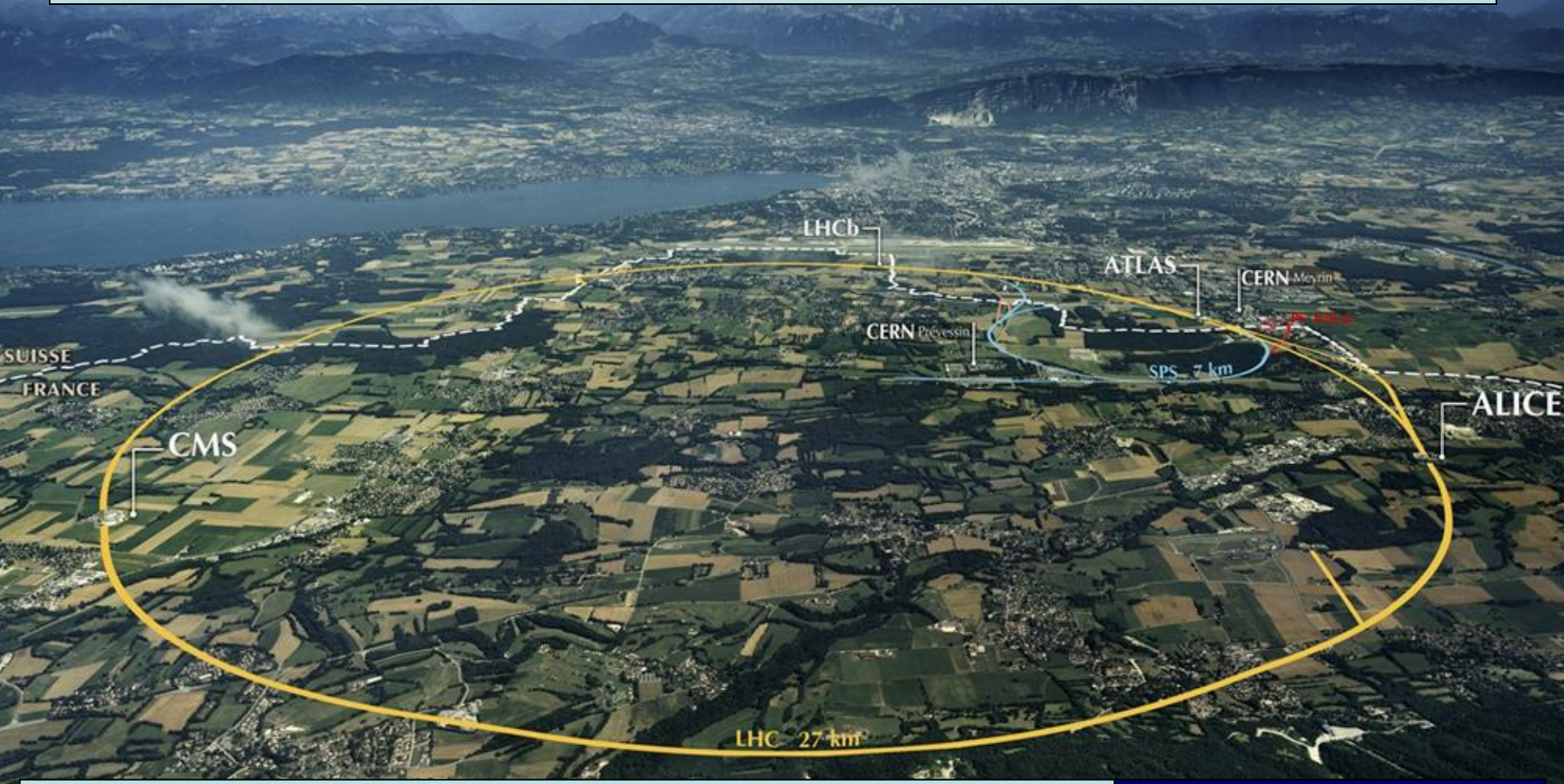
Beyond the Higgs Boson



The Higgs is just one of the questions

being studied at the LHC

John Ellis

King's College London

(& CERN)

Beyond the Higgs Boson

The Higgs is just one of the questions

being studied at the LHC

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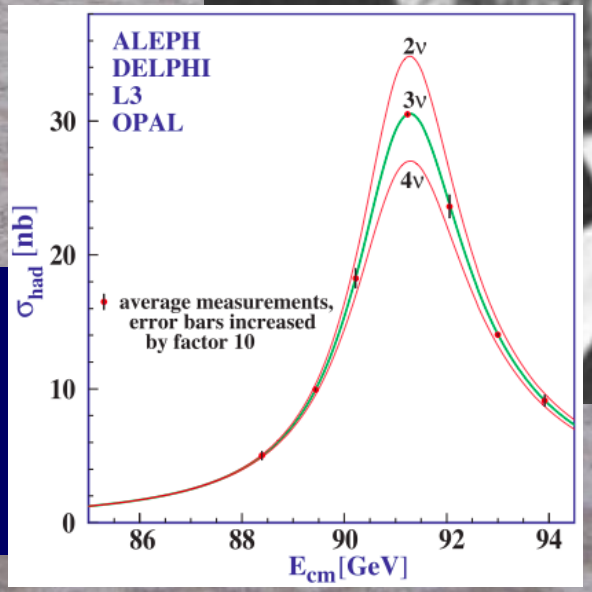
(& CERN)

The ‘Standard Model’ of Particle Physics

Proposed byAbdus Salam, Glashow and Weinberg

Tested by experiments at CERN

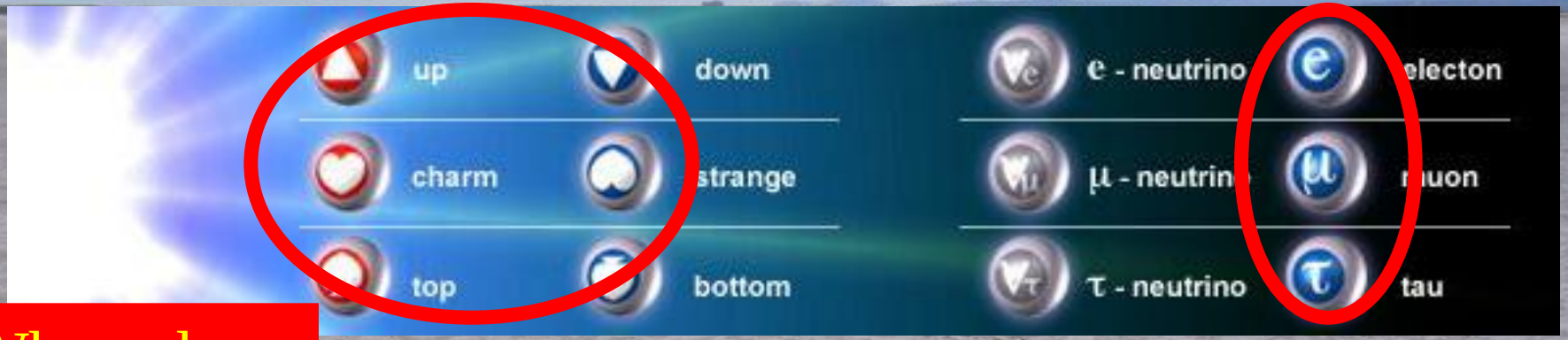


Perfect agreement between theory and experiments in all laboratories

The ‘Standard Model’

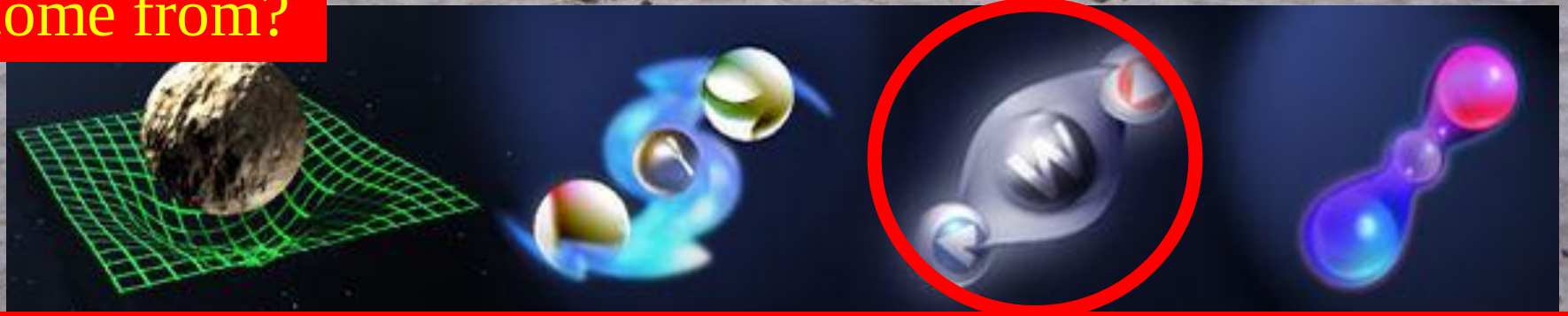
= Cosmic DNA

The matter particles



Where does mass come from?

The fundamental interactions



Gravitation electromagnetism weak nuclear force strong nuclear force

Summary of the Standard Model

- Particles and SU(3) × SU(2) × U(1) quantum numbers:

L_L	$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L , \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L , \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$	$(\mathbf{1},\mathbf{2},-1)$
E_R	$e_R^- , \mu_R^- , \tau_R^-$	$(\mathbf{1},\mathbf{1},-2)$
Q_L	$\begin{pmatrix} u \\ d \end{pmatrix}_L , \begin{pmatrix} c \\ s \end{pmatrix}_L , \begin{pmatrix} t \\ b \end{pmatrix}_L$	$(\mathbf{3},\mathbf{2},+1/3)$
U_R	u_R , c_R , t_R	$(\mathbf{3},\mathbf{1},+4/3)$
D_R	d_R , s_R , b_R	$(\mathbf{3},\mathbf{1},-2/3)$

- Lagrangian:

$$\begin{aligned} \mathcal{L} &= -\frac{1}{4} F^a_{\mu\nu} F^{a\ \mu\nu} && \text{gauge interactions} \\ &+ i\bar{\psi}\, \not{D}\psi + h.c. && \text{matter fermions} \\ &+ \psi_i y_{ij} \psi_j \phi + h.c. && \text{Yukawa interactions} \\ &+ |D_\mu \phi|^2 - V(\phi) && \text{Higgs potential} \end{aligned}$$

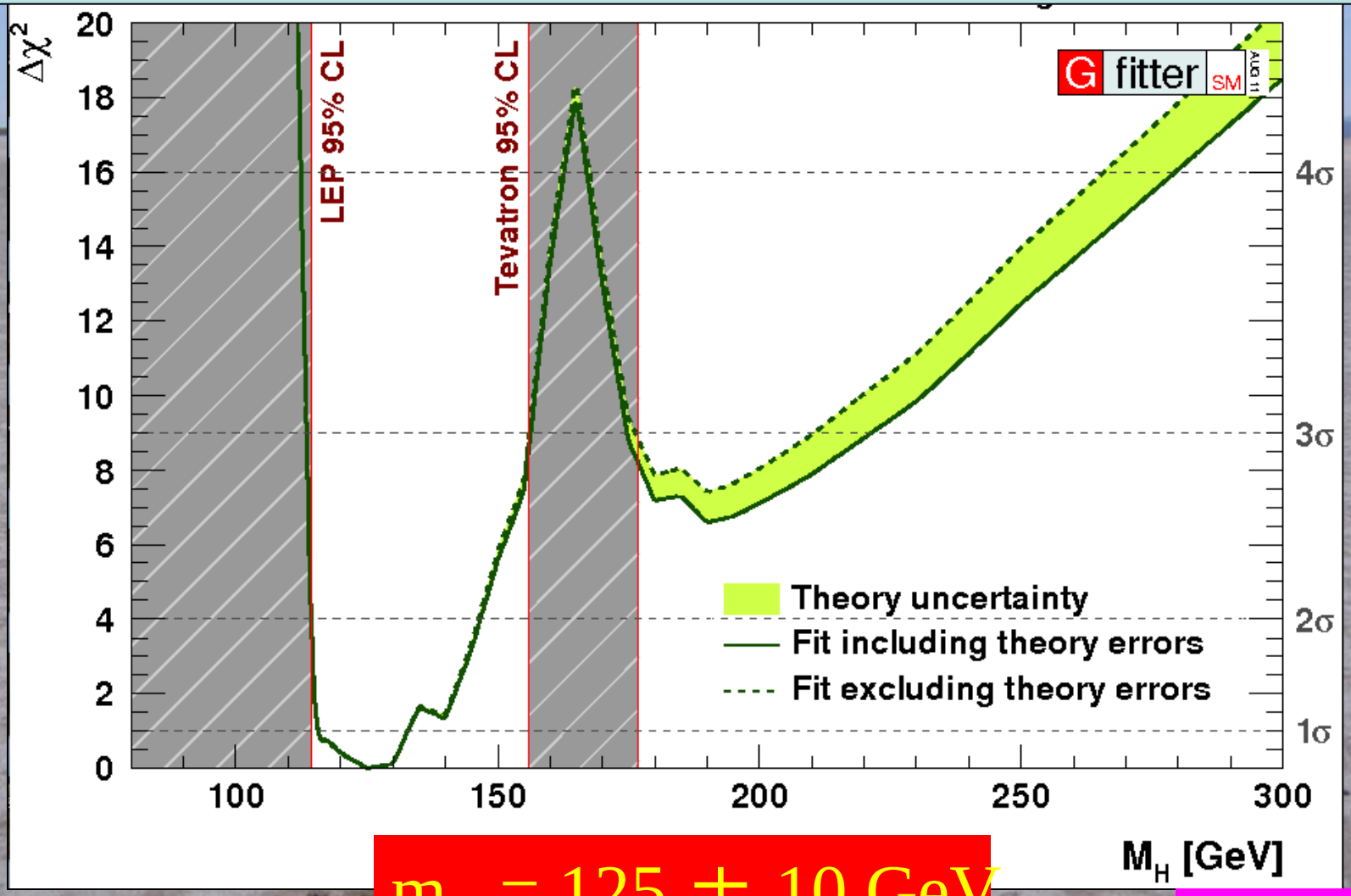
Now direct evidence

Status of the Standard Model

- Perfect agreement with all *confirmed* accelerator data
- Consistency with precision electroweak data (LEP et al) *only if there is a 'Higgs boson'*
- Agreement seems to require *a relatively light Higgs boson* weighing < ~ 180 GeV
- Raises many unanswered questions:

mass? flavour? unification?

Combining the Information from Direct Searches and Indirect Data



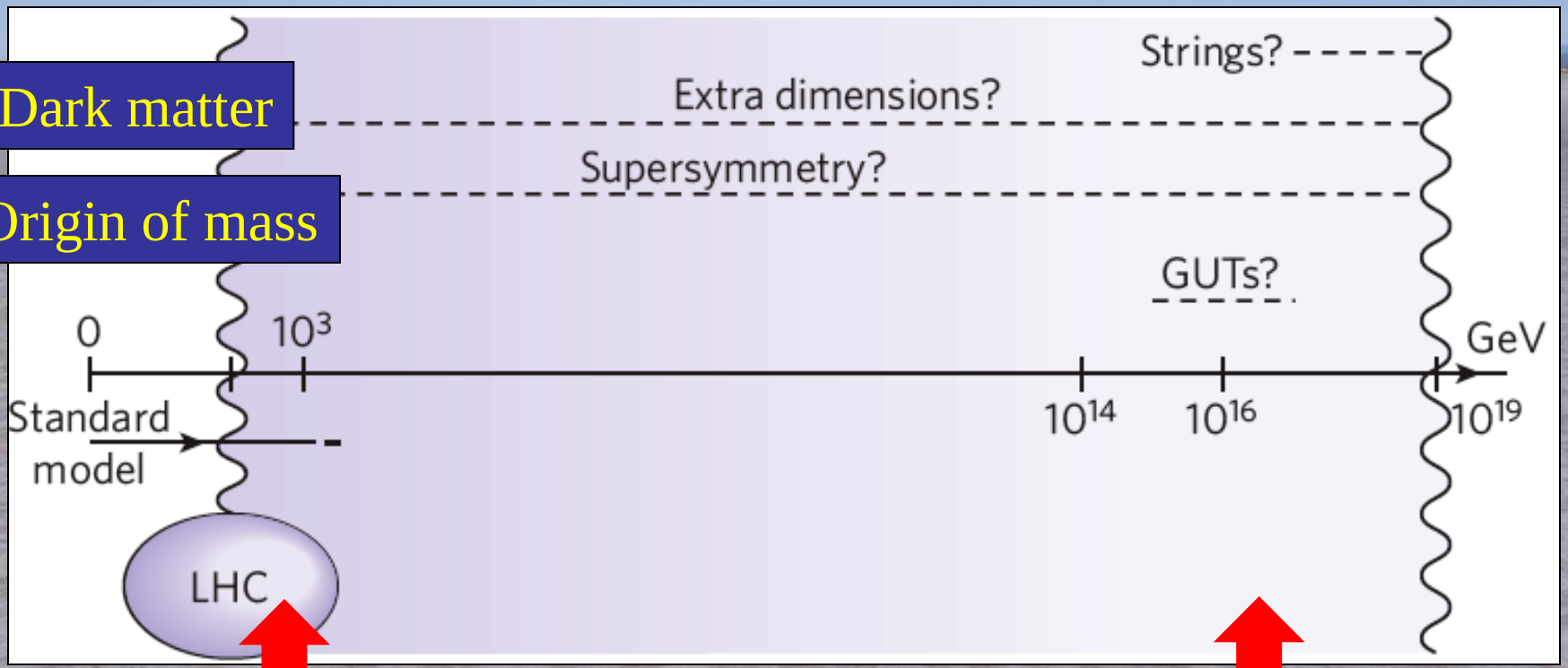
$m_H = 125 \pm 10$ GeV

Gfitter collaboration

Open Questions beyond the Standard Model

- What is the origin of particle masses? LHC
  due to a Higgs boson?
- Why so many flavours of matter particles LHC
- What is the dark matter in the Universe? LHC
- Unification of fundamental forces? LHC
- Quantum theory of gravity? LHC

At what Energy is the New Physics?



