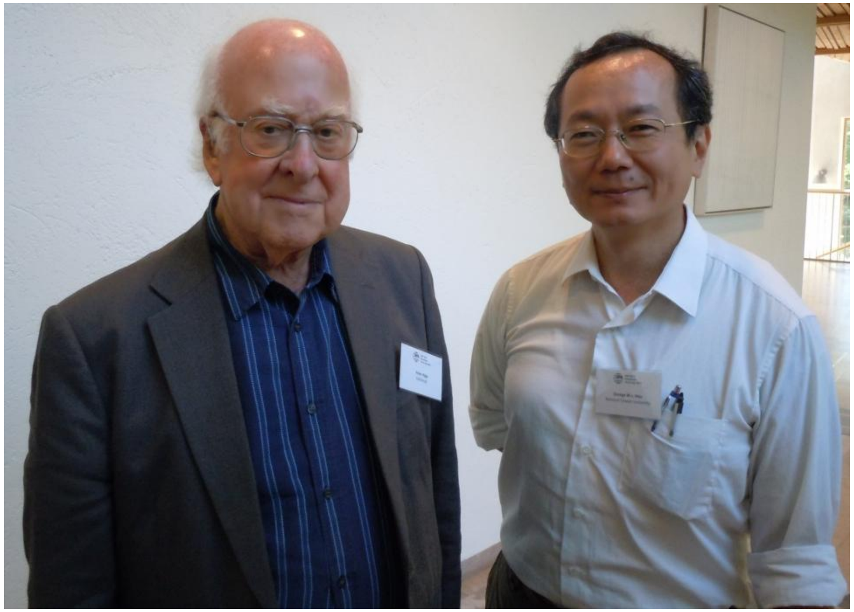
a Higgstory

— Special Colloquium on the 2013 Nobel Prize in Physics

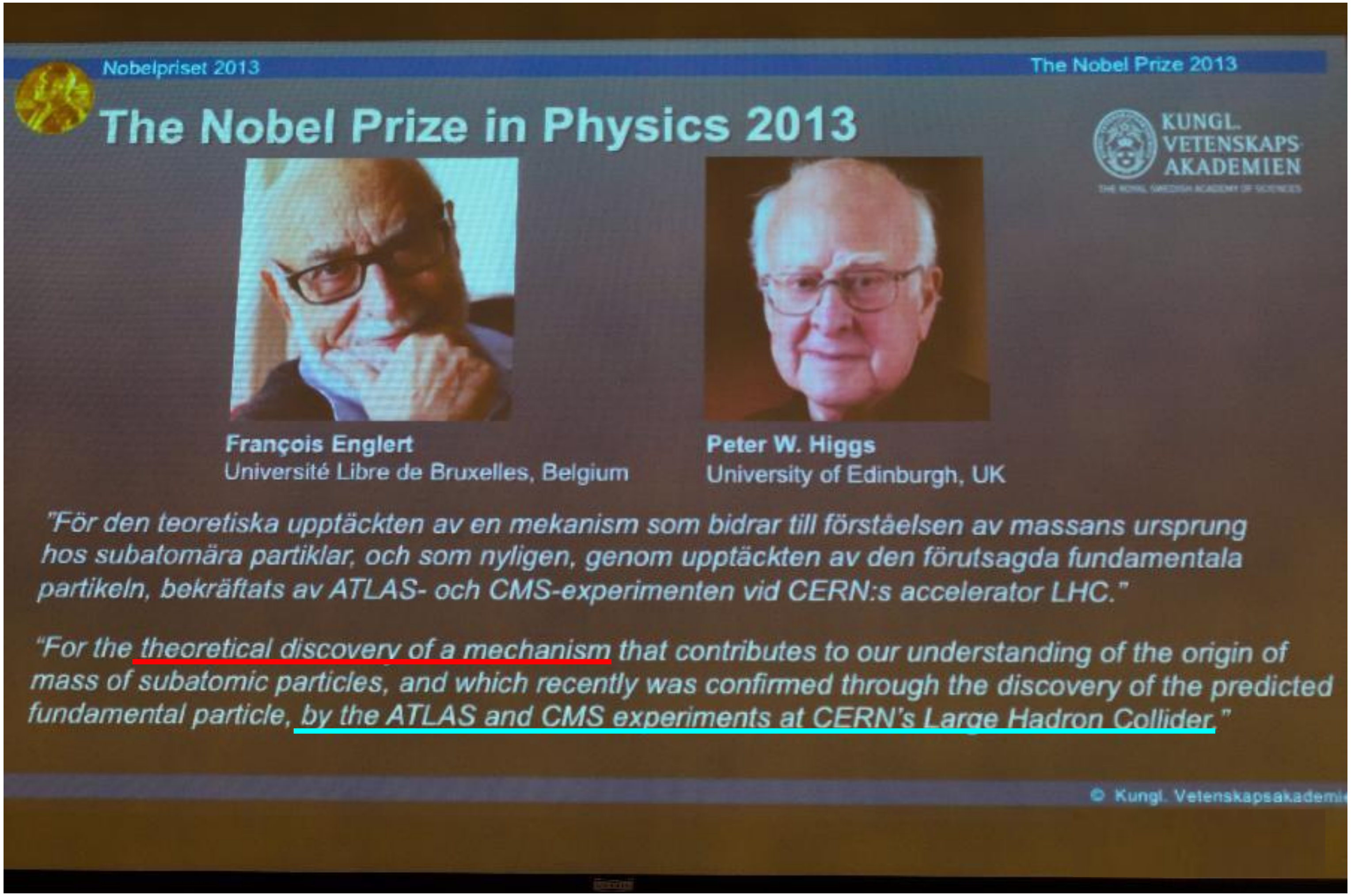
George W.S. Hou (侯維恕)
National Taiwan University

October 22, 2013, Joint Colloquium @ NTU



臺灣大學
National Taiwan University

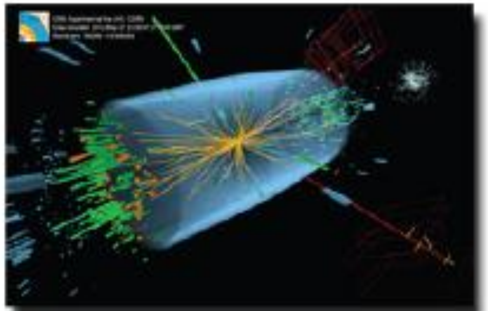
a Higgs Story

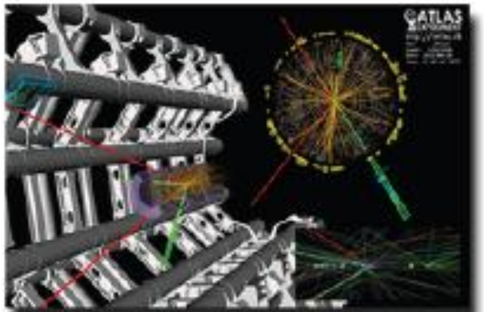


Origin of Mass

recent discovery of predicted fundamental particle

Return to CMS home page





The ATLAS and CMS experiments at CERN congratulate Professors François Englert and Peter Higgs for their pioneering work in identifying the electroweak-symmetry-breaking mechanism. CMS and ATLAS independently announced the discovery of a new particle on 4 July 2012, later identified as a Higgs boson, confirming the predictions of Professors Higgs, Englert and others in seminal papers published in 1964. We join in this celebration of the triumph of human curiosity and ingenuity.

ATLAS, CMS, and 3 First SPs Receive EPS Prize

European Physical Society
PRIZE

The 2013 High Energy and Particle Physics Prize

for an outstanding contribution to High Energy Physics

is awarded to the

ATLAS and CMS collaborations

"for the discovery of a Higgs boson, as predicted by the Brout-Englert-Higgs mechanism"

That's me, too !

and to

Michel Della Negra, Peter Jenni, and Tejinder Virdee

"for their pioneering and outstanding leadership rôles in the making of the ATLAS and CMS experiments"

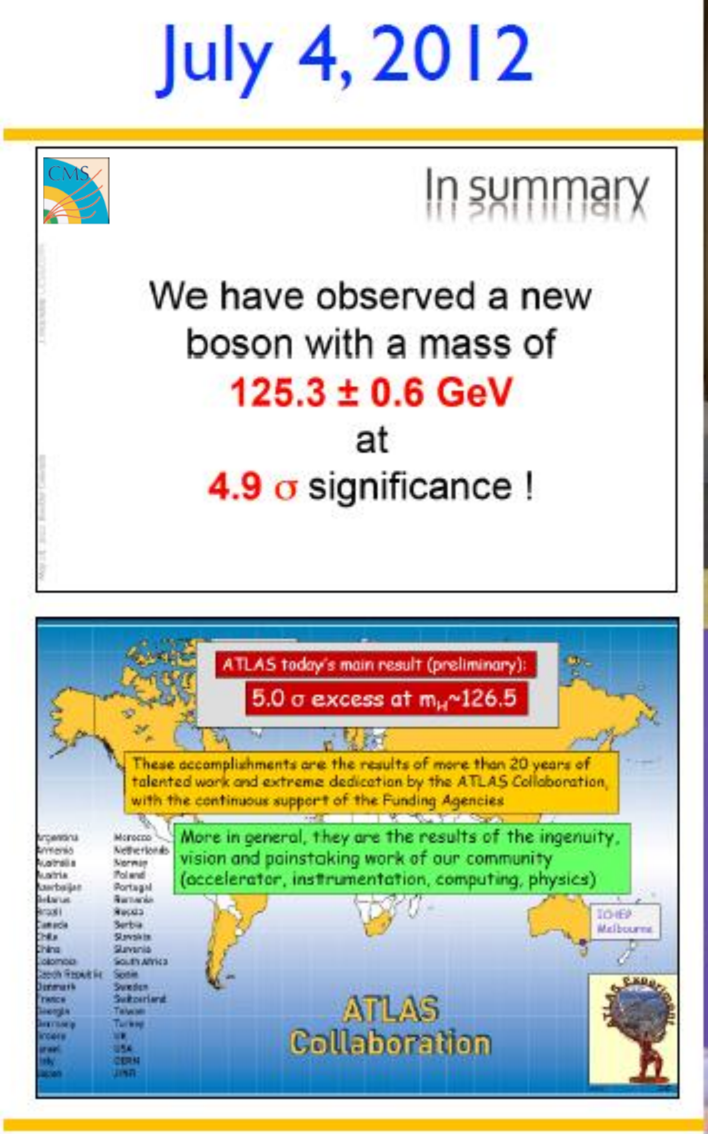
John Dudley
President
European Physical Society

Paris Sphicas
Chairman
High Energy and Particle Physics Division

Stockholm, Sweden, July 2013

Brout-Englert-Higgs received in 1997

a Higgs Story



a Higgs Story

- Higgs boson properties match SM Higgs boson very well
  - "Higgs-like" is now "Higgs" – renamed during Moriond QCD 2013

March

Experimental Summary, Dimitri Denisov (FNAL)

The relative hierarchy of observed $H \to \gamma\gamma$, $H \to ZZ^*$, $H \to WW^*$ couplings is clear enough indication that H **does** break EW symmetry, therefore it is legitimate to call it **a** Higgs boson

Theoretical Summary, Michelangelo Mangano (CERN)

posted March 14, 2013

New results indicate that new particle is a Higgs boson

http://home.web.**cern**.ch/about/updates/2013/03/new-results-indicate-new-particle-higgs-boson

Smells to me of a time threshold for Nobel …

a Higgstory

— Special Colloquium on the 2013 Nobel Prize in Physics

- a Higgs Story

P/F —bridge— CMP

50 yrs !

