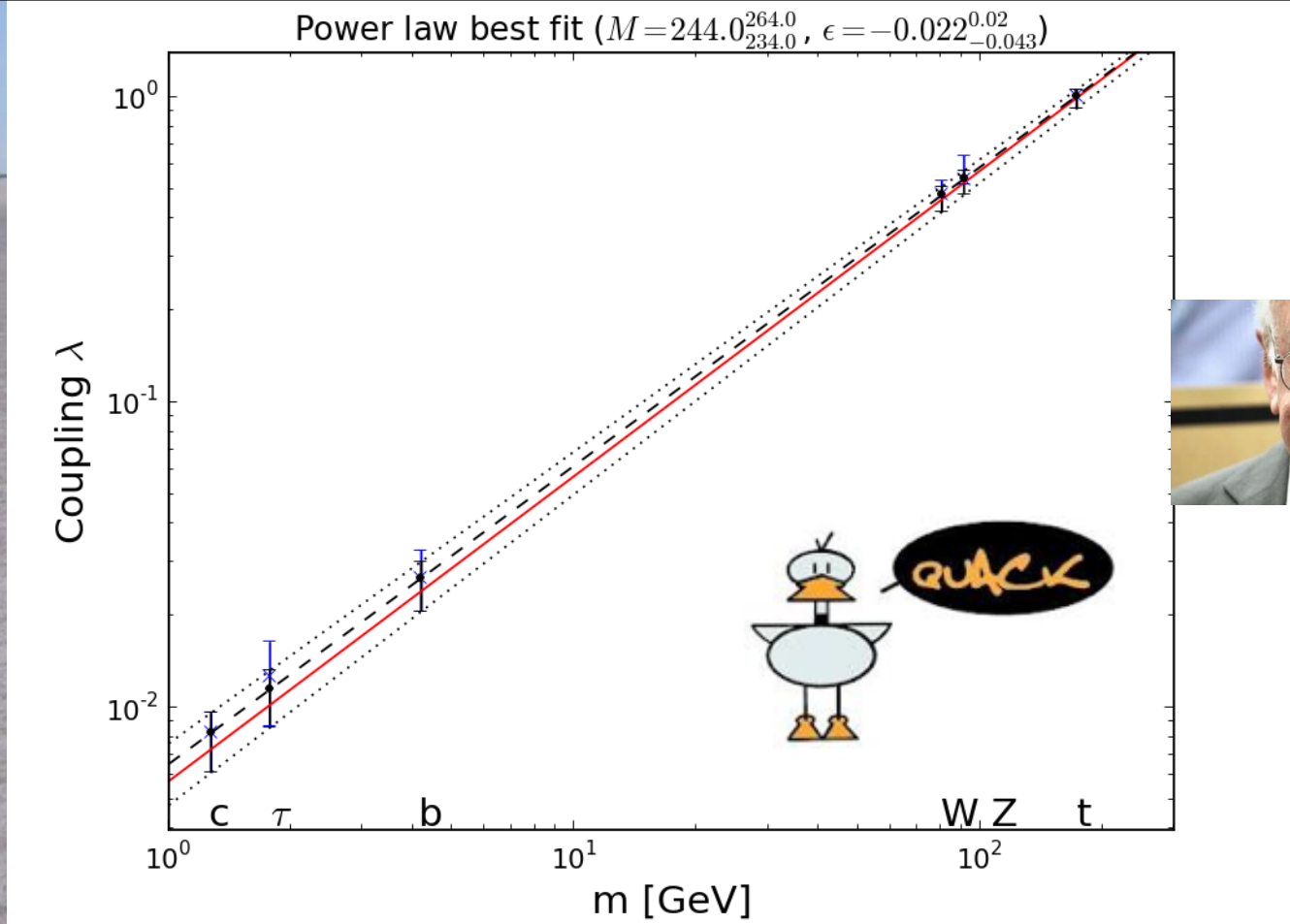
Global



No evidence for deviation from SM

- Standard Model:  $a = c = 1$

# It Walks and Quacks like a Higgs



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

# 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](http://www.nobelprize.org/nobel_prizes/physics/laureates/2013/advanced-physicsprize2013.pdf)