Dark matter

Origin of mass

A lot accessible to the LHC

Some accessible only via astrophysics & cosmology

Why do Things Weigh?

Newton:

Weight proportional to Mass

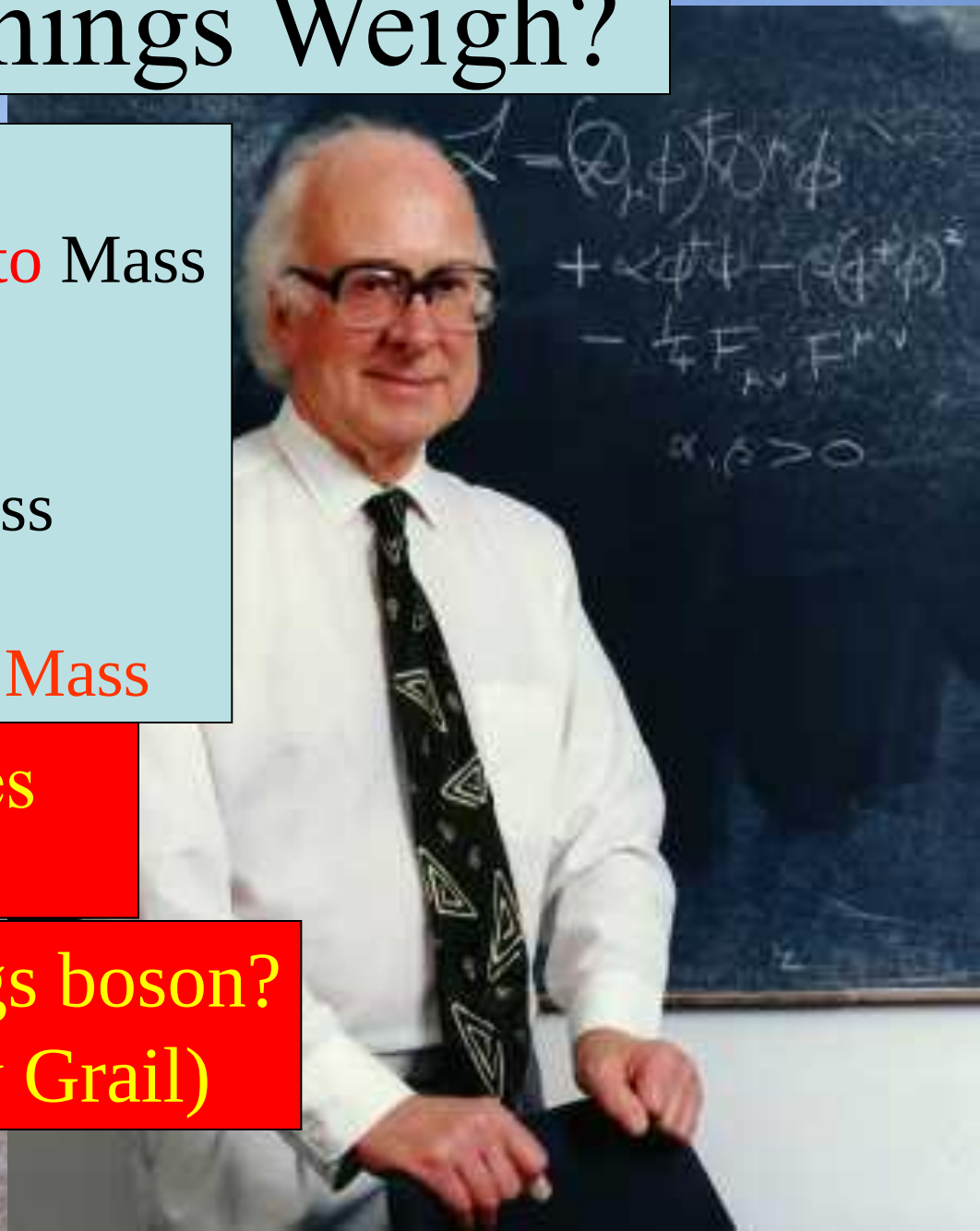
Einstein:

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)



Think of a Snowfield

Skier moves fast:
Like particle without mass
e.g., photon = particle of light

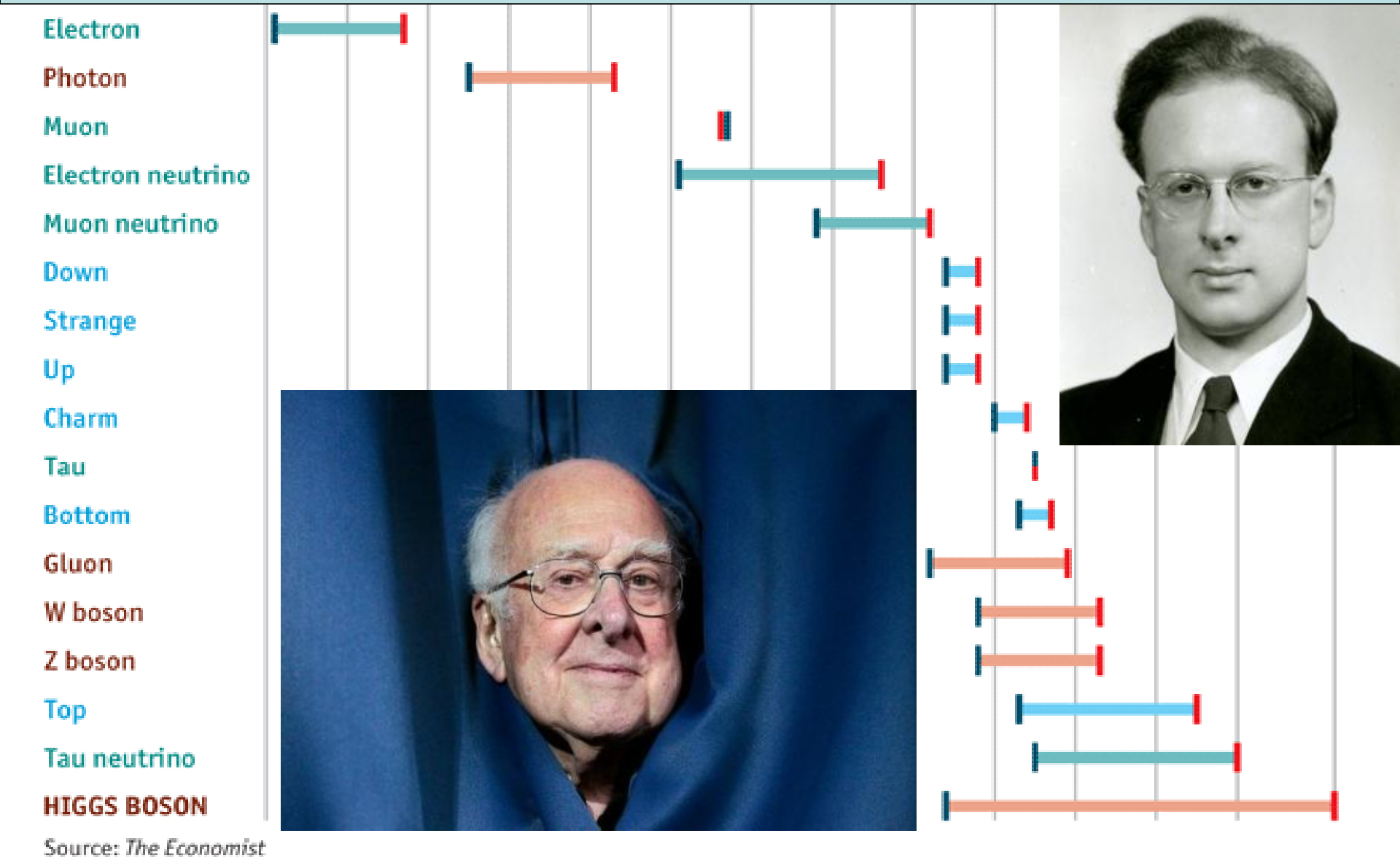
Snowshoer sinks into snow,
moves slower:
Like particle with mass
e.g., electron

The LHC will look for the snowflake: The Higgs Boson

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

Standard Model Particles:

Years from Proposal to Discovery



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)

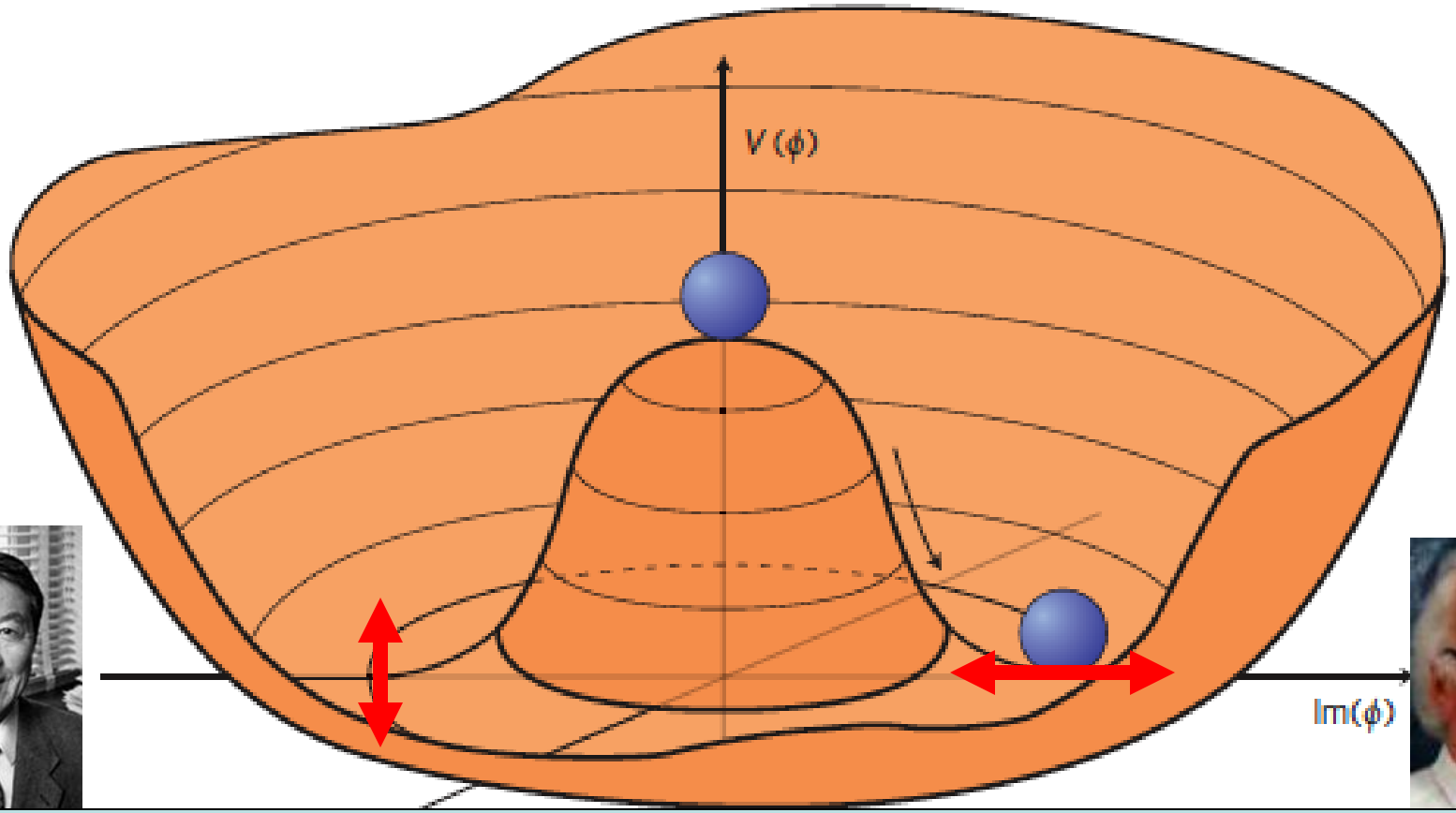
SPONTANEOUS BREAKDOWN OF STRONG INTERACTION SYMMETRY AND THE ABSENCE OF MASSLESS PARTICLES

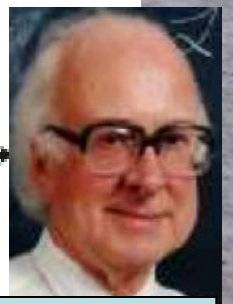
A. A. MIGDAL and A. M.

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, GHK** **and Higgs**





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

Accompanied by massive particle

A Phenomenological Profile of the Higgs Boson

- First attempt at systematic survey

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

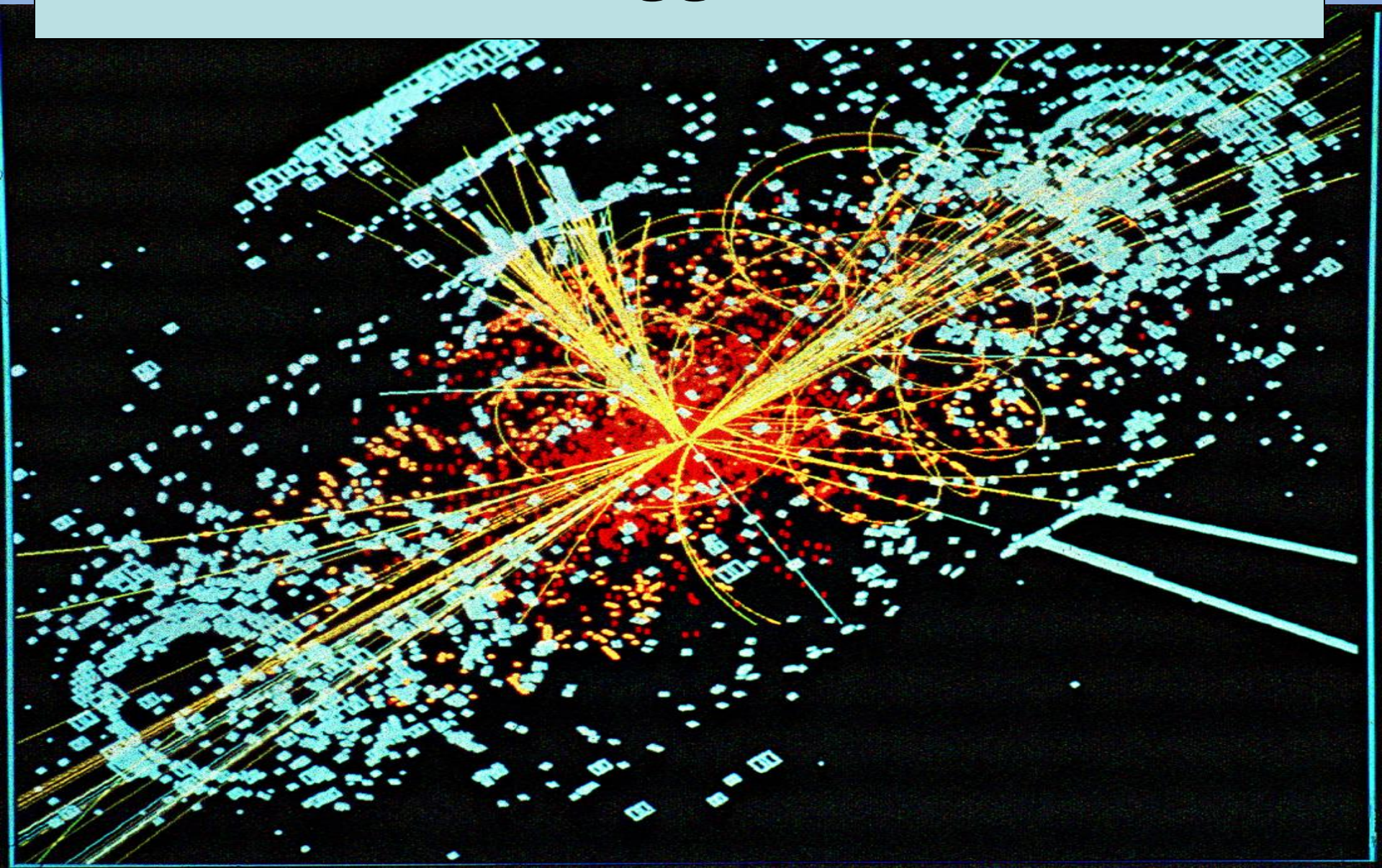
John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

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 Simulated Higgs Event @ LHC