- *a History of Higgs, or BEH, Mechanism*
  - Prehistory 1
  - Prehistory 2 BCS
  - *Making History: Nambu; Anderson; BE H (GHK)*
  - History Made — Standard Model

- the Hunt towards gg-fusion Search/Discovery

Epilogue — the Squalid-Higgs, etc.

a History of Higgs, or BEH, Mechanism

Our Common Heritage

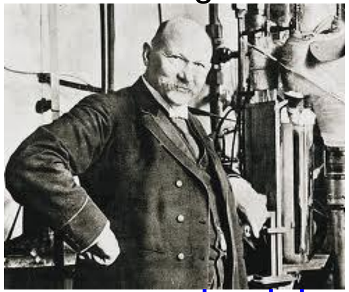
J.J. Thomson

electron

Henri Becqurel

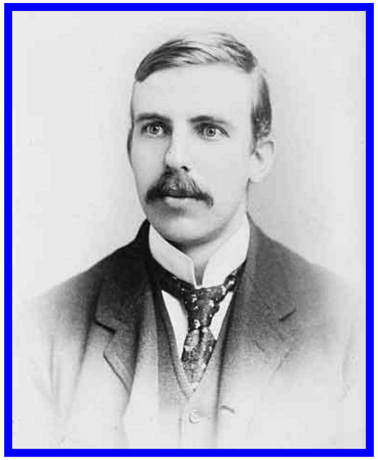
radioactivity

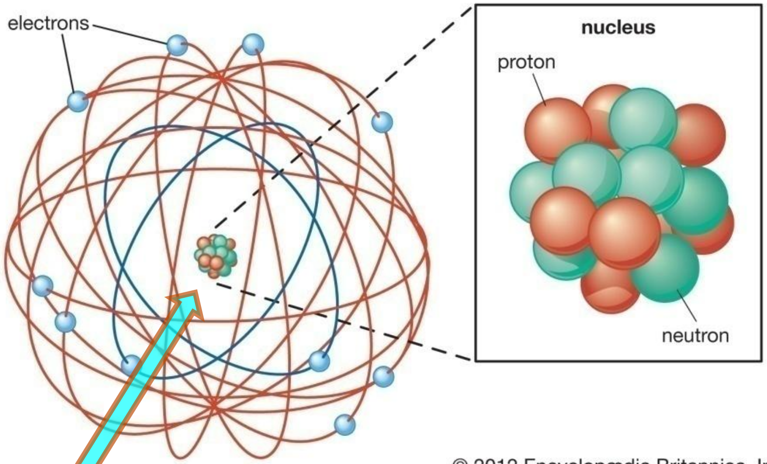
H. Kamerlingh Onnes



superconductivity

Ernest Rutherford





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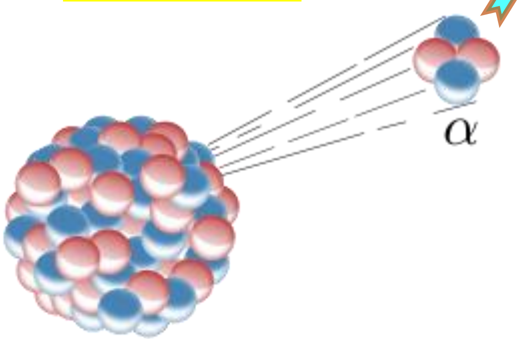
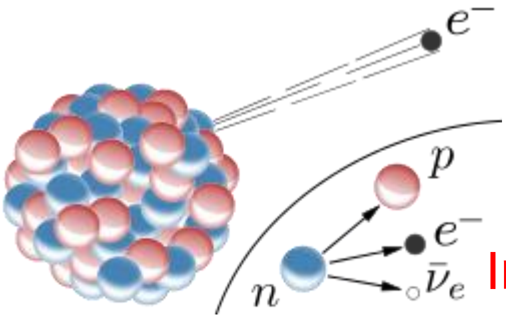
α, β, γ





Weak Interaction

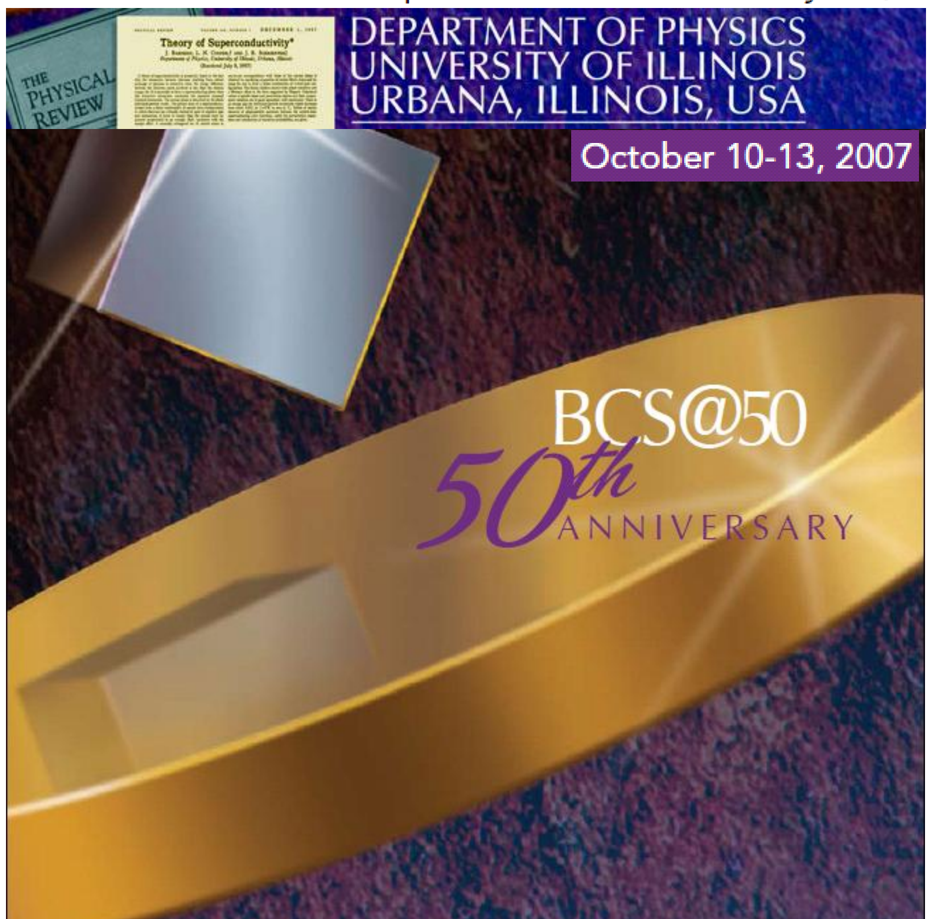
Prehistory 2: 1950 – 1957

"Give it another month, or a month and a half. Wait 'til I get back and keep working. Maybe something'll happen."

With these parting words to Bob Schrieffer, John Bardeen left for Sweden in late November of 1956 to accept the Nobel Prize in Physics, his first,

Theory of Superconductivity*

J. Bardeen, L. N. Cooper,† and J. R. Schrieffer‡
Department of Physics, University of Illinois, Urbana, Illinois
(Received July 8, 1957)



Triumph of Squalid* State Physics !

P/F & CMP have parted ways

* quip due to Gell-Mann

N.B. BCS theory can be put in simpler form as Ginzburg-Landau theory w/ "order parameter" φ ~ Cooper pair

Making History

Nambu

The Nobel Prize in Physics 2008

SSB

CMP —— bridge —— P/F

"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

CP Violation in SM

Photo: Universtity of Chicago

Yoichiro Nambu

1/2 of the prize

USA

Enrico Fermi Institute, University of Chicago Chicago, IL, USA

b. 1921 (in Tokyo, Japan)

Photo: KEK

Makoto Kobayashi

1/4 of the prize

Japan

High Energy Accelerator Research Organization (KEK) Tsukuba, Japan

b. 1944

Photo: Kyoto University

Toshihide Maskawa

1/4 of the prize

Japan

Kyoto Sangyo University; Yukawa Institute for Theoretical Physics (YITP), Kyoto University Kyoto, Japan

b. 1940

naturenews

7 October 2008

The Belle detector in Japan helped to confirm the symmetry breaking effects predicted by theoretical physicists.

KEK

B Factories (BaBar & Belle)

Nambu's background

from Nambu's Nobel Lecture slides

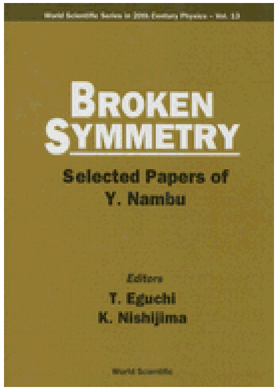
Y. Nambu, preliminary Notes for the Nobel Lecture

I will begin by a short story about my background. I studied physics at the University of Tokyo. I was attracted to particle physics because of the three famous names, Nishina, Tomonaga and Yukawa, who were the founders of particle physics in Japan. But these people were at different institutions than mine. On the other hand, condensed matter physics was pretty good at Tokyo. I got into particle physics only when I came back to Tokyo after the war. In hindsight, though, I must say that my early exposure to condensed matter physics has been quite beneficial to me.