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



# 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?



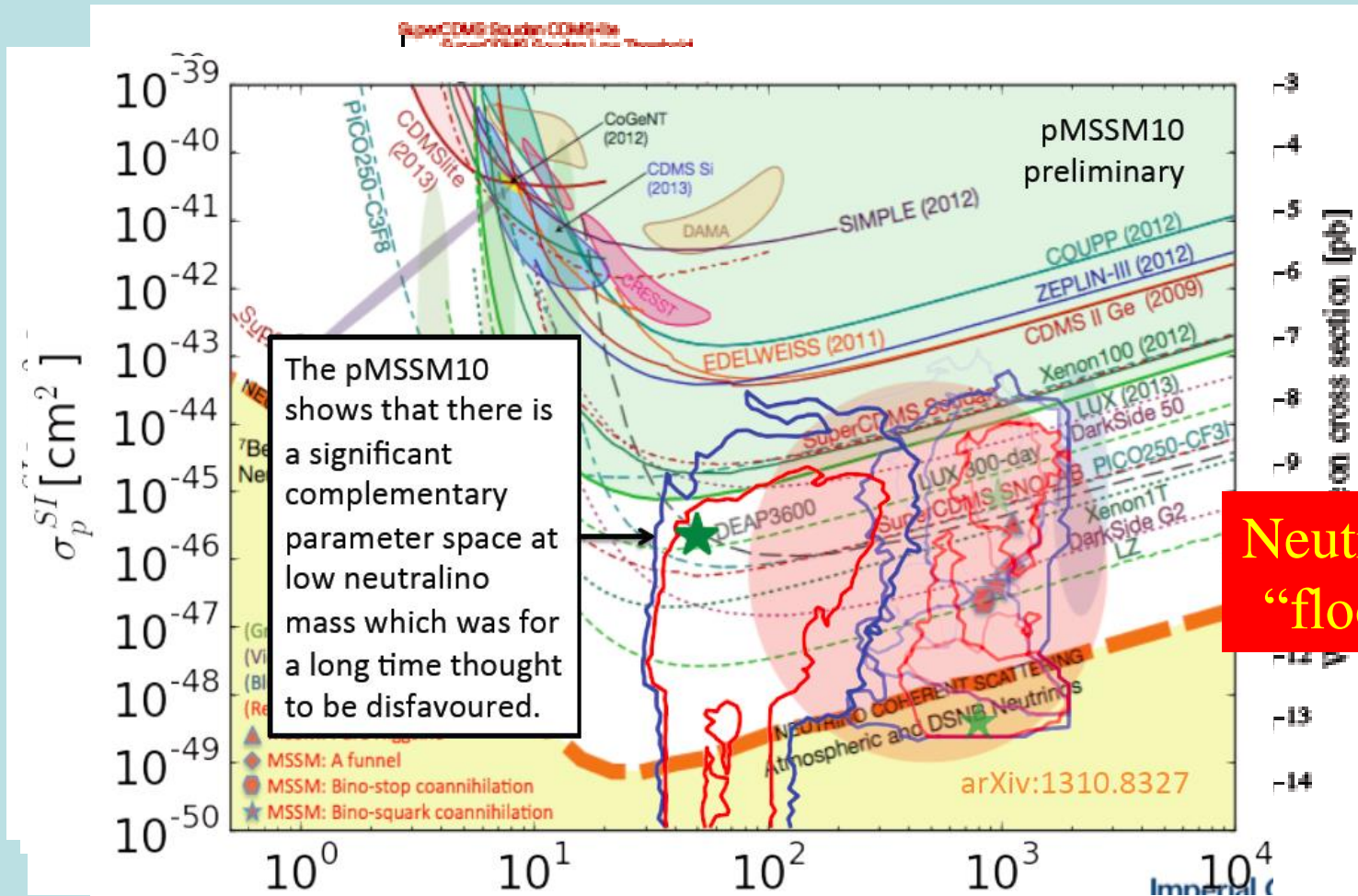
Where do we go from there?

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