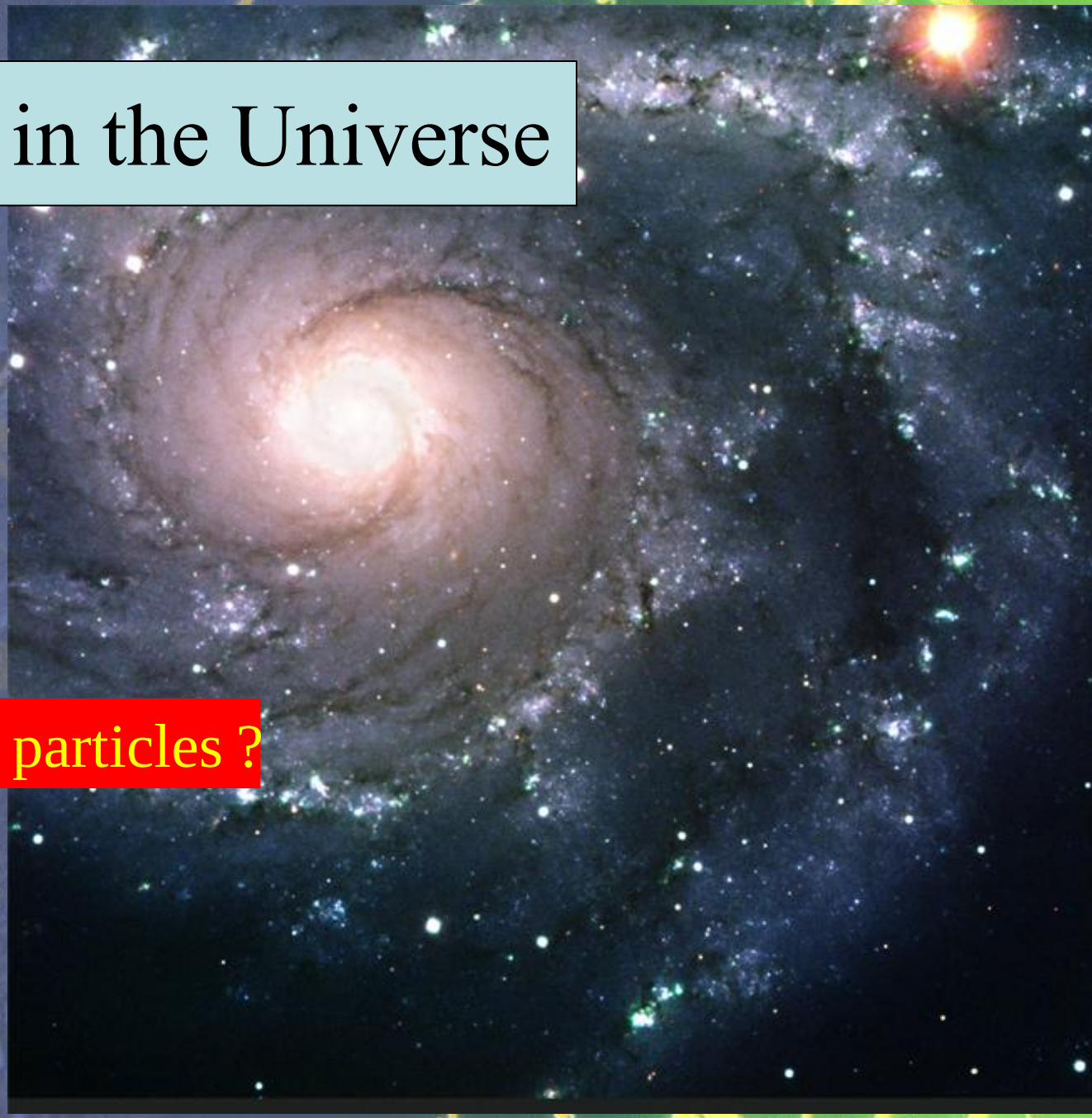


Dark Matter in the Universe

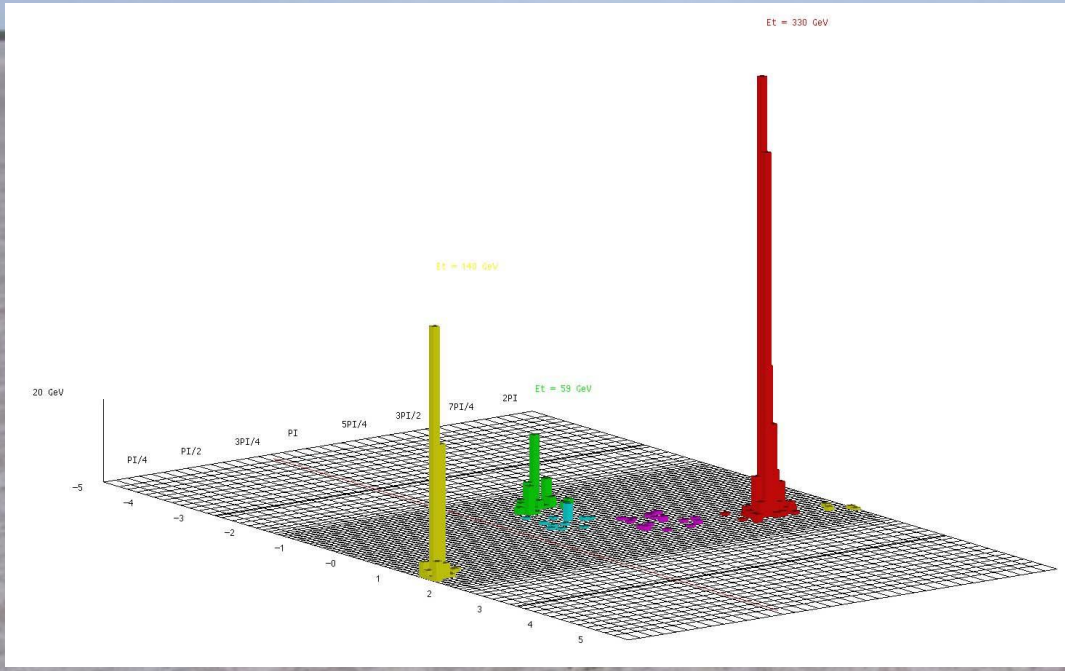
Astronomers say that most of the matter in the Universe is invisible
Dark Matter

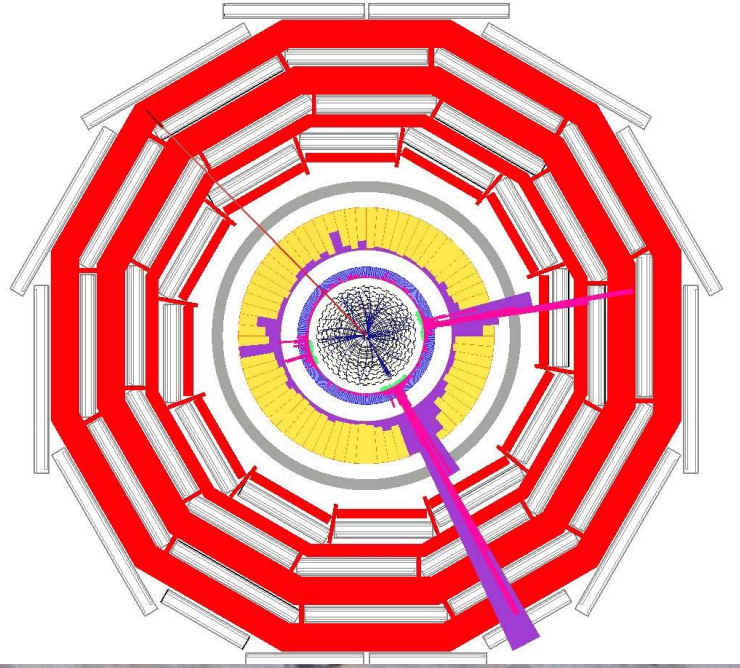
‘Supersymmetric’ particles ?

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

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

How to Create the Matter in the Universe?

Sakharov

- Need a difference between matter and antimatter
  observed in the laboratory
- Need interactions able to creat matter
  present in unified theories
  not yet seen by experiment
- Must break thermal equilibrium
  Possible in the decays of heavy particles

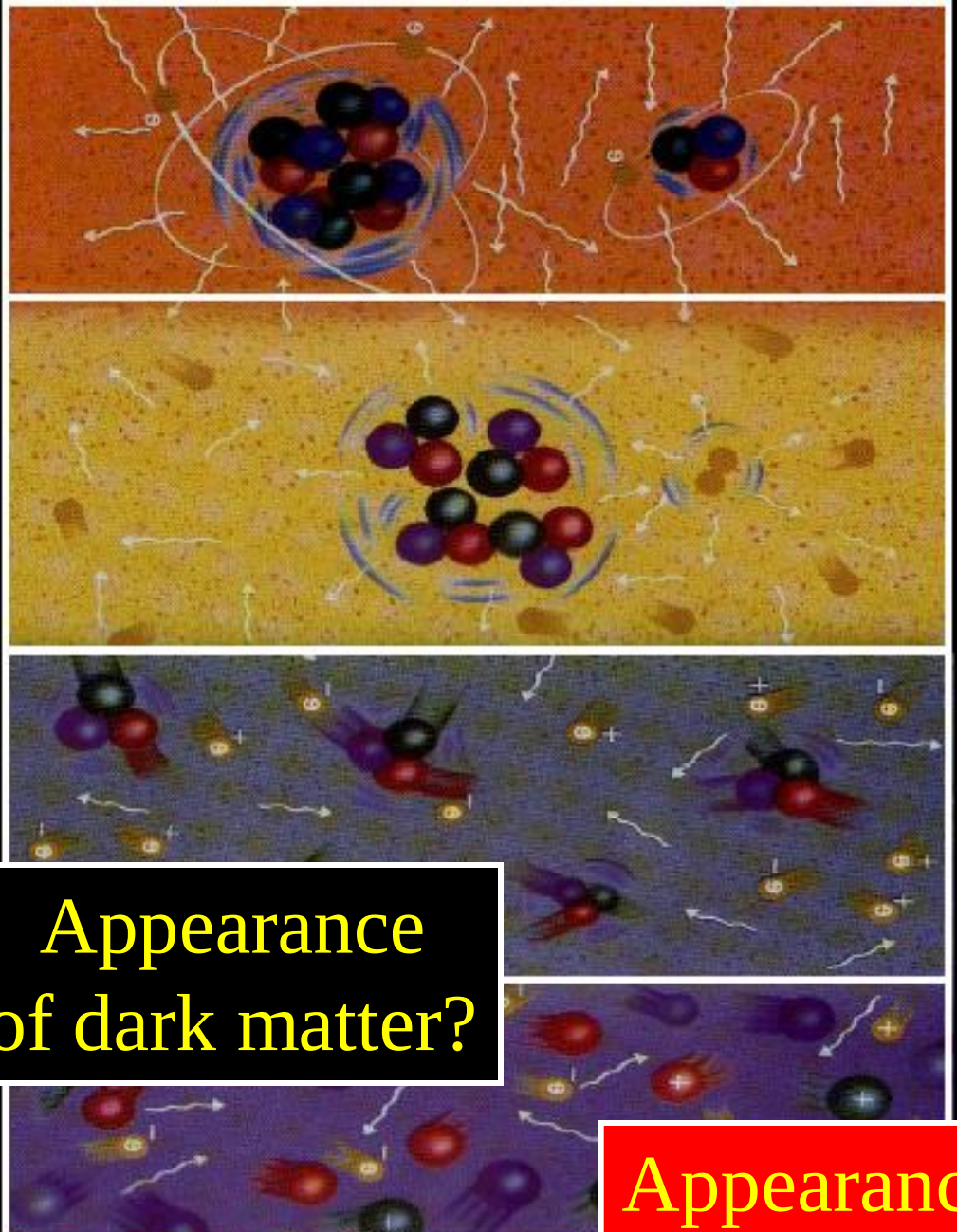
Will we be able to calculate using laboratory data?

300,000 years

3 minutes

1 micro-second

1 pico-second



Formation of atoms

Formation of nuclei

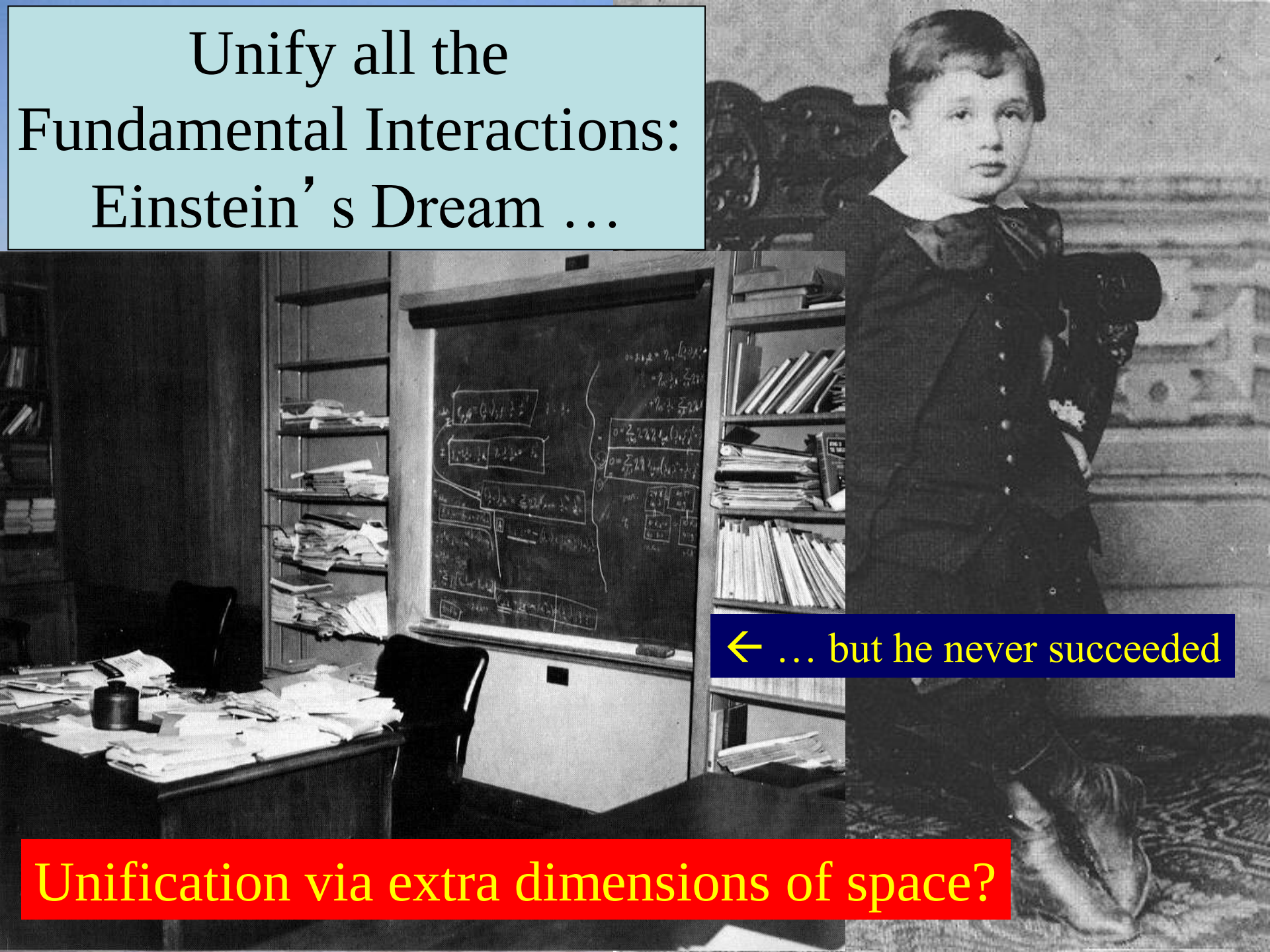
Formation of protons & neutrons

Appearance of mass?

Appearance of dark matter?

Appearance of matter?

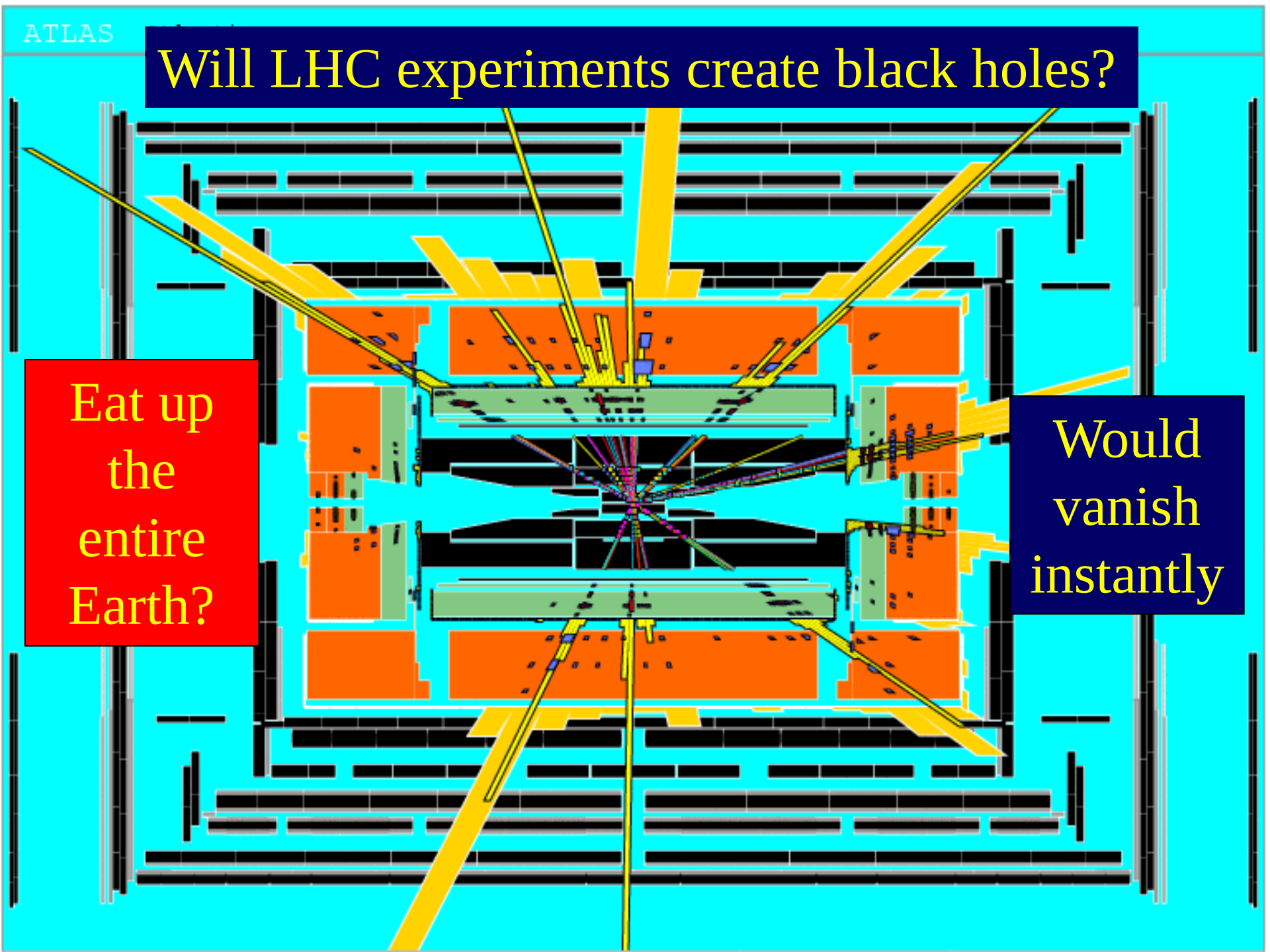
Unify all the Fundamental Interactions: Einstein's Dream …



← … but he never succeeded

Unification via extra dimensions of space?