Sc.D., 1952
(age:31)

BCS, Spontaneous Symmetry Breaking, and Gauge Inv.

Autobiography in



One day before publication of the BCS paper, Bob Schrieffer, still a student, came to Chicago to give a seminar on the BCS theory in progress. . . . I was very much disturbed by the fact that their wave function did not conserve electron number. It did not make sense. . . . At the same time I was impressed by their boldness and tried to understand the problem.

Schrieffer joined Chicago faculty for a year

PHYSICAL REVIEW VOLUME 117, NUMBER 3 FEBRUARY 1, 1960

Quasi-Particles and Gauge Invariance in the Theory of Superconductivity*

YOICHIRO NAMBU
The Enrico Fermi Institute for Nuclear Studies and the Department of Physics, The University of Chicago, Chicago, Illinois

(Received July 23, 1959)

it took him two years

The gauge invariance, to the first order in the external electromagnetic field, can be maintained in the quasi-particle picture by taking into account a certain class of corrections to the charge-current operator due to the phonon and Coulomb interaction. In fact, generalized forms of the Ward identity are obtained between certain vertex parts and the self-energy. The Meissner effect calculation is thus rendered strictly gauge invariant, but essentially keeping the BCS result unaltered for transverse fields.

6. THE COLLECTIVE EXCITATIONS

In order to understand the mechanism by which gauge invariance was restored in the calculation of the Meissner effect, and also to solve the integral equations

...

We interpret this as describing a pair of a particle and an antiparticle interacting with each other to form a bound state with zero energy and momentum $q=p'-p=0$.

"zero modes"

ACKNOWLEDGMENT

We wish to thank Dr. R. Schrieffer for extremely helpful discussions throughout the entire course of the

Nambu-Goldstone Boson and Higgs Mechanism

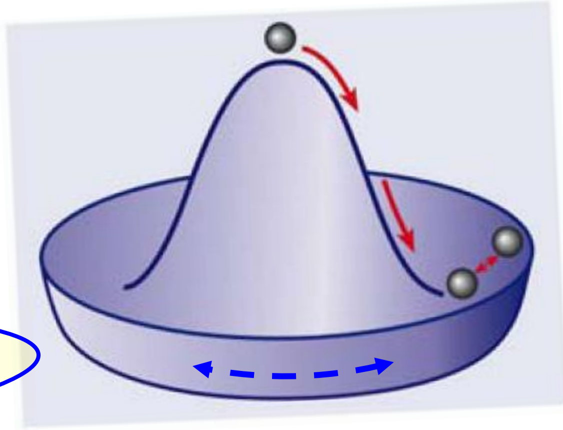
From Yukawa's Pion to Spontaneous Symmetry Breaking

Y. Nambu, J. Phys. Soc. Japan **76**, 111002 (2007)

The BCS theory assumed a condensate of charged pairs of electrons or holes, hence the medium was not gauge invariant. There were found intrinsically massless collective excitations of pairs (Nambu-Goldstone modes) that restored broken symmetries, and they turned into the plasmons by mixing with the Coulomb field.

Meissner Effect

~ Higgs Mechanism



A Mexican hat illustrates the Goldstone theorem. Though the hat is invariant under rotations about a vertical axis, a small ball will come to rest off the axis of symmetry, somewhere on the brim of the hat, but it can move freely with no restoring force around the brim. Broken approximate symmetry is illustrated by slightly tilting the hat; this produces a small restoring force, analogous to the small mass of the pion.

NR — Anderson (1958; 1963)

Englert & Brout (1964)
Higgs (1964; 1966)
} Wolf Prize 2004

[Guralnik, Hagen, Kibble (1964)]

Ginzburg & Landau (1950)

Nambu uses the term Ginzburg-Landau-Higgs "effective" field

Nambu (1960); NJL (1961)
Goldstone (1961);
Goldstone, Salam & Weinberg (1962)

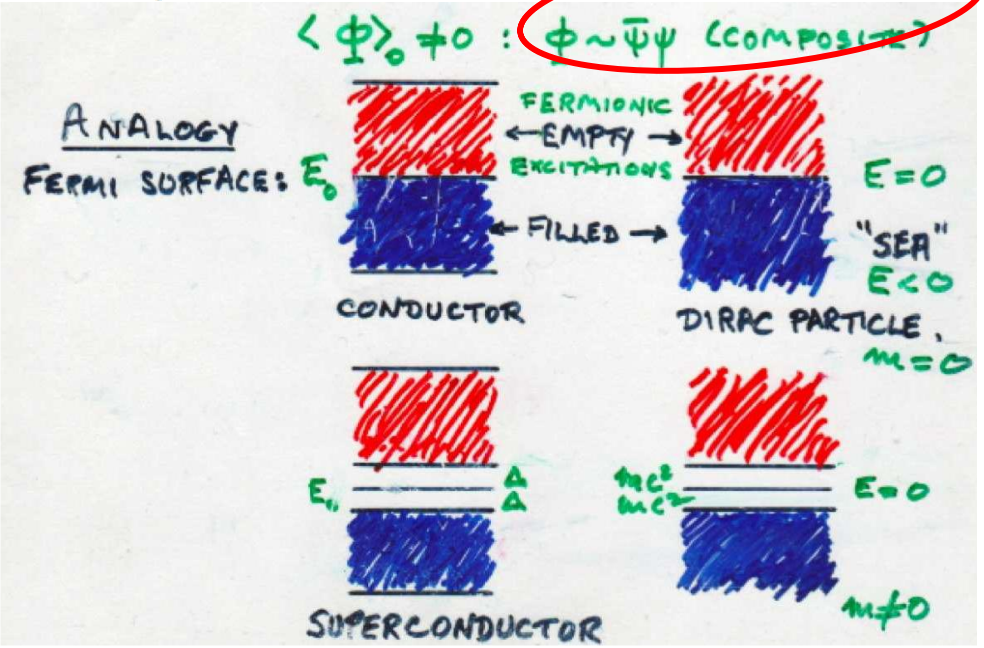
Nambu's comment

Y. Nambu, preliminary Notes for the Nobel Lecture

In hindsight I regret that I should have explored in more detail the general mechanism of mass generation for the gauge field. But I thought the plasma and the Meissner effect had already established it. I also should have paid more attention to the Ginzburg-Landau theory which was a forerunner of the present Higgs description.

N.B. Nambu pierced thru the clouds and saw how proton mass arose.

hand-drawn by Higgs to illustrate Nambu's model



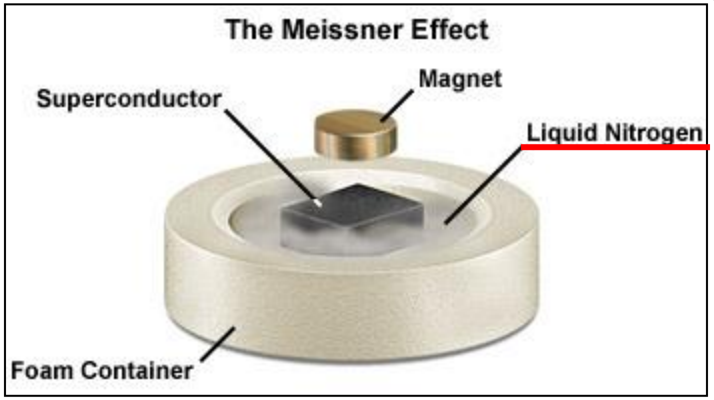
But Brout and Englert (curiously not Higgs), give clear reference that their interest started with Nambu 1960 !

For BCS, $\phi \sim \psi_e \psi_e$

$\langle\phi\rangle \neq 0$, or condensate, is SSB

What is Meissner Effect ?

Walther Meissner
(1882-1974)



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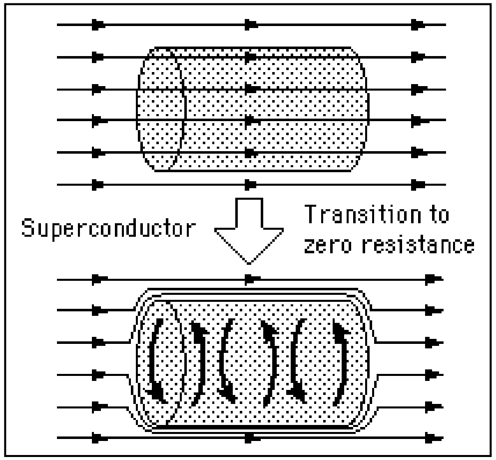
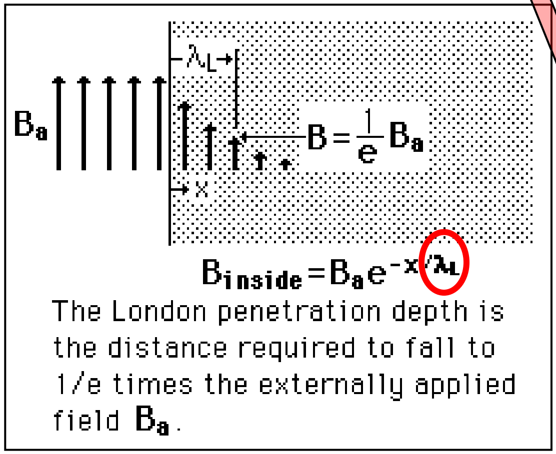


Absence of B in SC



Attentuation, or
penetration depth

Magnetic Field damped

Photon acquires "Mass"

Higgs Mechanism !