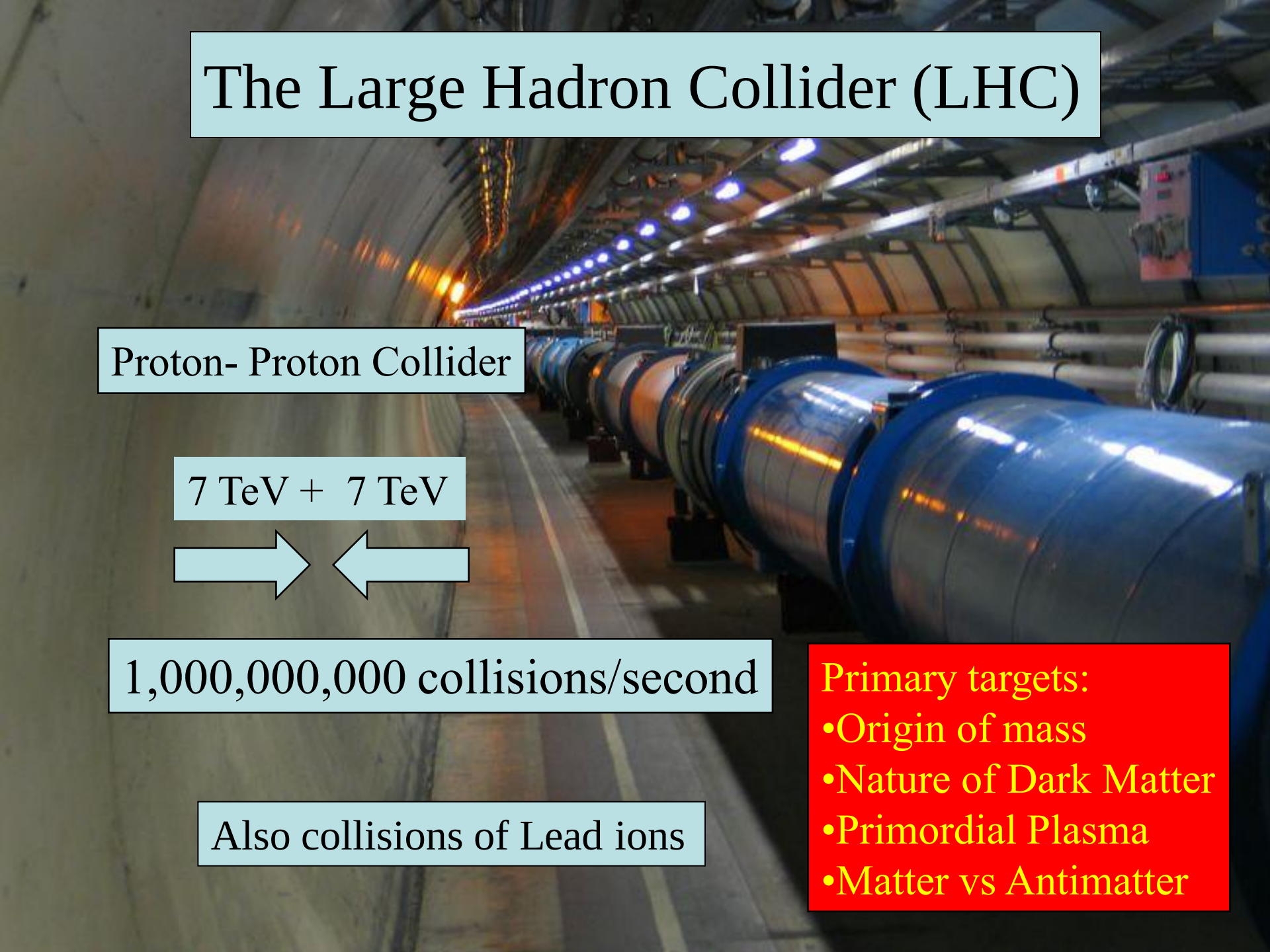
Will LHC experiments create black holes?



Eat up the entire Earth?

Would vanish instantly

The Large Hadron Collider (LHC)



Proton- Proton Collider

7 TeV + 7 TeV

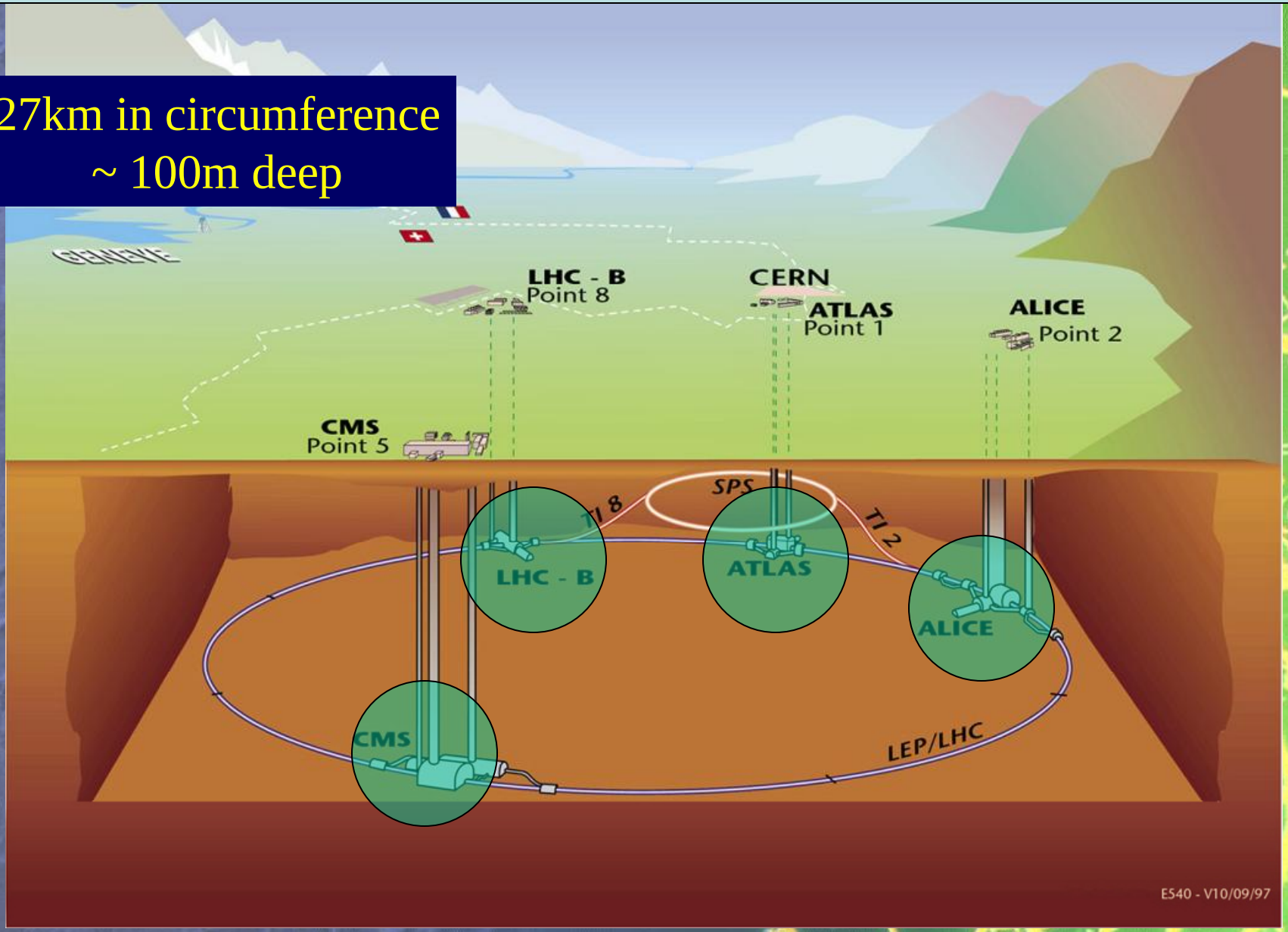
1,000,000,000 collisions/second

Also collisions of Lead ions

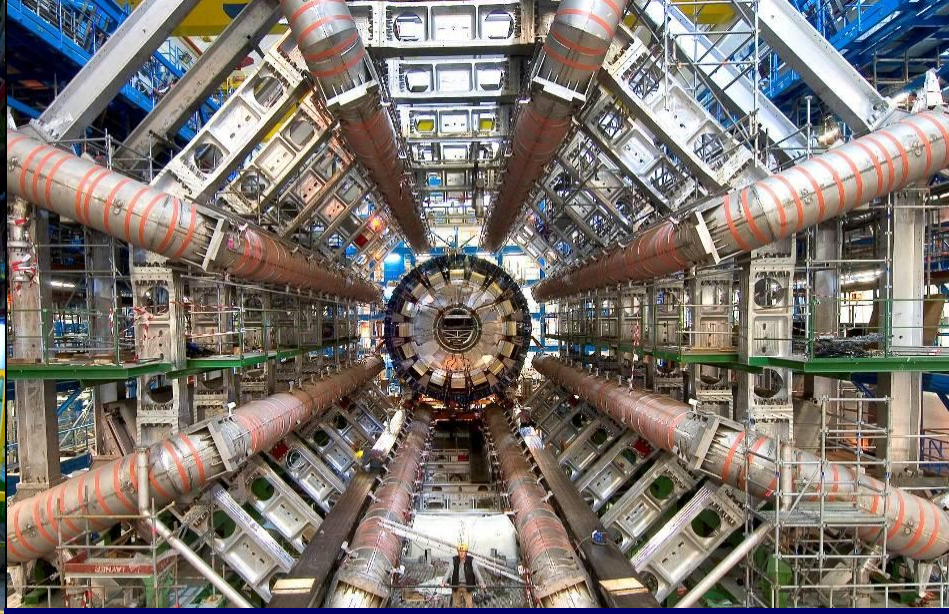
Primary targets:
- Origin of mass
- Nature of Dark Matter
- Primordial Plasma
- Matter vs Antimatter