1928 - 2011

Born American, on Cornell faculty since 1953 with field in statistical physics and phase transitions. Englert was his postdoc at Cornell, 1959-1961, but when Englert returned to Brussels in 1961, Brout resigned from Cornell and moved to Brussels, becoming Belgian citizen eventually. [the 9/2008 LHC accident/delay really costed him]

Higgs and Brout knew each other. According to Higgs, Brout recalls that in 1960 at a Cornell seminar Victor Weisskopf remarked that "*Particle physicists are so desperate these days that they have to borrow from the new things coming up in many-body theory like BCS. Perhaps something will come of it.*"

In reading Nambu's 1960 papers, Jeffrey Goldstone published a paper on field theories with superconductor solutions. He introduced elementary scalar fields and the Mexican hat (Higgs prefers calling it "wine bottle"; me too !) potential

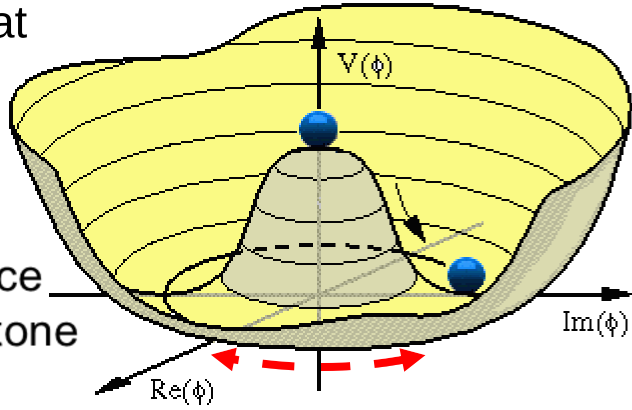
:

$$V(\varphi) \sim -\mu^2|\varphi|^2 + \lambda|\varphi|^4$$

One can easily visualize spontaneous symmetry breaking, because the lowest-energy state (note minus sign) of the system is down in the trough of the wine bottle, not at the symmetry point. The minimum is at

:

$$|\varphi|^2 = \upsilon^2 \sim \mu^2/\lambda$$



Shifting fields, one can do the math, which we refrain from.

One sees that for the "phase" direction, there is no resistance or inertia, hence a "massless" excitation, the Nambu-Goldstone boson.

Goldstone Theorem: In Lorentz invariant theory, SSB necessitates massless particles w.r.t. the broken symmetries.

Goldstone, Salam and Weinberg (1962)

Problem: No such massless states observed !

comment by Higgs

Anderson (1963), and an influential work of Schwinger

PHYSICAL REVIEW VOLUME 125, NUMBER 1 JANUARY 1, 1962

Gauge Invariance and Mass

JULIAN SCHWINGER
Harvard University, Cambridge, Massachusetts, and University of California, Los Angeles, California
(Received July 20, 1961)

It is argued that the gauge invariance of a vector field does not necessarily imply zero mass for an associated particle if the current vector coupling is sufficiently strong. This situation may permit a deeper understanding of nucleonic charge conservation as a manifestation of a gauge invariance, without the obvious conflict with experience that a massless particle entails.

PHYSICAL REVIEW VOLUME 130, NUMBER 1 1 APRIL 1963

Plasmons, Gauge Invariance, and Mass

P. W. ANDERSON
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received 8 November 1962)

Schwinger has pointed out that the Yang-Mills vector boson implied by associating a generalized gauge transformation with a conservation law (of baryonic charge, for instance) does not necessarily have zero mass, if a certain criterion on the vacuum fluctuations of the generalized current is satisfied. We show that the theory of plasma oscillations is a simple nonrelativistic ... exhibiting all of the features of Schwinger's idea. It is also shown that Schwinger's criterion tha... implies that the matter spectrum before including the Yang-Mills interaction co... ductivity illustrates that the physical spectrum need not... ideas and the zero-mass difficulty in theories with broken...

It is likely, then, considering the superconducting analog, that the way is now open for a degenerate-vacuum theory of the Nambu type[9] without any difficulties involving either zero-mass Yang-Mills gauge bosons or zero-mass Goldstone bosons. These two types of bosons seem capable of "canceling each other out" and leaving finite mass bosons only. It is not at

Conjecture from NR

Digression on Yang-Mills: Non-Abelian Gauge Theory

PHYSICAL REVIEW VOLUME 96, NUMBER 1 OCTOBER 1, 1954

Conservation of Isotopic Spin and Isotopic Gauge Invariance*

C. N. YANG † AND R. L. MILLS
Brookhaven National Laboratory, Upton, New York
(Received June 28, 1954)

It is pointed out that the usual principle of invariance under isotopic spin rotation is not consistant with the concept of localized fields. The possibility is explored of having invariance under local isotopic spin rotations. This leads to formulating a principle of isotopic gauge invariance and the existence of a **b** field which has the same relation to the isotopic spin that the electromagnetic field has to the electric charge. The **b** field satisfies nonlinear differential equations. The quanta of the **b** field are particles with spin unity, isotopic spin unity, and electric charge $\pm e$ or zero.

motivated by strong interaction

Abelian g.i., i.e. U(1)

$$F_{\mu\nu} = \frac{\partial}{\partial x^\mu} A_\nu - \frac{\partial}{\partial x^\nu} A_\mu$$

Non-Abelian g.i., e.g. SU(2)

$$F^a{}_{\mu\nu} = \frac{\partial}{\partial x^\mu} A^a{}_\nu - \frac{\partial}{\partial x^\nu} A^a{}_\mu + g f^{abc} A^b{}_\mu A^c{}_\nu$$

$$L = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + \bar{\psi}^i \left(i \gamma^\mu D^{ij}{}_\mu - m\right)\psi^j$$

covariant derivative $D^{ij}{}_\mu = \partial_\mu \delta^{ij} + ig\, C^{ij}_a A^a_\mu$

Problem: No massless “isotopic photon” observed !

Anderson Conjecture: “Cancel” YM against Goldstone?

Pauli & Yang

Spat of Ben Lee and Walter Gilbert [Chemistry Nobel 1980]

SC has preferred frame
… so, R ?

VOLUME 12, NUMBER 10 PHYSICAL REVIEW LETTERS 9 MARCH 1964

DOES SPONTANEOUS BREAKDOWN OF SYMMETRY IMPLY ZERO-MASS PARTICLES?*

Abraham Klein and Benjamin W. Lee†
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania
(Received 8 January 1964)

There is relatively intense interest at present in exploring more deeply and widely the suggestion[1] that the mathematical methods essential to the understanding of material media which exhibit long-range order (ferromagnets, superconductors, etc.) may also be basic or useful for the theory of elementary particles. The original work had two connected aspects: the generation of fermion masses (by extension of the underlying group, mass differences) by the "spontaneous breakdown of symmetry," and the consequent occurrence of collective boson excitations.

It is well known, however, that the theorem cannot obtain if one removes the requirement of Lorentz invariance. For in this case there is the example of the theory of superconductivity, where the presence of the long-range Coulomb interaction results in a collective boson excitation of finite rest mass – the plasmon. Anderson[7] has conjectured that one should be able to construct the relativistic analog of the plasmon phenomenon. Baker, Johnson, and Lee[8] have presented arguments that a new version of quantum electrodynamics due to Johnson, Baker, and Willey,[9] which

preferred frame
not possible for R !

VOLUME 12, NUMBER 25 PHYSICAL REVIEW LETTERS 22 JUNE 1964

BROKEN SYMMETRIES AND MASSLESS PARTICLES*

Walter Gilbert
Jefferson Laboratory of Physics, Harvard University, Cambridge, Massachusetts
(Received 30 March 1964)

In a recent note Klein and Lee[1] have discussed the Goldstone theorem[2,3]: that any solution of a Lorentz-invariant theory that violates an internal symmetry operation of that theory will contain a massless scalar particle. They showed that this theorem does not necessarily apply in nonrelativistic theories and they implied that their work cast doubt upon the original theorem. In this they were mistaken. The theorem fails, trivially, in the nonrelativistic case for reasons which cannot affect the relativistic version.

Assoc. Prof. of Biophys.

Prof. of Biochem. 1968

VOLUME 13, NUMBER 9 PHYSICAL REVIEW LETTERS 31 AUGUST 1964

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)

Schwinger

YM? conclusion unchanged

It is of interest to inquire whether gauge vector mesons acquire mass through interaction[1]; by a gauge vector meson we mean a Yang-Mills field[2] associated with the extension of a Lie group from global to local symmetry. The importance of this problem resides in the possibility that strong-interaction physics originates from massive gauge fields related to a system of conserved currents.[3] In this note, we shall show that in certain cases vector mesons do indeed acquire mass when the vacuum is degenerate with respect to a compact Lie group.

Theories with degenerate vacuum (broken symmetry) have been the subject of intensive study since their inception by Nambu.[4-6] A characteristic feature of such theories is the possible existence of zero-mass bosons which tend to restore the symmetry.[7,8] We shall show that it is precisely these singularities which maintain the gauge invariance of the theory, despite the fact that the vector meson acquires mass.

φ_2 Goldstone

scalar electrodynamics, $\varphi = \frac{1}{\sqrt{2}}(\varphi_1 + i\,\varphi_2)$

$$H_{int} = ie\,A_\mu\,\varphi^* \overleftrightarrow{\partial^\mu}\,\varphi - e^2\,\varphi^*\varphi\,A_\mu\,A^\mu$$

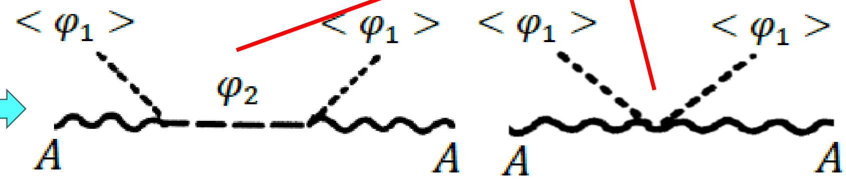
$$<\varphi> = <\varphi^*> = <\varphi_1>/\sqrt{2}$$

$$H_{int}' = -e\,\frac{<\varphi_1>}{\sqrt{2}}\,A_\mu\,\partial^\mu\,\varphi_2 - \frac{e^2}{2}<\varphi_1>^2 A_\mu\,A^\mu$$

gauge invariant self-energy: $q_\mu \Pi_{\mu\nu}(q) = 0$

$$\Pi_{\mu\nu}(q) = (2\pi)^4\, ie^2 <\varphi_1>^2 \left[g_{\mu\nu} - \frac{q_\mu\, q_\nu}{q^2}\right]$$

g.i. vector mass



Volume 12, number 2 PHYSICS LETTERS 15 September 1964

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

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

Received 27 July 1964

sent 7/24 Fri (PL office @ CERN)

1.1 page, refute Gilbert: "gauge fixing" (e.g. Coulomb gauge) gives "special frame"

[no cite of Nambu, nor Anderson/Schwinger]

In a subsequent note it will be shown, by considering some classical field theories which display broken symmetries, that the introduction of gauge fields may be expected to produce qualitative changes in the nature of the particles described by such theories after quantization.

sent 7/31 Fri

< 1.5 page

In a recent note[1] it was shown that the Goldstone theorem,[2] that Lorentz-covariant field theories in which spontaneous breakdown of symmetry under an internal Lie group occurs contain zero-mass particles, fails if and only if the conserved currents associated with the internal group are coupled to gauge fields. The purpose of the present note is to report that, as a consequence of this coupling, the spin-one quanta of some of the gauge fields acquire mass; the longitudinal degrees of freedom of these particles (which would be absent if their mass were zero) go over into the Goldstone bosons when the coupling tends to zero. This phenomenon is just the relativistic analog of the plasmon phenomenon to which Anderson[3] has drawn attention: that the scalar zero-mass excitations of a superconducting neutral Fermi gas become longitudinal plasmon modes of finite mass when the gas is charged.

The simplest theory which exhibits this behavior is a gauge-invariant version of a model used by Goldstone[2] himself: Two real[4] scalar fields φ_1, φ_2 and a real vector field A_μ interact . . .

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland

(Received 31 August 1964)

Scalar electrodynamics (gauging Goldstone's complex scalar field), same as Englert & Brout, except $<\varphi_2> = \varphi_0$, so φ_1 is the Goldstone.

Making small oscillations $\Delta\varphi_1, \Delta\varphi_2$ around the minimum $<\varphi_2> = \varphi_0$ and absorbing $\Delta\varphi_1$ by a gauge transform, one gets

$$B_\mu = A_\mu - (e\varphi_0)^{-1}\partial_\mu \Delta\varphi_1, \quad G_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu,$$

with

$$\partial_\nu G^{\mu\nu} + (e\varphi_0)^2 B^\mu = 0, \qquad \partial_\mu B^\mu = 0,$$

which is equation for massive vector field. For remaining scalar, he finds

$$[\partial_\mu \partial^\mu - 4\varphi_0{}^2 V''(\varphi_0{}^2)]\, \Delta\varphi_2 = 0,$$

with mass squared $4\varphi_0{}^2 V''(\varphi_0{}^2)$. Only Higgs gave this, hence the name "Higgs boson".

sumably related to the weak interactions) is introduced in order to break Y conservation, one of these gauge fields will acquire mass, leaving the photon as the only massless vector particle. A detailed discussion of these questions will be presented elsewhere.

It is worth noting that an essential feature of the type of theory which has been described in this note is the prediction of incomplete multiplets of scalar and vector bosons.[8] It is to be

[4]In the present note the model is discussed mainly in classical terms; nothing is proved about the quantized theory. It should be understood, therefore, that the conclusions which are presented concerning the masses of particles are conjectures based on the quantization of linearized classical field equations. However, essentially the same conclusions have been reached independently by F. Englert and R. Brout, Phys. Rev. Letters 13, 321 (1964): These authors discuss the same model quantum mechanically in lowest order perturbation theory about the self-consistent vacuum.

brought to Higgs's attention by referee: Nambu; but paper still did not cite Nambu.

Both Englert & Brout (with Thiry), and Higgs published further work in 1966 …

"Footnotes" to History

SOVIET PHYSICS JETP VOLUME 24, NUMBER 1 JANUARY, 1967

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

A. A. MIGDAL and A. M. POLYAKOV ← neither yet turned 19!

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

J. Exptl. Theoret. Physics (U.S.S.R.) **51**, 135–146 (July, 1966) originally written early 1964

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 operators $M_a(p) - M_b(p)$ of particles a and b belonging to a supermultiplet an equation which is identical to the Bethe-Salpeter equation for the wave function of a scalar bound state of vanishing mass (a "zeron") in the annihilation channel $\bar{a}b$ of the corresponding particles. It is shown that if symmetry is spontaneously violated in a Yang–Mills type theory involving vector mesons, the zerons interact only with virtual particles and therefore unobservable. On the other hand, the vector mesons acquire a mass in spite of the generalized gauge invariance. It is shown in Appendices A and B that the asymmetrical solution corresponds to a minimal energy of the vacuum and that C-invariance of the solution implies strangeness conservation for it.

VOLUME 13, NUMBER 20 PHYSICAL REVIEW LETTERS 16 NOVEMBER 1964

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

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Department of Physics, Imperial College, London, England
(Received 12 October 1964)

In all of the fairly numerous attempts to date to formulate a consistent field theory possessing a broken symmetry, Goldstone's remarkable theorem[1] has played an important role. This theorem, briefly stated, asserts that if there exists a conserved operator Q_i such that

troduction of vector gauge fields and the consequent breakdown of manifest covariance.[3] This, of course, represents a departure from the assumptions of the theorem, and a limitation on its applicability which in no way reflects on the general validity of the proof.

History Made

Standard Model dynamics*

$SU_C(3) \times SU(2) \times U(1)$

$SU(2)xU(1) \xrightarrow{SSB} U_Q(1)$

Glashow (1961) Weinberg (1967)
Salam (1968)

Deeply Inelastic Scattering expt

Friedman, Kendall, Taylor (1969)
Bjorken scaling, Feynman Parton

Breakthru: SB NAGT renormalizable

't Hooft (1971); 't Hooft & Veltman (1972)

Asymptotic Freedom ...

Gross & Wilczek (1973), Politzer (1973)

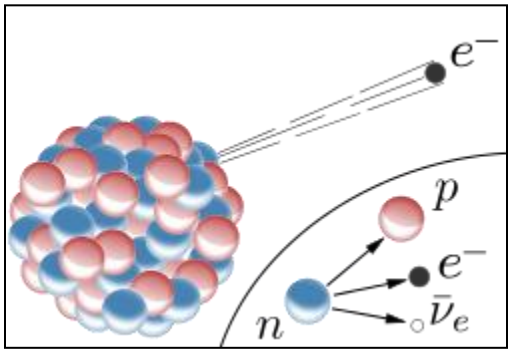
$SU_C(3)$ [Fritzsch & Gell-Mann (1972)]

- 1979: Electroweak Theory
- 1984: W, Z boson — Rubbia & van der Meer
- 1990: D.I.S. (quark-parton)
- 1999: Electroweak Renorm.
- 2004: Asymptotic Freedom
- 2008: SSB & Broken CP — N & Kobayashi/Maskawa
- 2013: Higgs Mech./Particle — Englert & Higgs

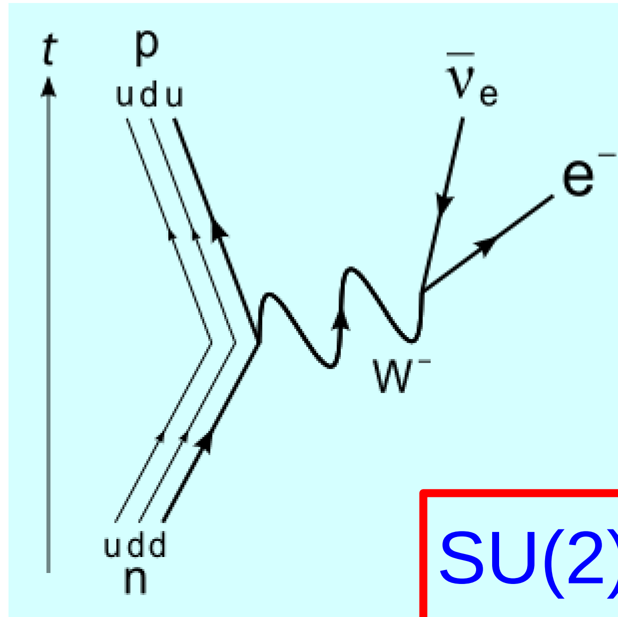
* Leave out matter fields

β Decay, Weak Interaction, W & Z Weak Bosons

Rutherford



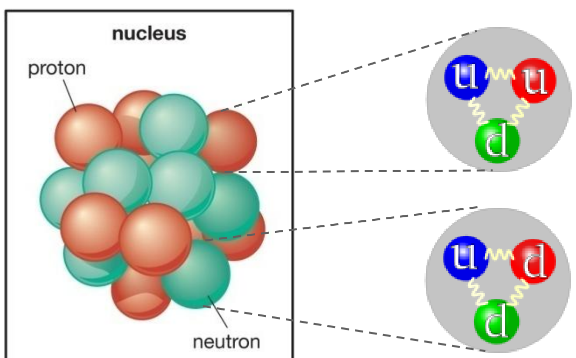
Fermi

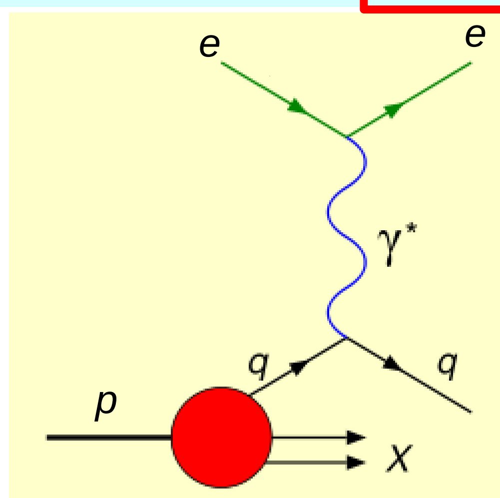


$M_W \simeq 80.4\ \mathrm{GeV}/c^2$

$M_Z \simeq 91.2\ \mathrm{GeV}/c^2$

$SU(2)xU(1) \xrightarrow[\text{BEH}]{\text{SSB}} U_Q(1)$





Deeply Inelastic Scattering

$M_\gamma \simeq 0$

the Hunt towards gg-fusion Search/Discovery

Ellis, Gaillard and Nanopoulos (1976):

“We should perhaps finish with an apology and a caution. We apologize to experimentalists for not having any idea what is the mass of the Higgs boson, unlike the case with charm, 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.”

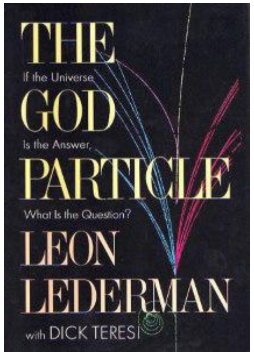
1983: W, Z bosons discovered at CERN ➽ 1984 Nobel to Rubbia & van der Meer

⮡ SSC approved

Dawson, Gunion, Haber and Kane(1990), *the Higgs-Hunters Guide*:

“The success of the Standard Model has been astonishing.

The central problem in particle physics today is to understand the Higgs sector.”