General View of LHC & its Experiments

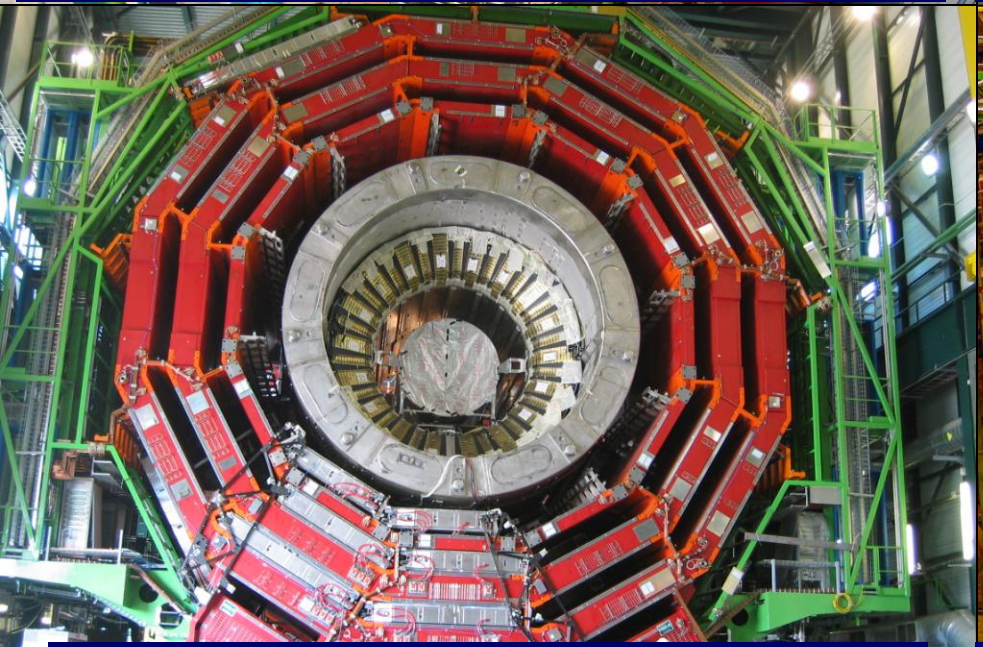
27km in circumference
~ 100m deep



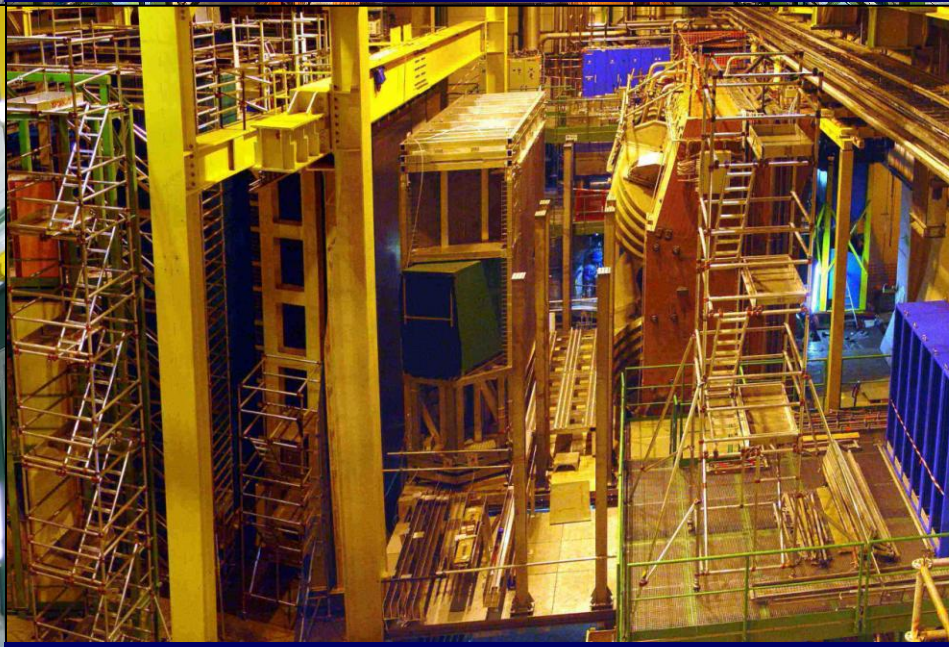
ALICE: Primordial cosmic plasma



ATLAS: Higgs and supersymmetry

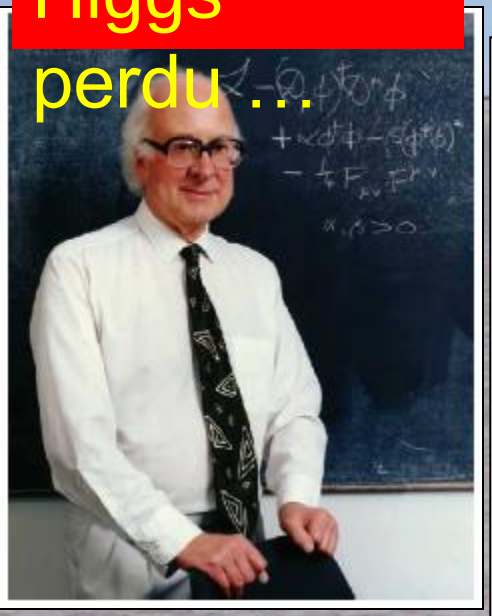


CMS: Higgs and supersymmetry

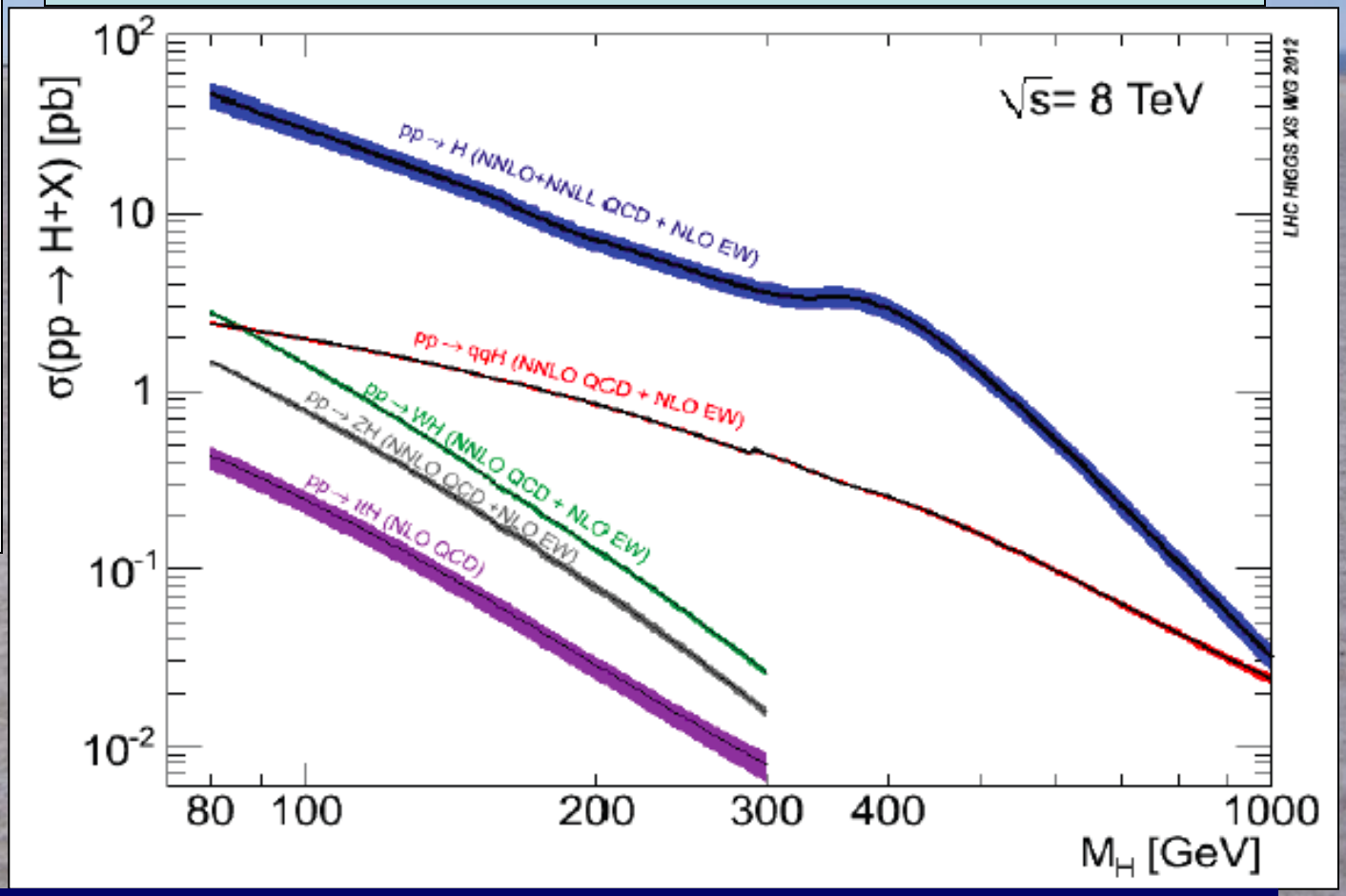


LHCb: Matter-antimatter difference

A la recherche du Higgs perdu …



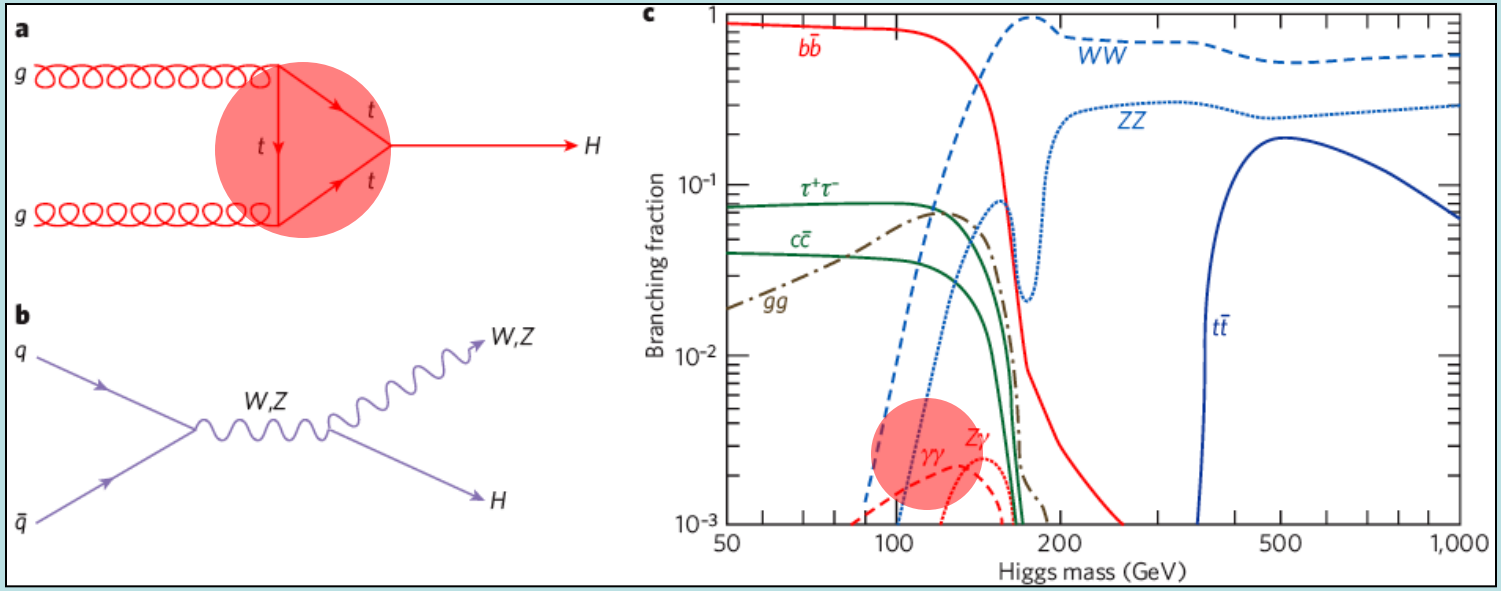
Higgs Production at the LHC



Many production modes measurable if M_h ~ 125 GeV

Higgs Decay Branching Ratios

- Couplings proportional to masses (?)



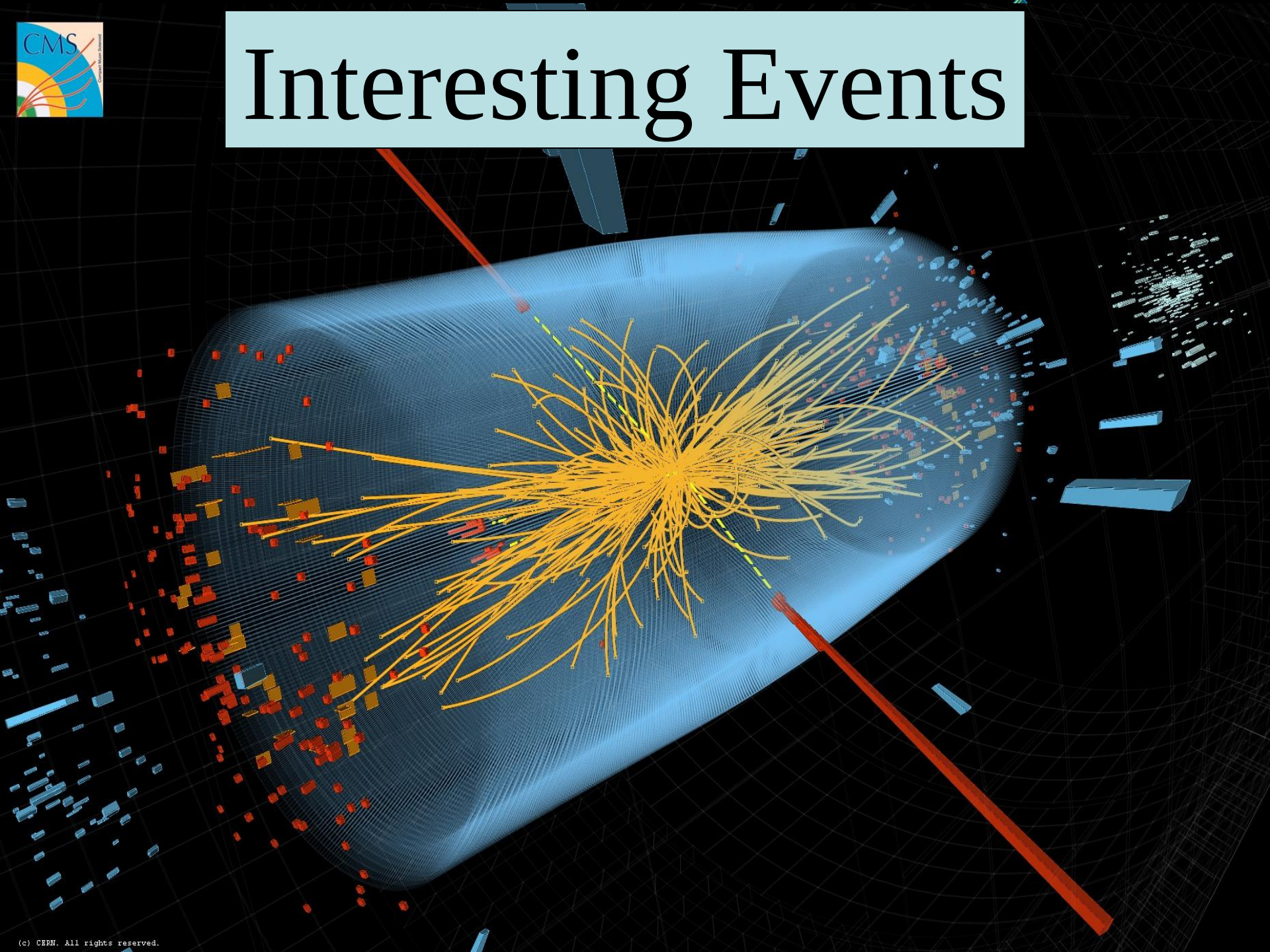
- Important couplings through loops:
  - gluon + gluon → Higgs → γγ

Many decay modes measurable if M_h ~ 125 GeV

Is the Higgs Boson finally being Revealed?