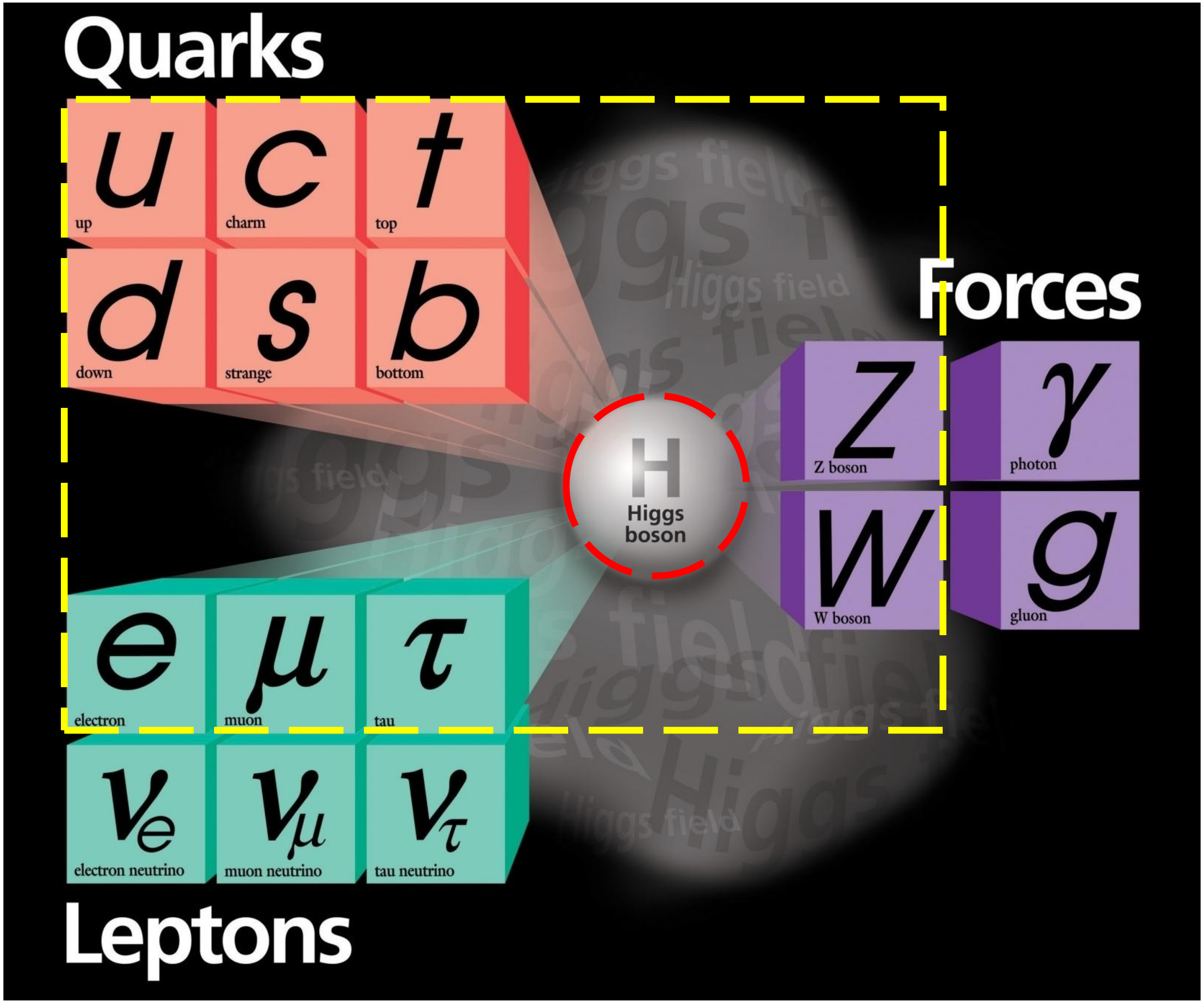


The God Particle: If the Universe Is the Answer, What Is the Question?

Lederman (1993)

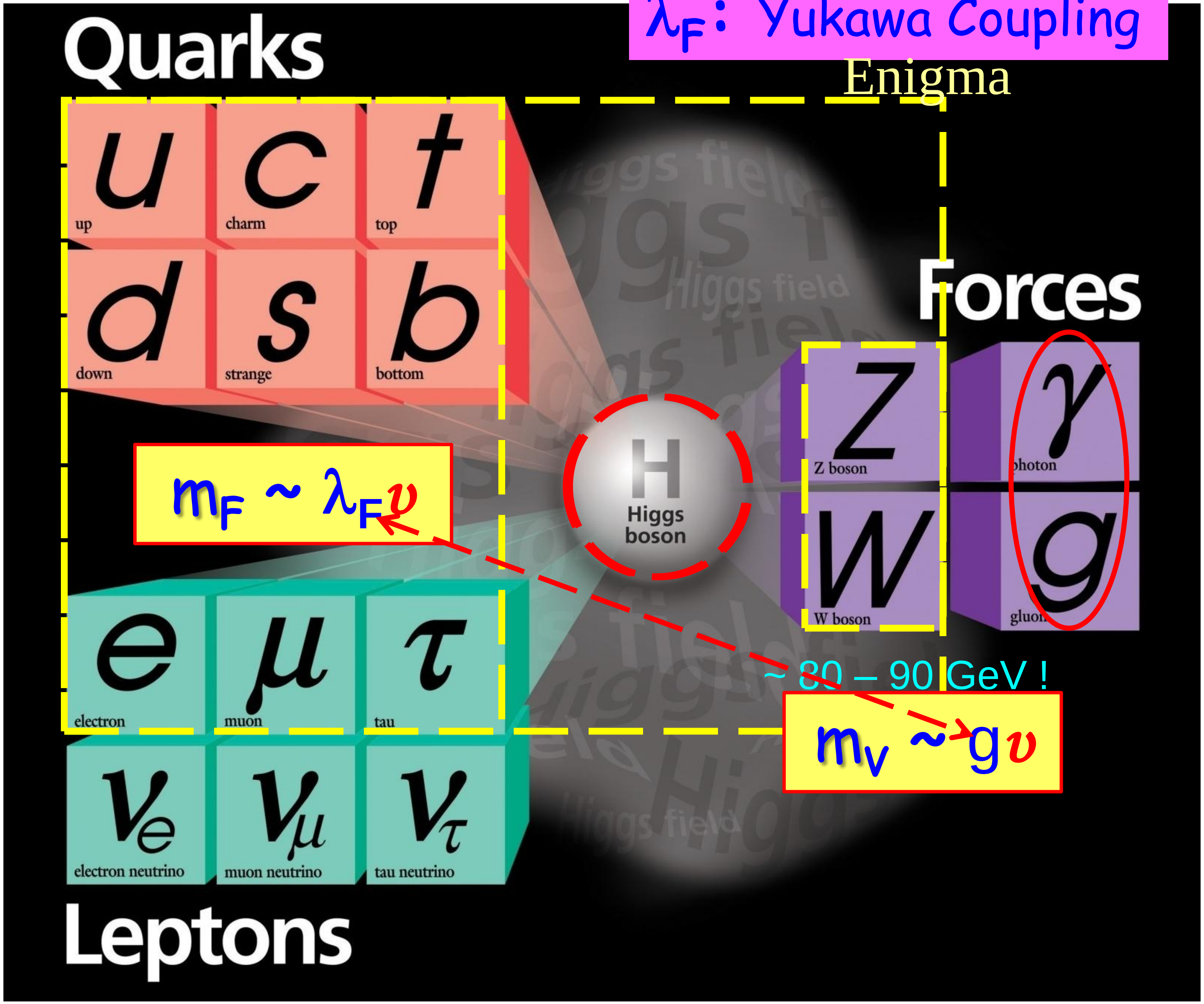
SSC canceled later 1993 … LHC approved 1994

The “God” Particle: the Origin of Mass



The "God" Particle: the Origin of Mass

λ_F: Yukawa Coupling

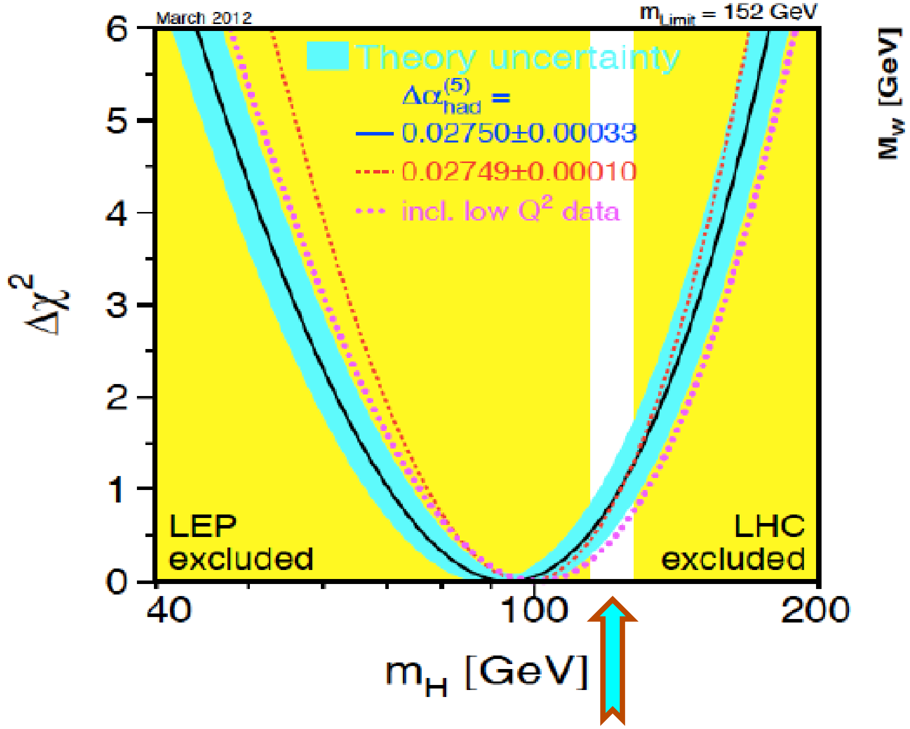


unbroken
massless

g
gauge coupling

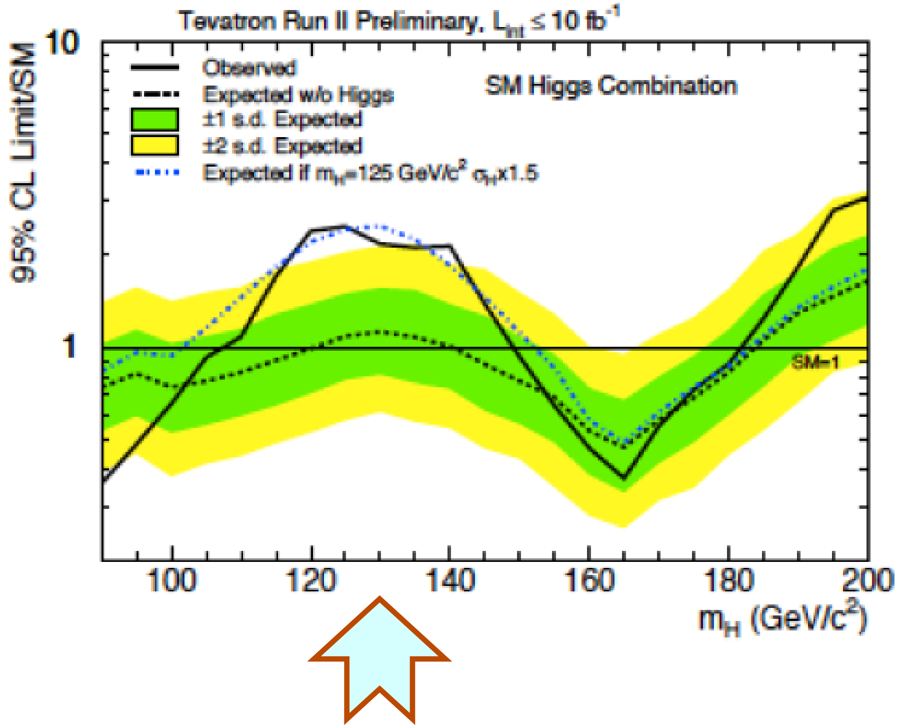
"Blueband" plot

(electroweak precision data)



Tevatron swan song

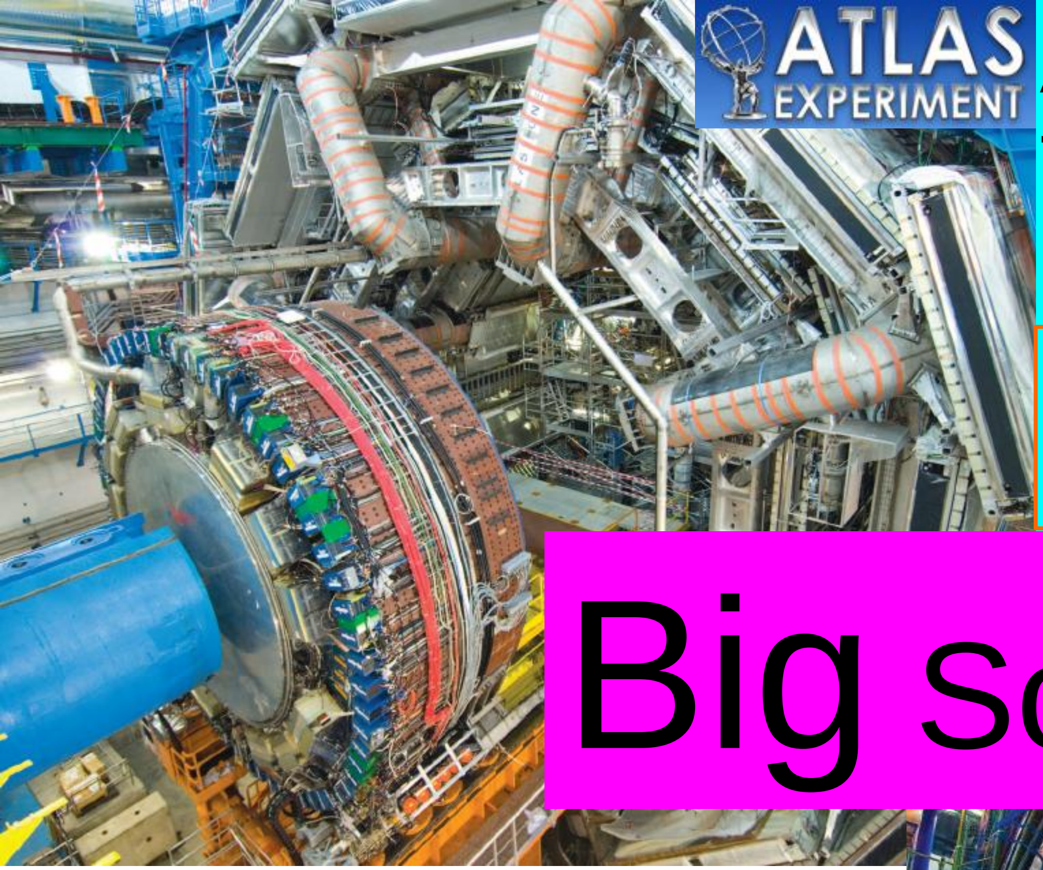
(Higgs direct search)



Holy  Grail !!

TIME
&
Science

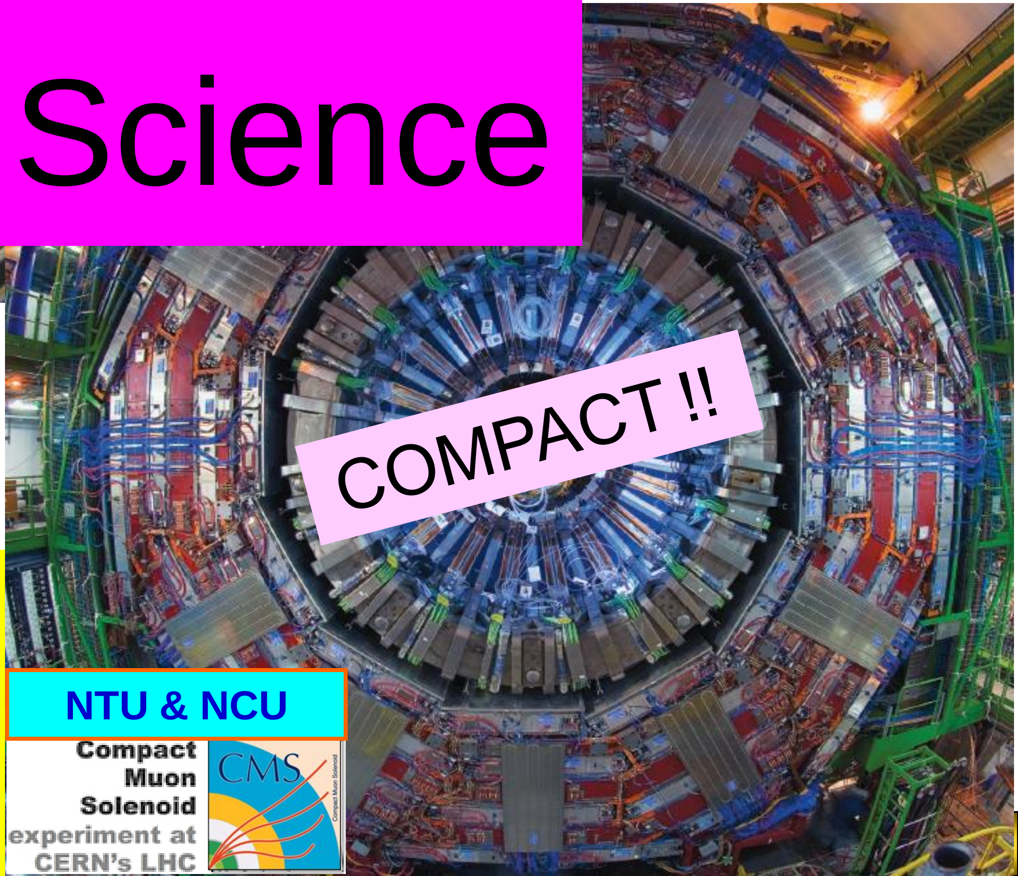
Triumphal at CERN, July 4th, 2012
[5 former CERN DGs]



A T L A S

Toroidal
LHC
Apparatu**S**

Big Science



COMPACT !!