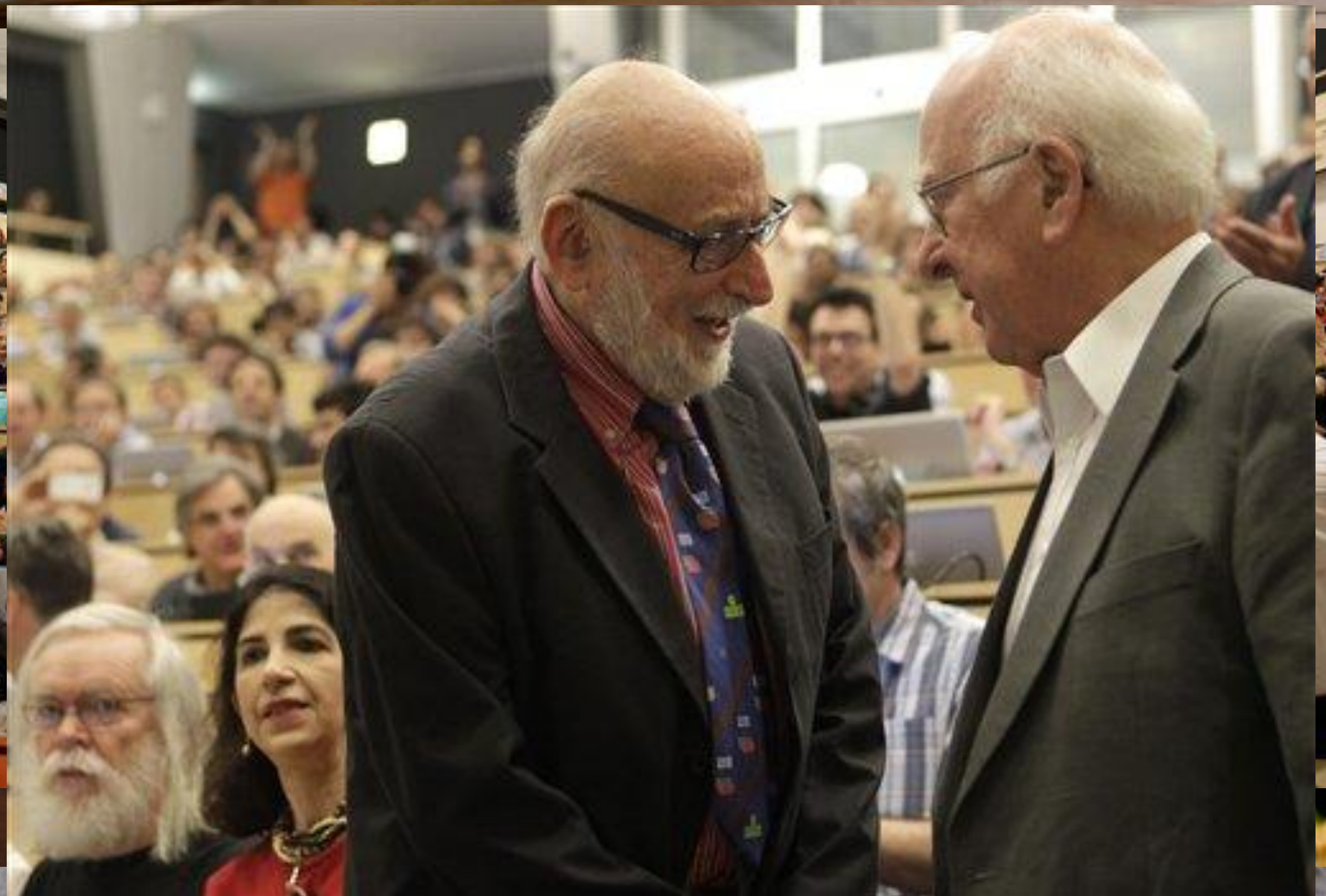
Mass Higgsteria

Interesting Events

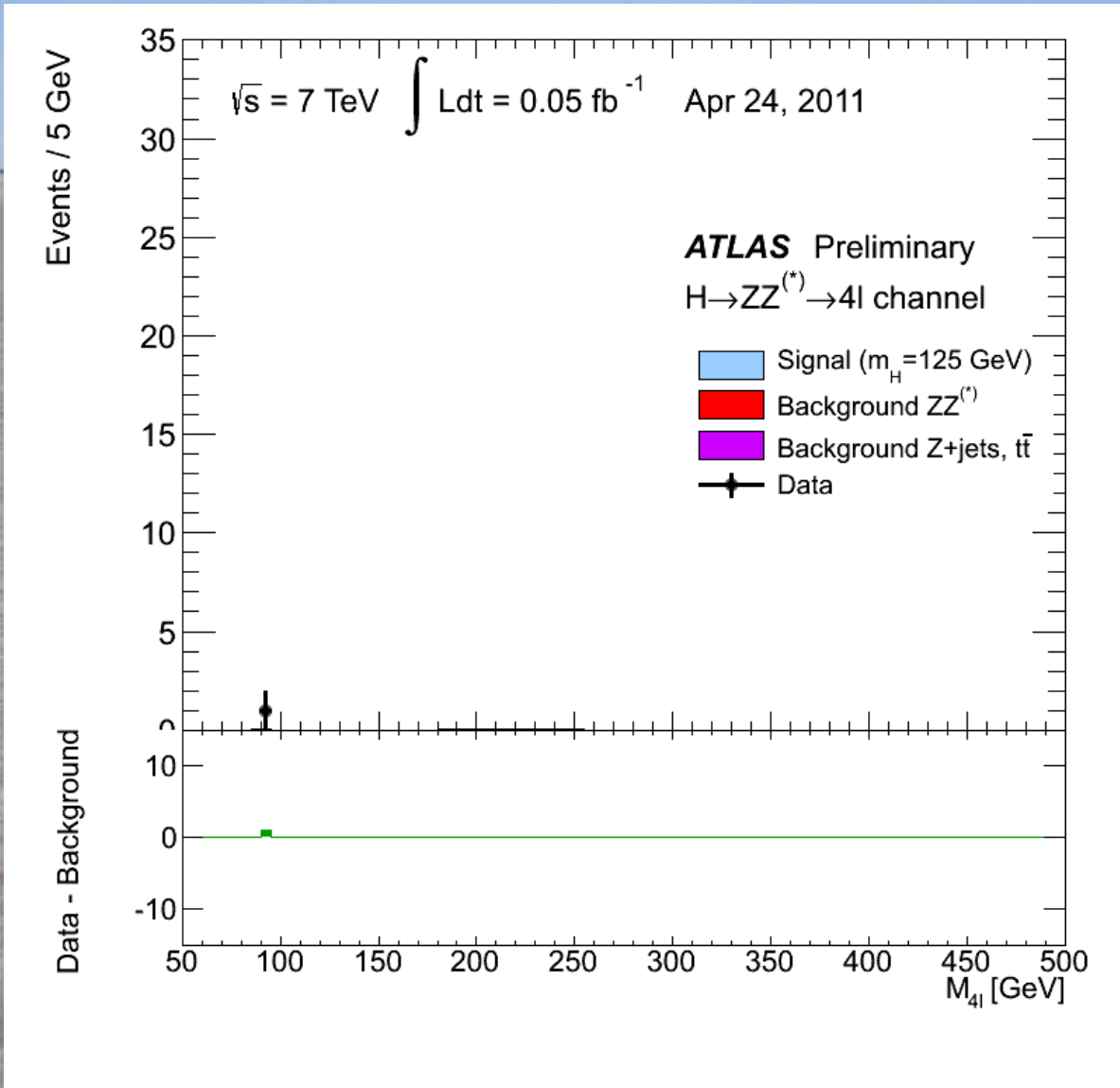


July 4th 2012
The discovery of a new particle

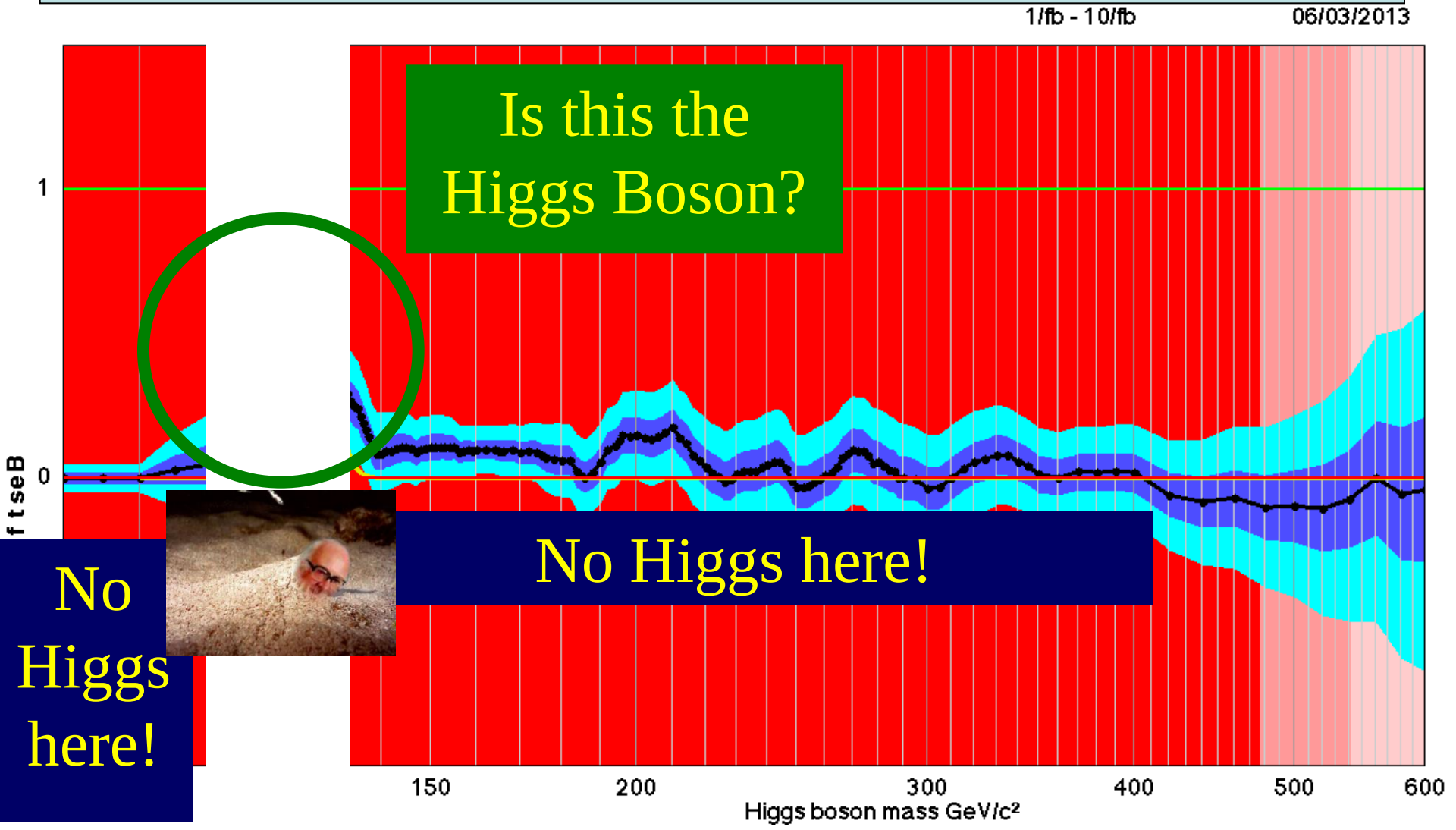
Higgsdependence Day!



How the Higgs Signal has Grown



Unofficial Combination of Higgs Search Data from March 6th

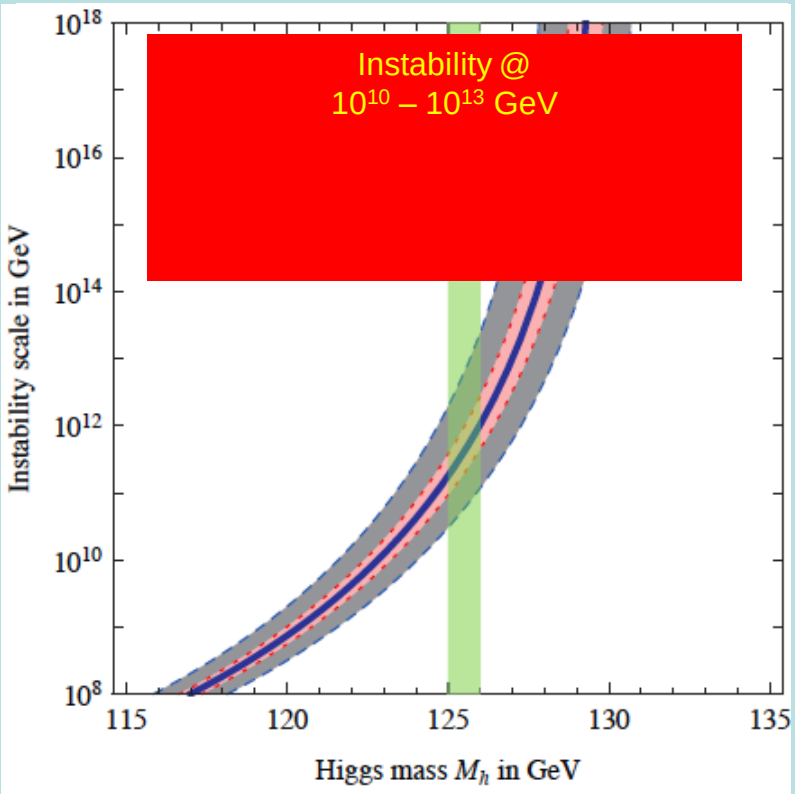


Theoretical Constraints on Higgs Mass

- Large M_h → large self-coupling → blow up at

$$\lambda(Q) = \lambda(v) - \frac{3m_t^4}{2\pi^2 v^4} \log \frac{Q}{v}$$

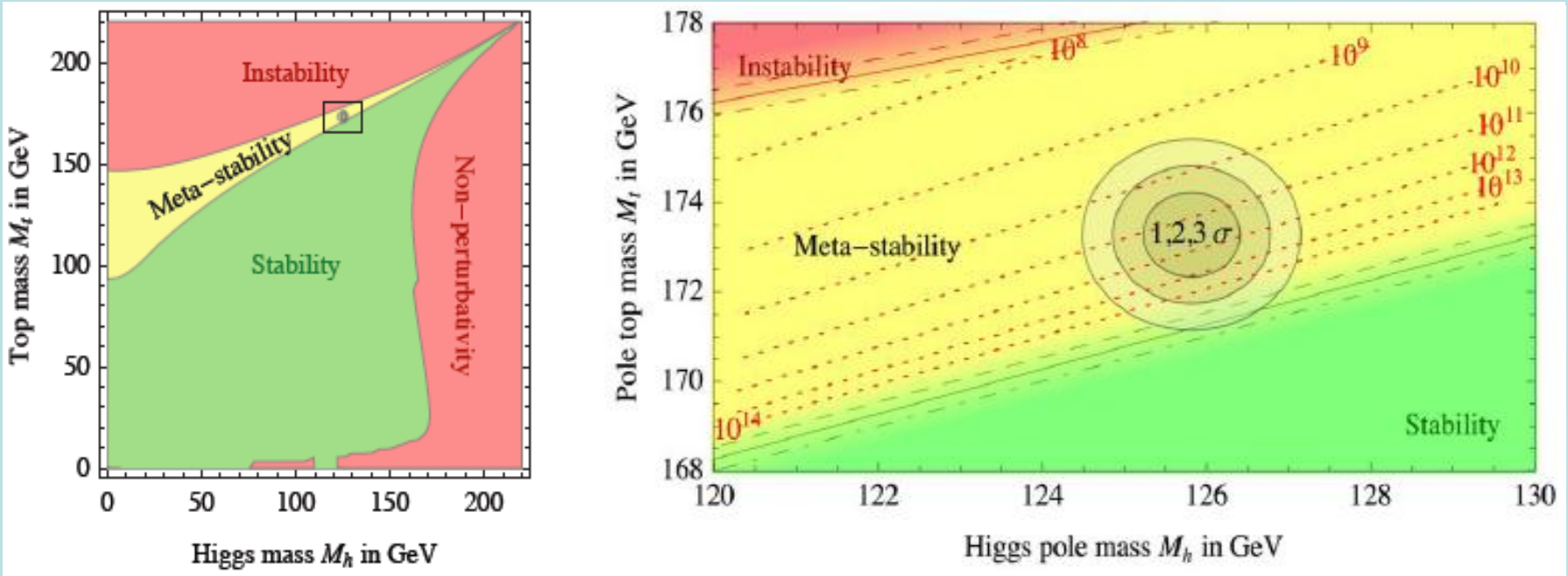
- Small: renormalization due to t quark drives quartic coupling < 0 at some scale Λ → vacuum unstable
- Vacuum could be stabilized by **Supersymmetry**



Degrassi, Di Vita, Elias-Miro, Giudice, Isodori & Strumia, arXiv:1205.6497

Vacuum Instability in the Standard Model

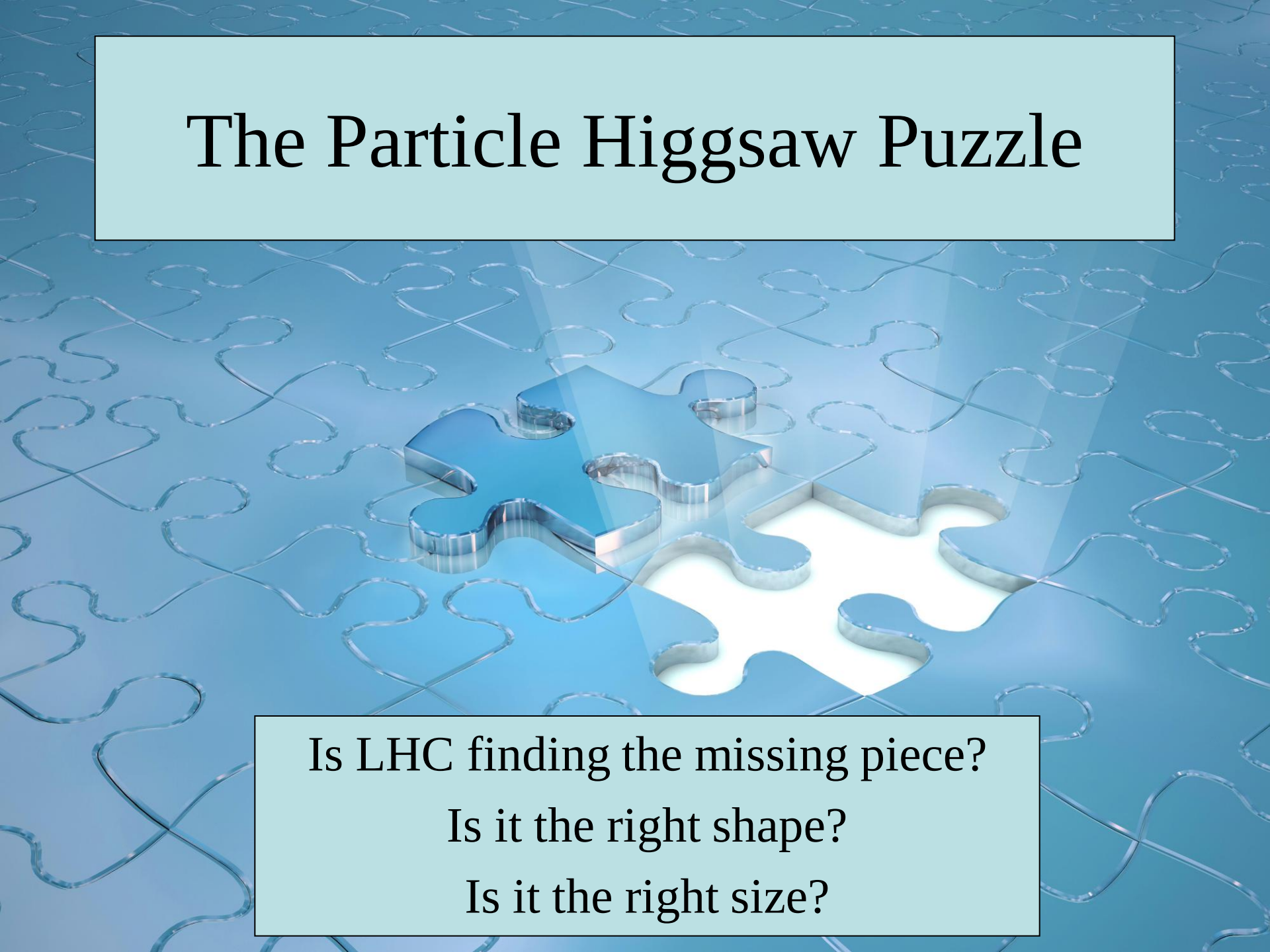
- Very sensitive to m_t as well as M_H



- Present vacuum probably metastable with lifetime >> age of the Universe

Degrassi, Di Vita, Elias-Miro, Giudice, Isodori & Strumia, arXiv:1205.6497

The Particle Higgsaw Puzzle



Is LHC finding the missing piece?

Is it the right shape?

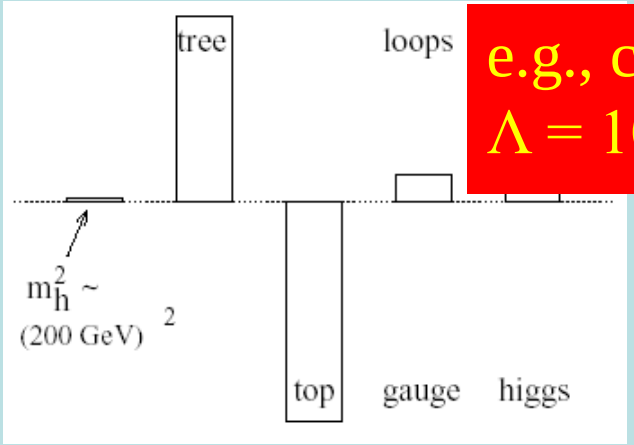
Is it the right size?

Elementary Higgs or Composite?

- Higgs field:

  $\langle 0|H|0\rangle \neq 0$

- Quantum loop problems



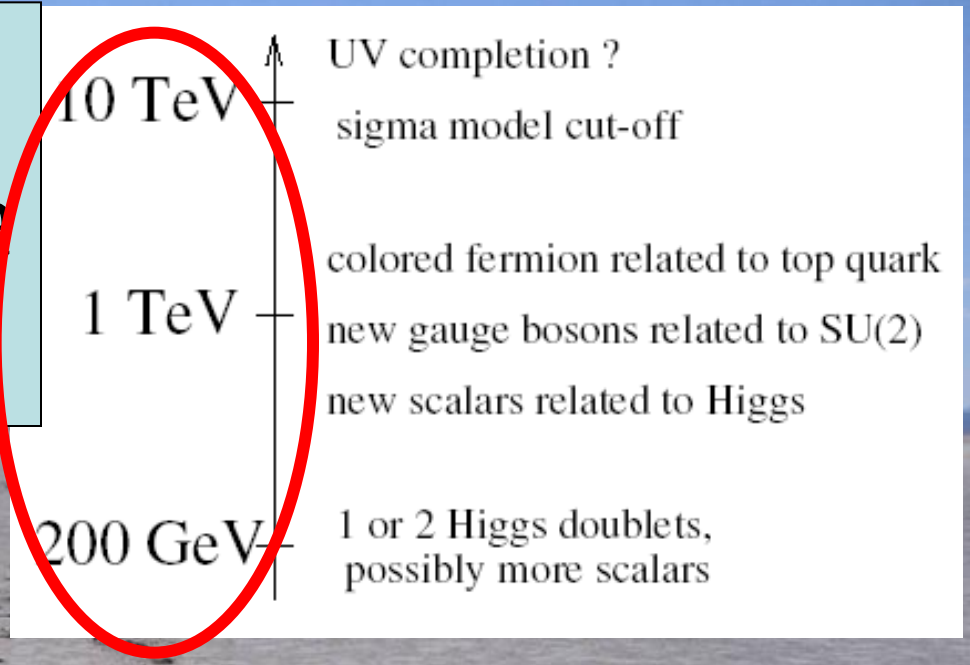
e.g., cutoff
Λ = 10 TeV

Cut-off $\Lambda \sim 1$ TeV with Supersymmetry?

- Fermion-antifermion condensate
- Just like QCD, BCS superconductivity
- Top-antitop condensate? needed $m_t > 200$ GeV

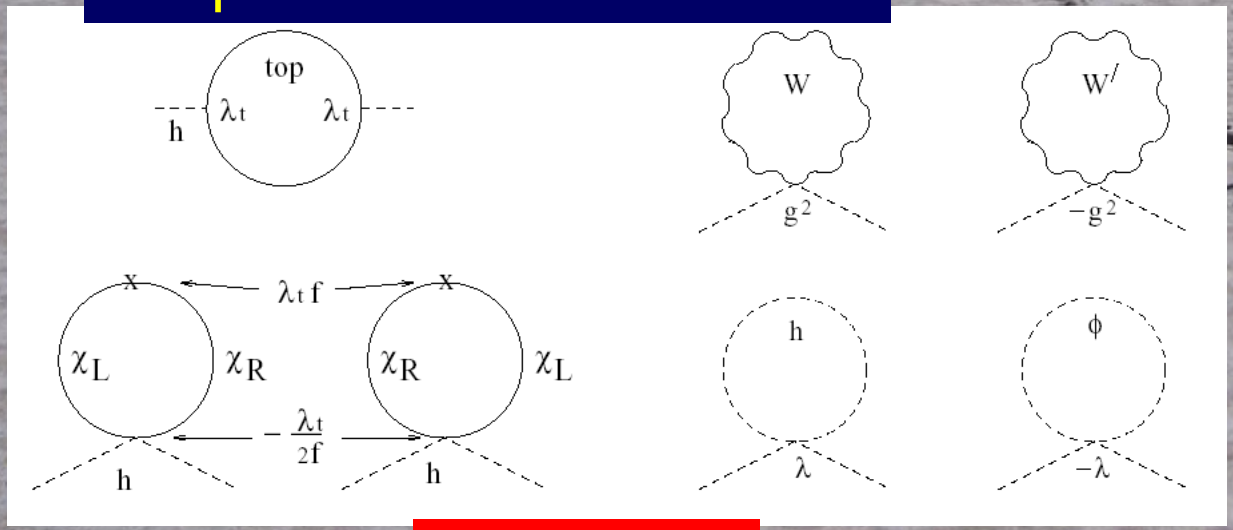
New technicolour force?
-Heavy scalar resonance?
-Inconsistent with precision electroweak data?

Higgs as a Pseudo-Goldstone Boson

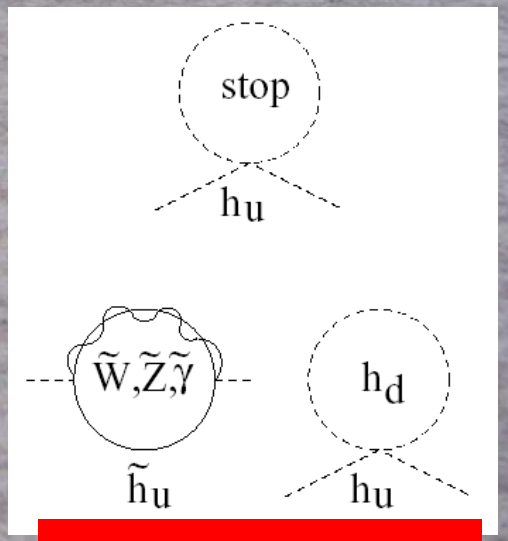


'Little Higgs' models
(breakdown of larger symmetry)

Loop cancellation mechanism

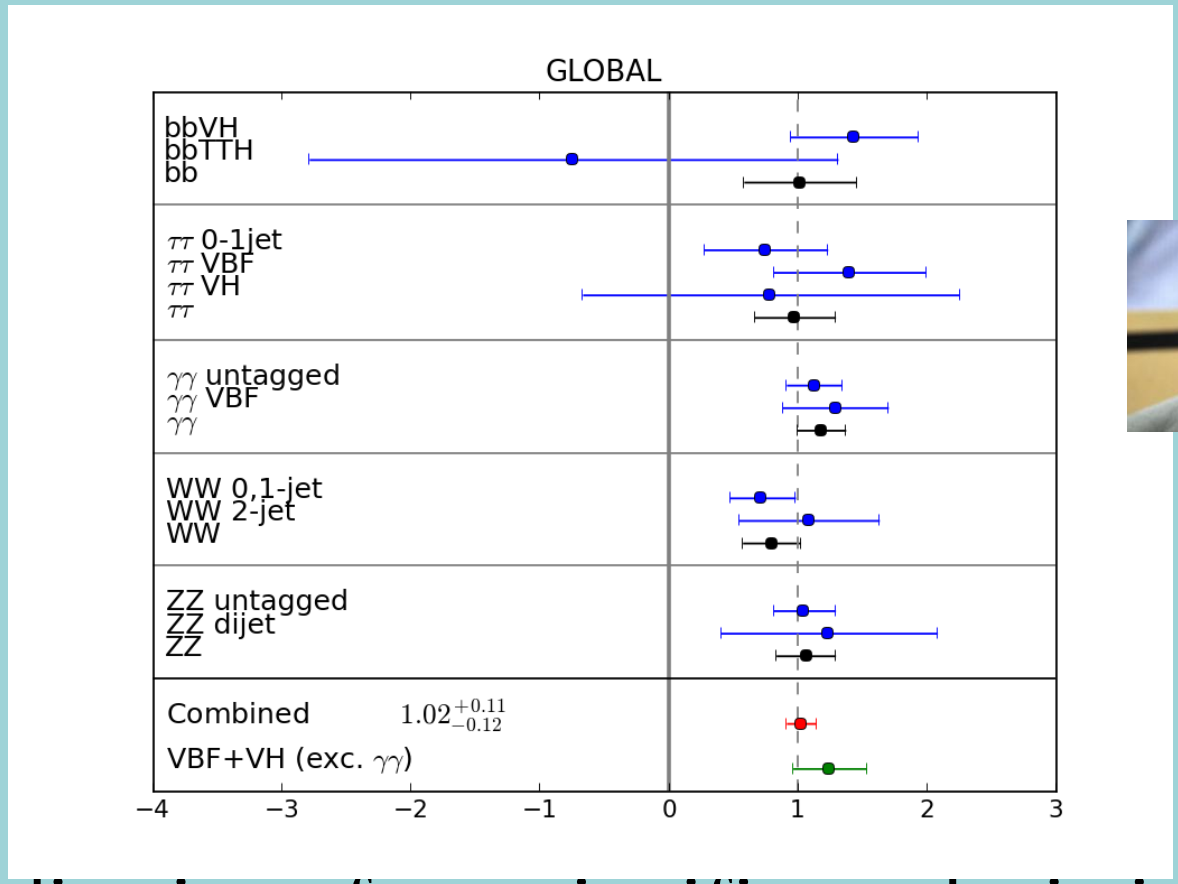


Little Higgs



Supersymmetry

Couplings resemble Higgs of Standard Model



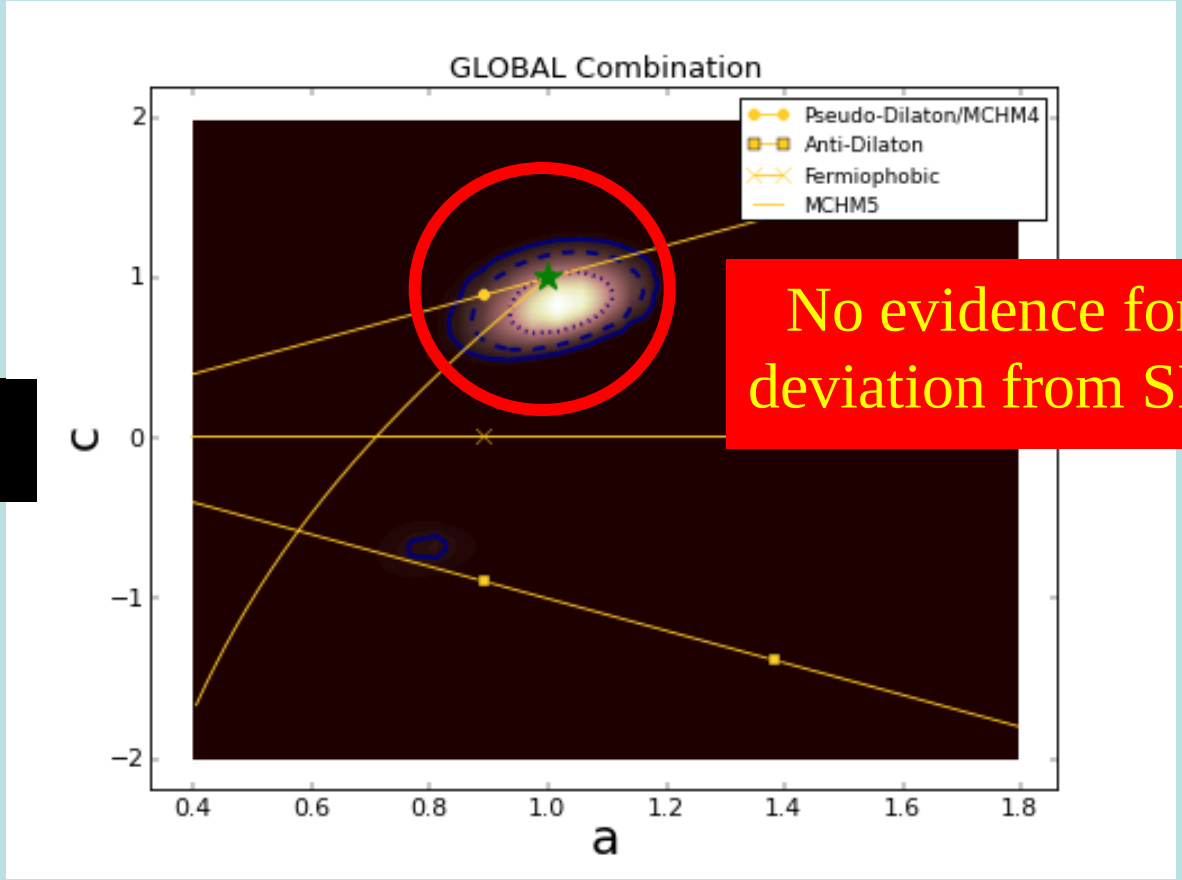
- No indication of any significant deviation from the Standard Model predictions

JE & Tevong You, arXiv:1303.3879

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: $a = c = 1$

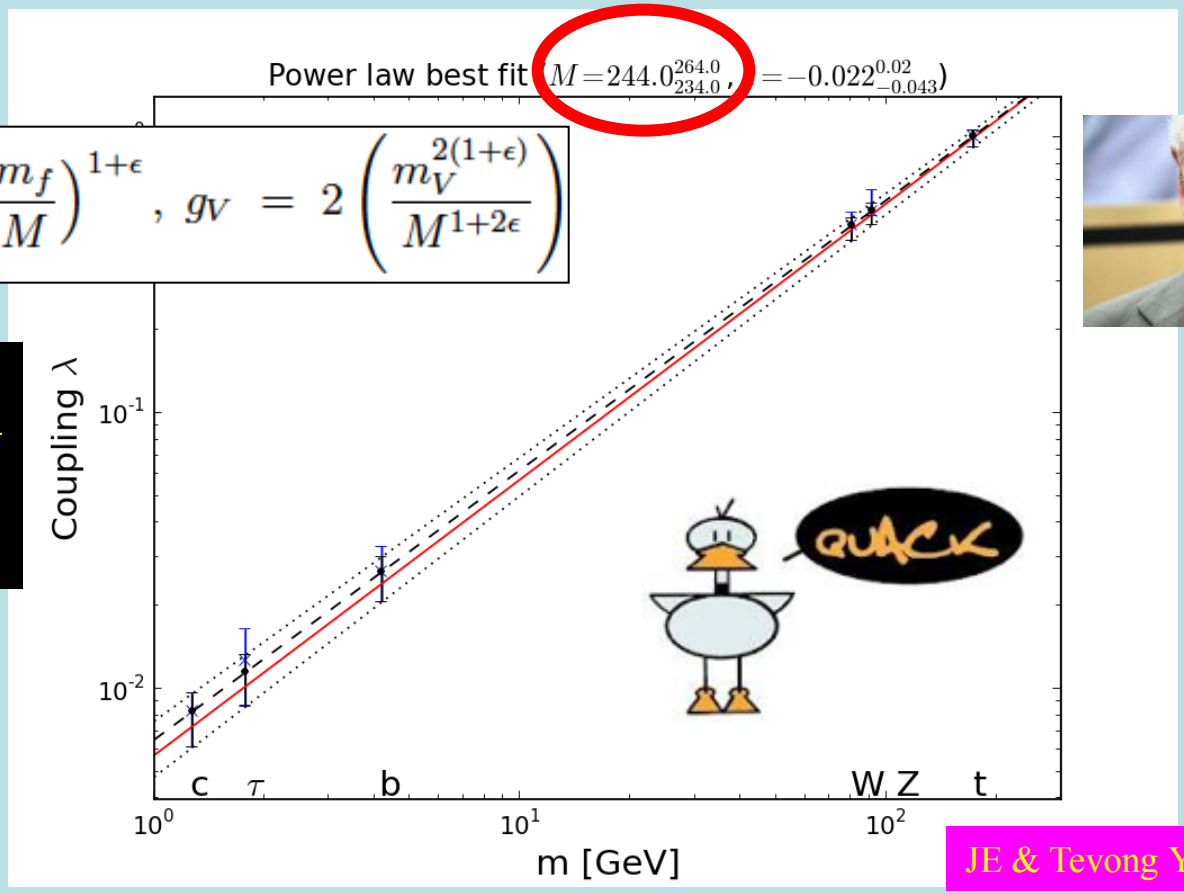
JE & Tevong You, arXiv:1303.3879

It Walks and Quacks like a Higgs

- Do couplings scale ~ mass? With scale = v?

$$\lambda_f = \sqrt{2}\left(\frac{m_f}{M}\right)^{1+\epsilon}, \; g_V = 2\left(\frac{m_V^{2(1+\epsilon)}}{M^{1+2\epsilon}}\right)$$

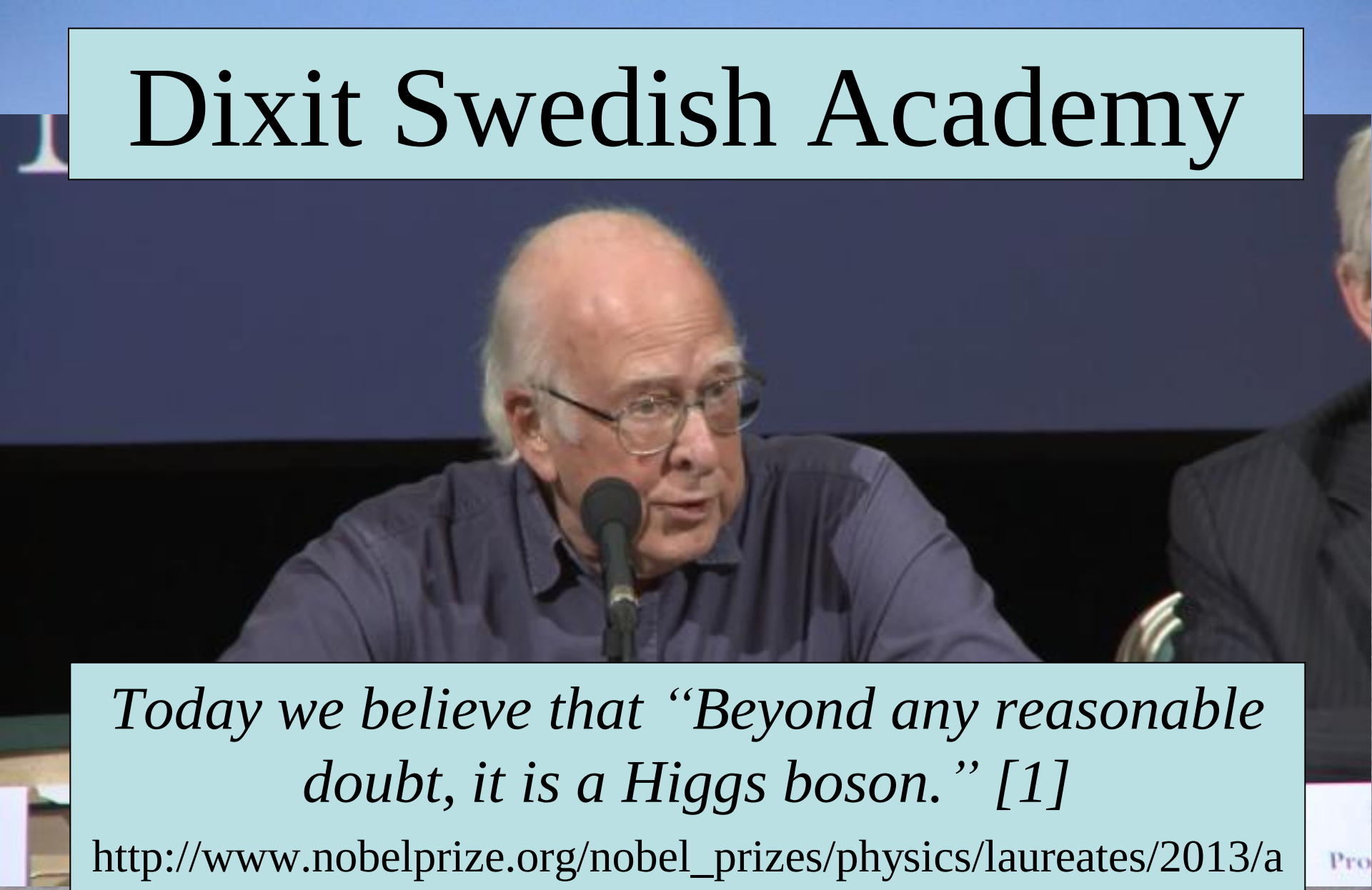
Global fit



JE & Tevong You, arXiv:1303.3879

- **Red line = SM**, dashed line = best fit

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

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

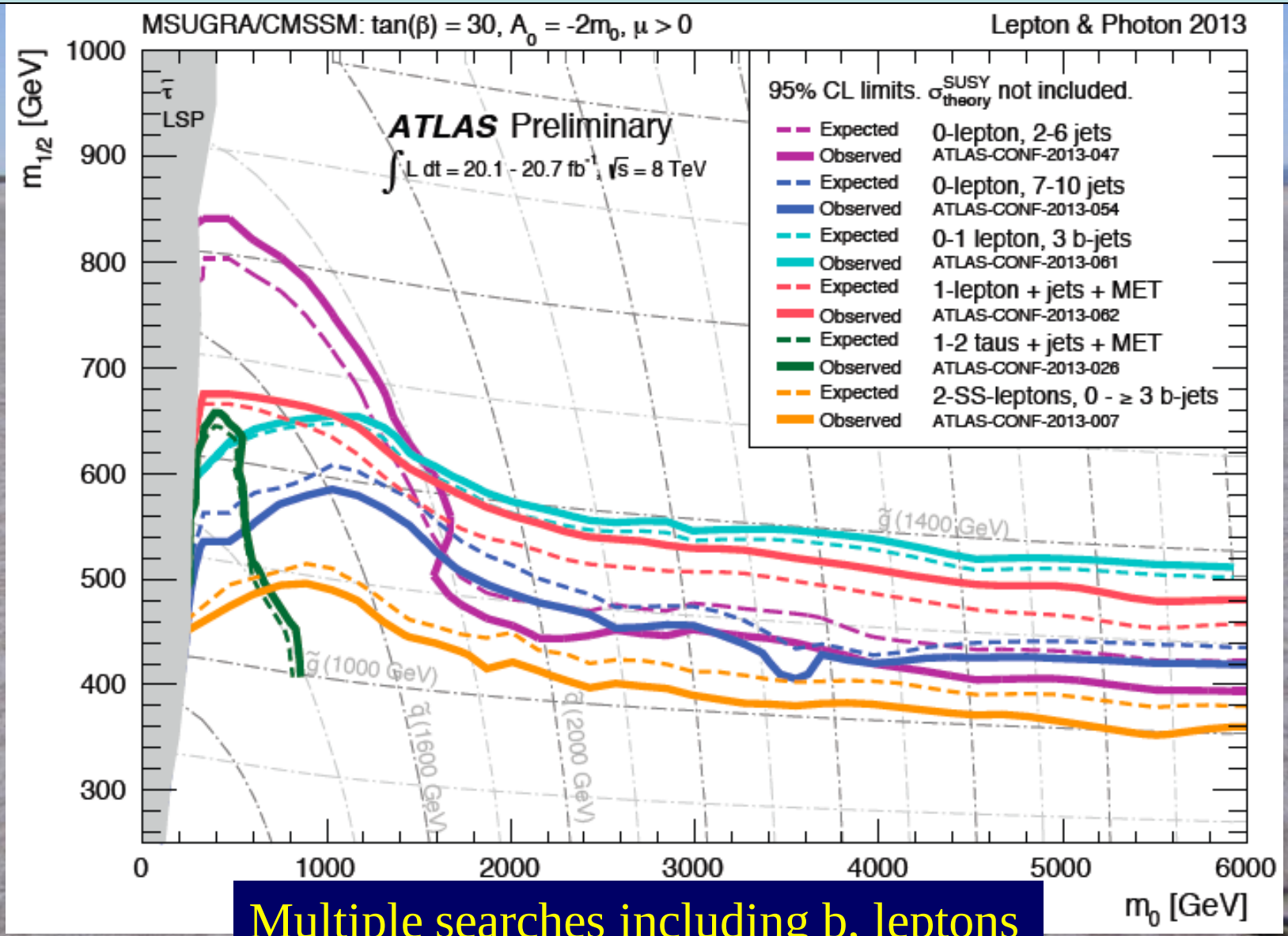
Its existence is a big deal!

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, … (???)

Searches with 8 TeV Data

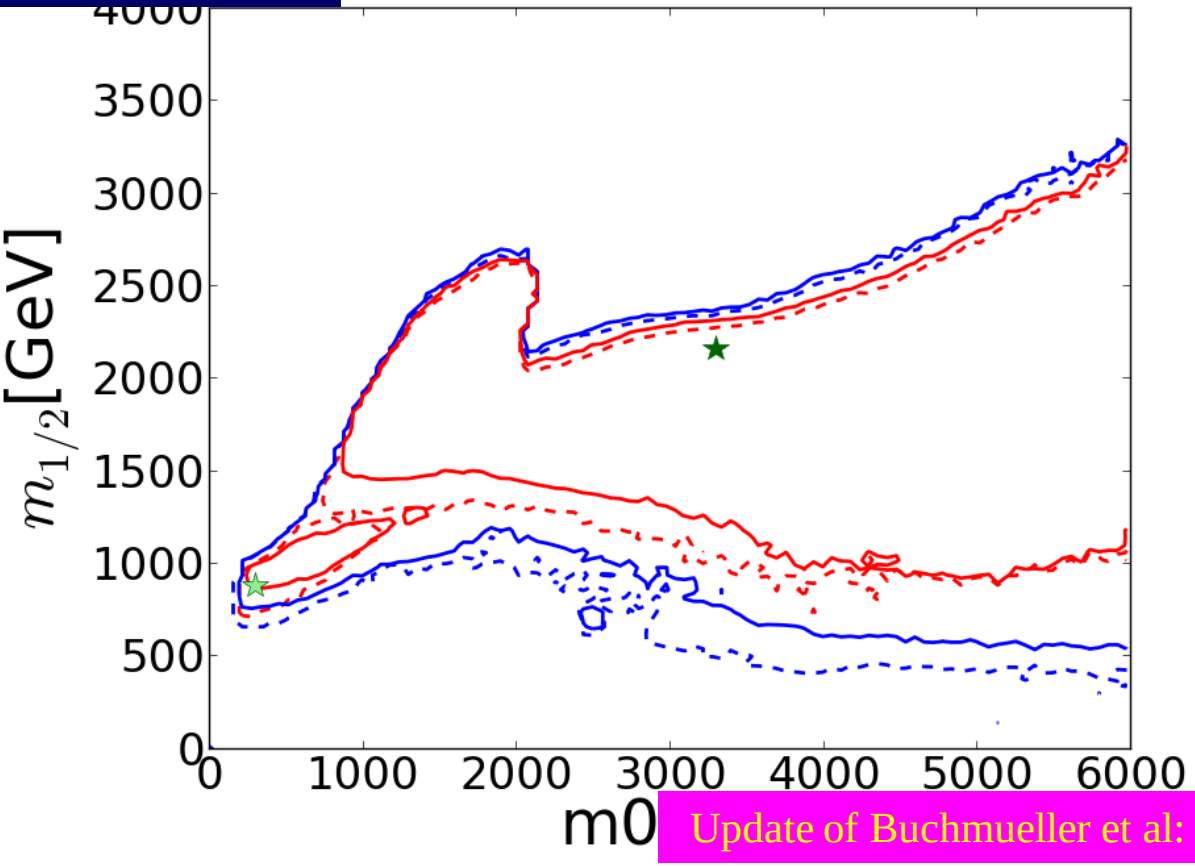


Multiple searches including b, leptons

Post-LHC, Post-XENON100

2012 ATLAS + CMS with 20/fb of LHC Data

Scan of CMSSM



Update of Buchmueller et al: arXiv:1207.3715

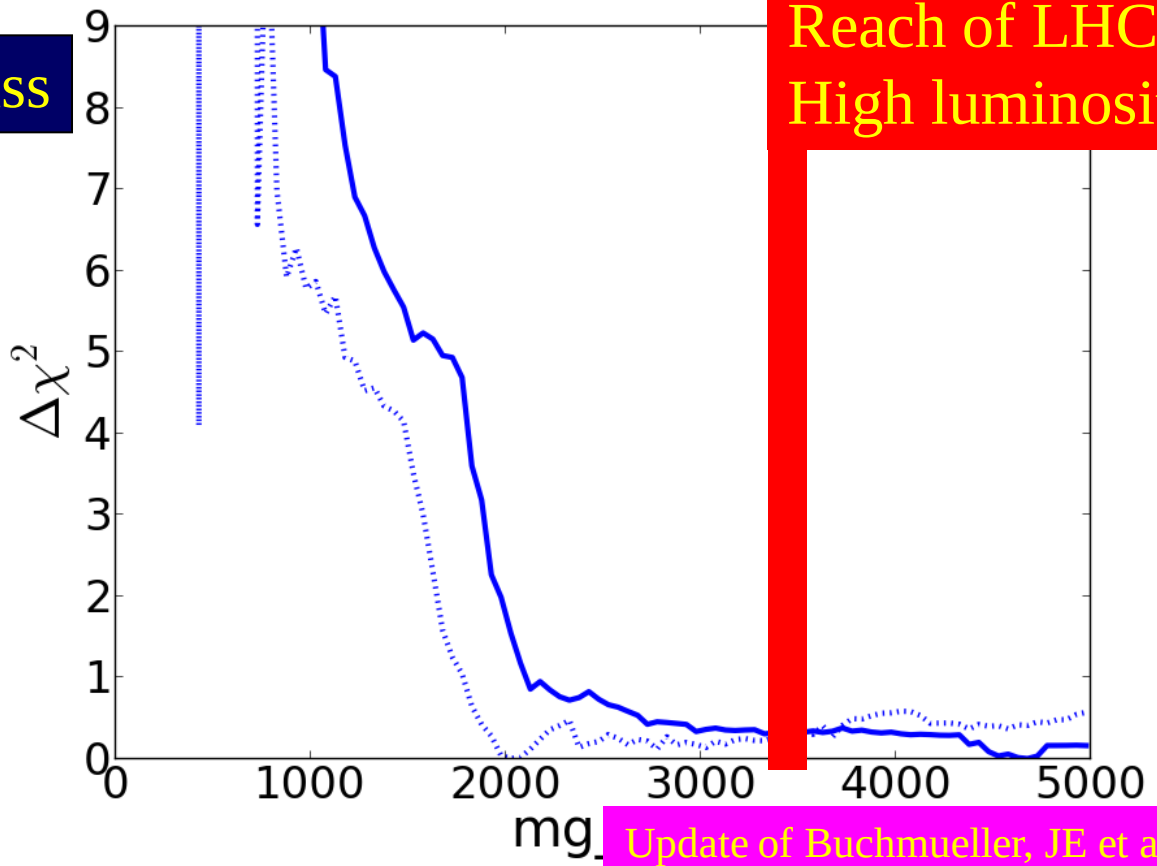
Red and blue curves represent $\Delta\chi^2$ from global minimum, located at ★

p-value of simple models < 10%

Post-LHC, Post-XENON100

2012 ATLAS + CMS with 20/fb of LHC Data

Gluino mass



Reach of LHC at High luminosity

Update of Buchmueller, JE et al: arXiv:1207.3715

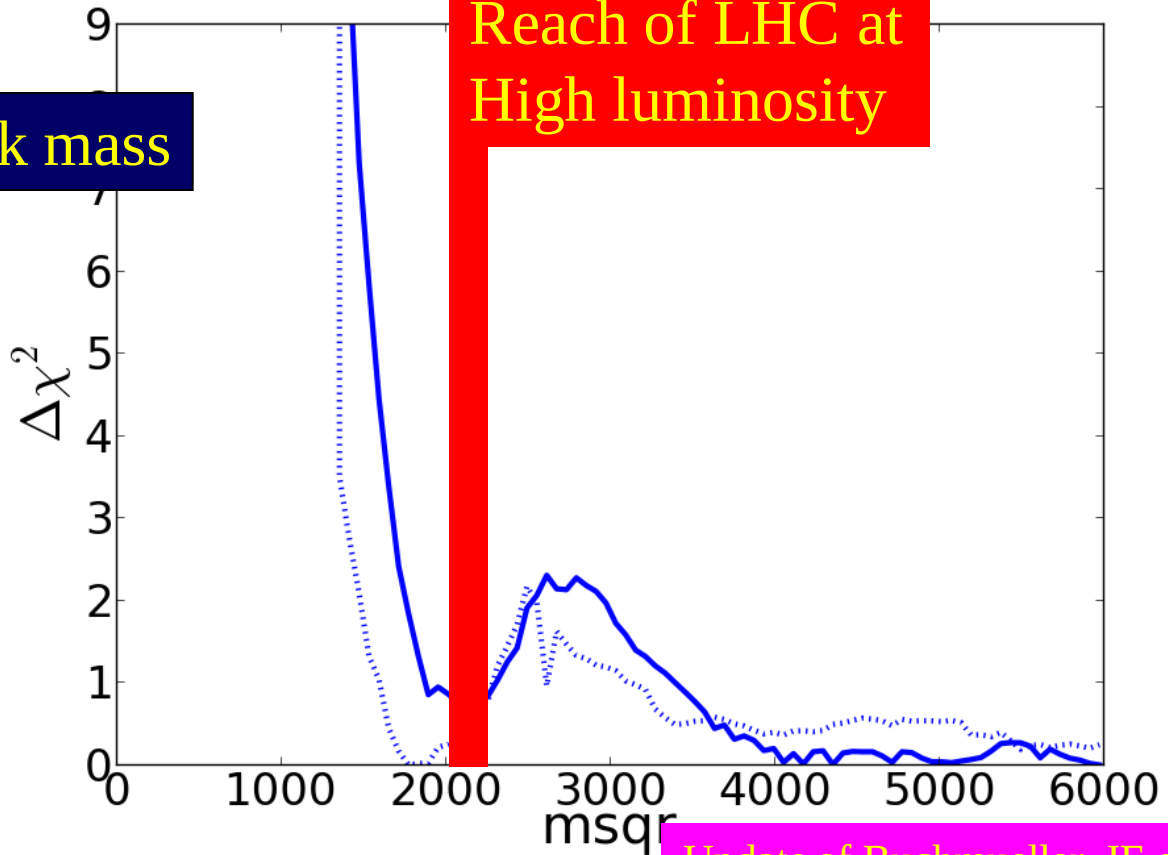
Favoured values of gluino mass significantly above pre-LHC, > 2 TeV

Post-LHC, Post-XENON100

2012 ATLAS + CMS with 20/fb of LHC Data

Squark mass

Reach of LHC at High luminosity

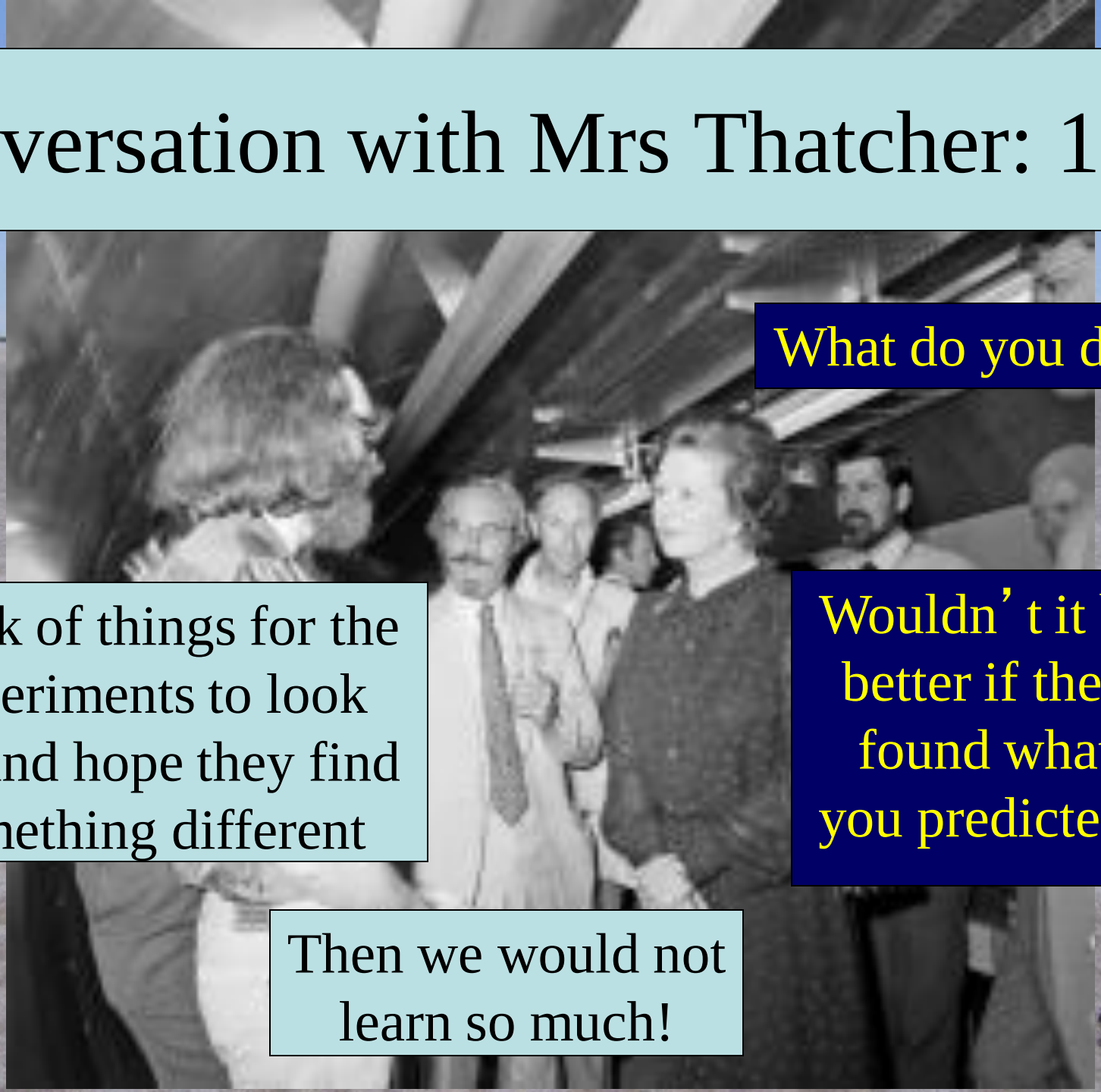


Update of Buchmueller, JE et al: arXiv:1207.3715

Favoured values of squark mass:
~ 2000 GeV or more

A Vision for the 21st Century

Conversation with Mrs Thatcher: 1982



What do you do?

Think of things for the experiments to look for, and hope they find something different

Wouldn't it be better if they found what you predicted?

Then we would not learn so much!