Compact
Muon
Solenoid

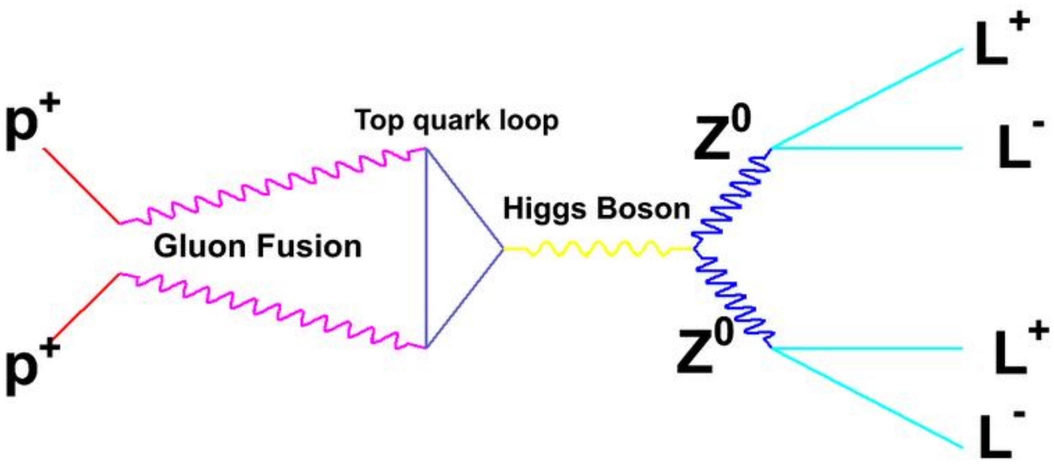
C M S

NTU & NCU

Compact Muon Solenoid experiment at CERN's LHC

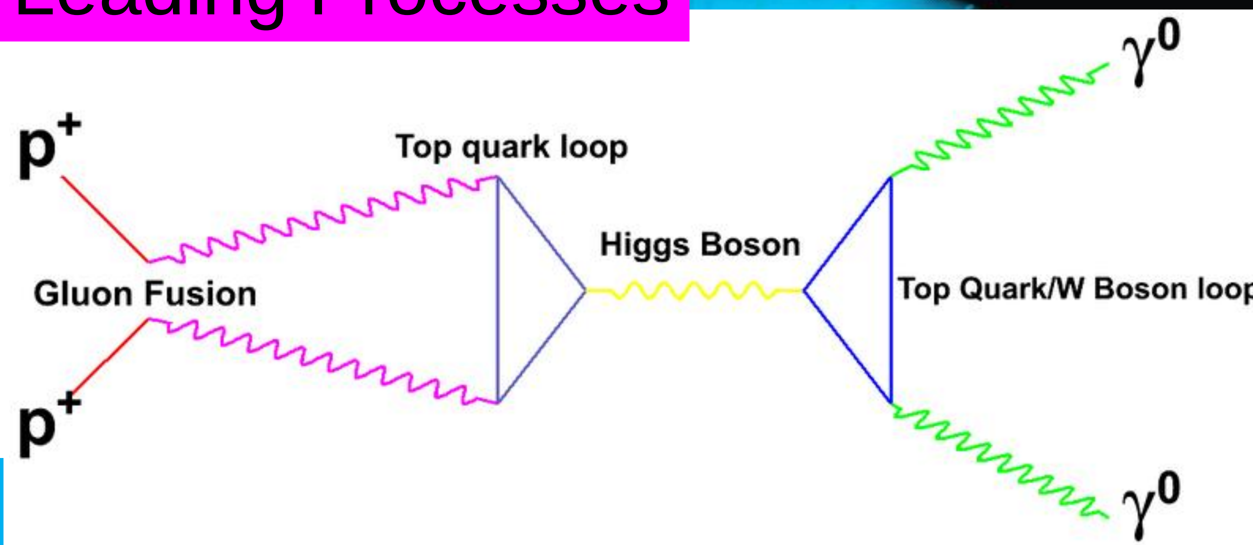
Production & Decay: Complex Processes

$H \rightarrow ZZ^* \rightarrow ee\mu\mu$



vents

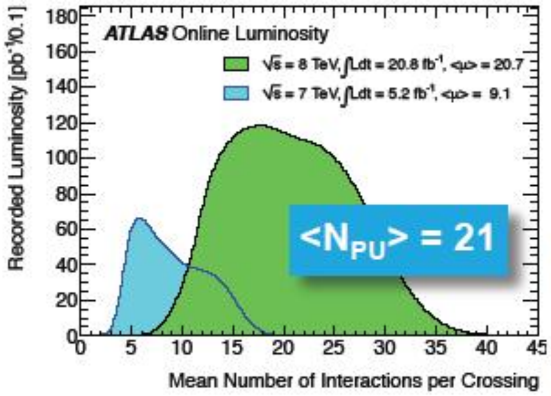
Leading Processes

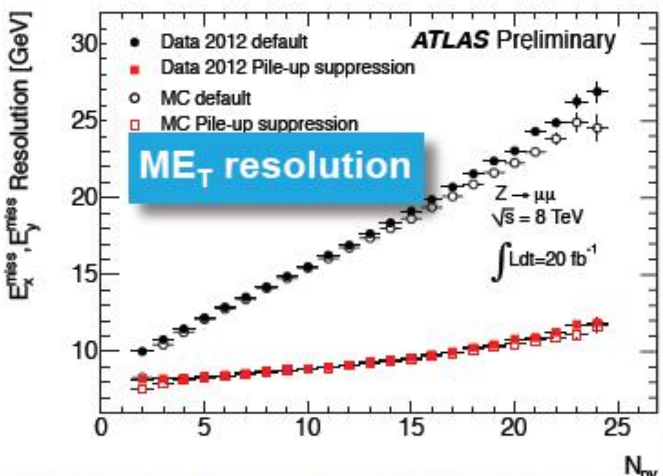


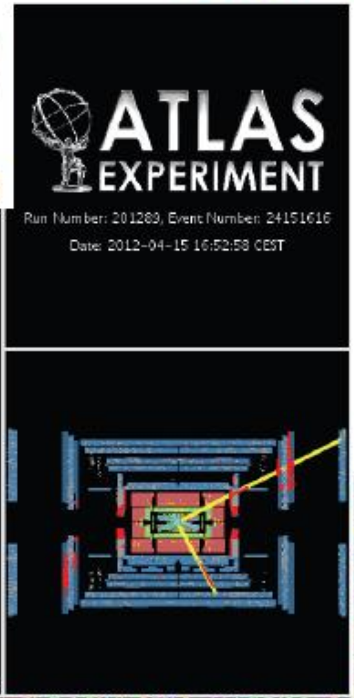
$H \rightarrow \gamma\gamma$

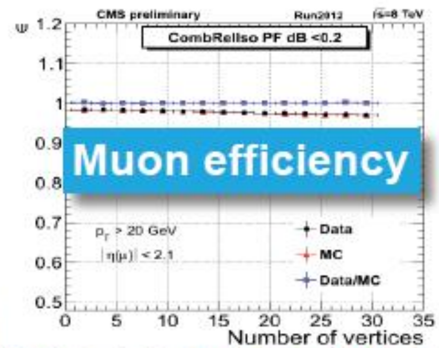
Against Horrendous Background

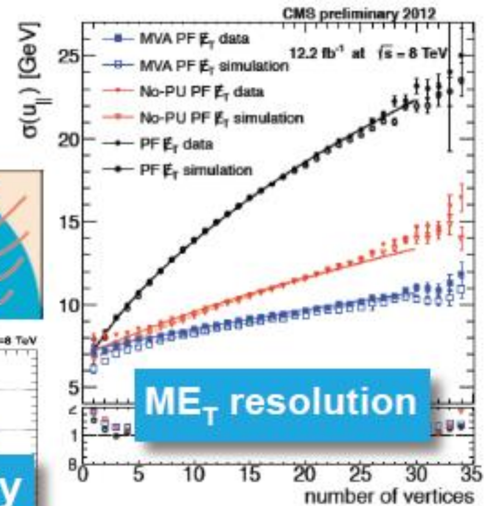
LHC already reached nominal pileup rate; experiments cope well!

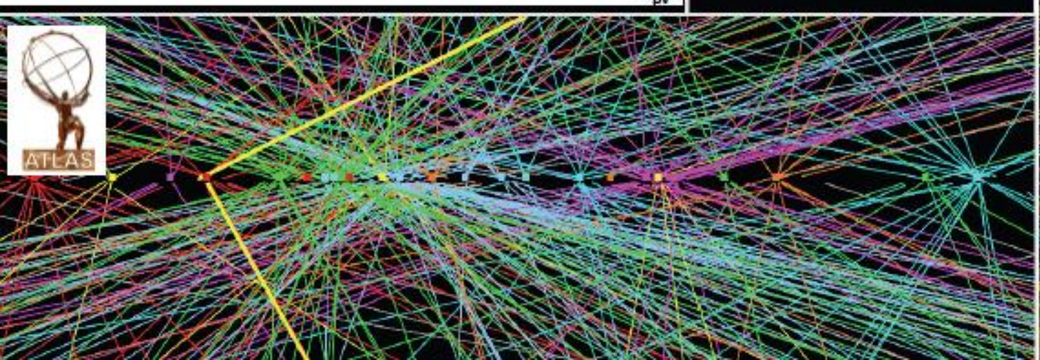




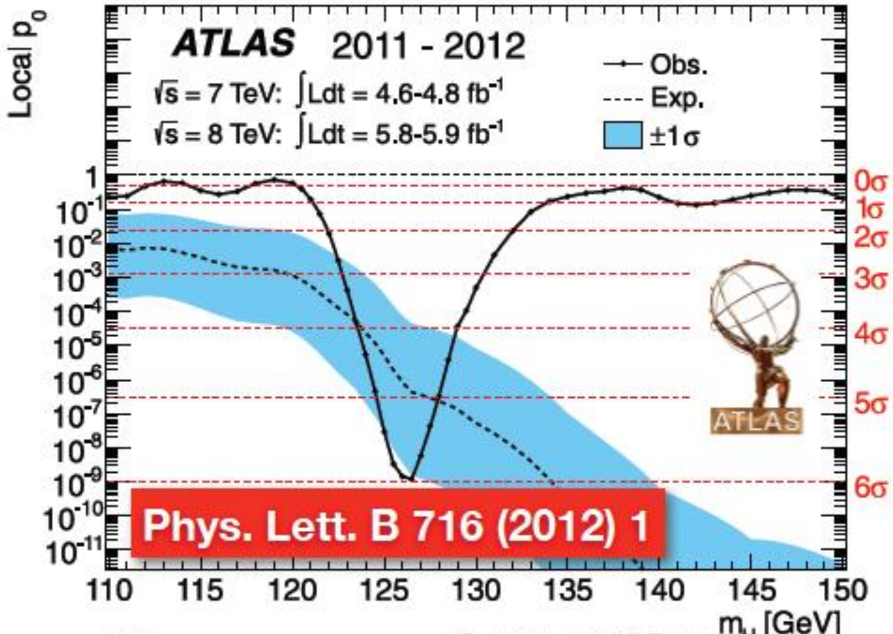


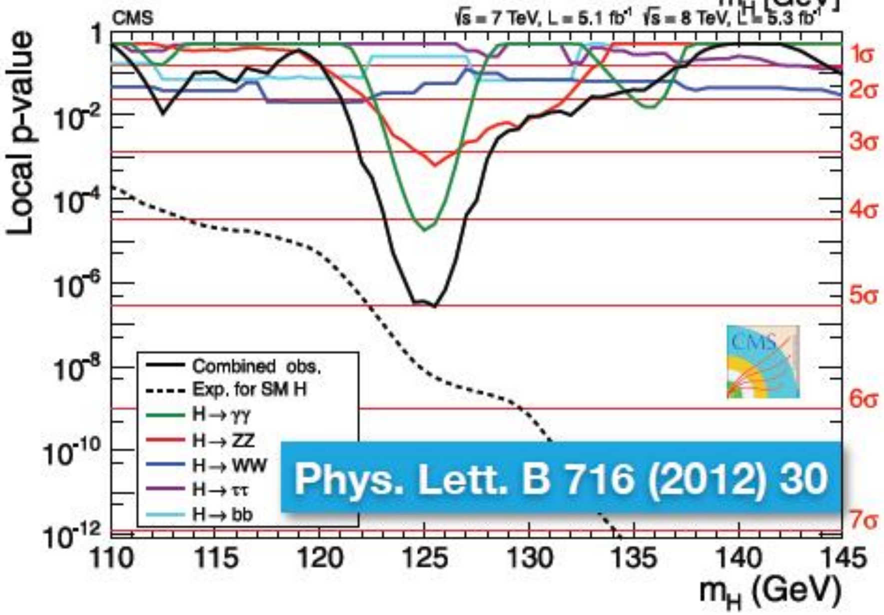


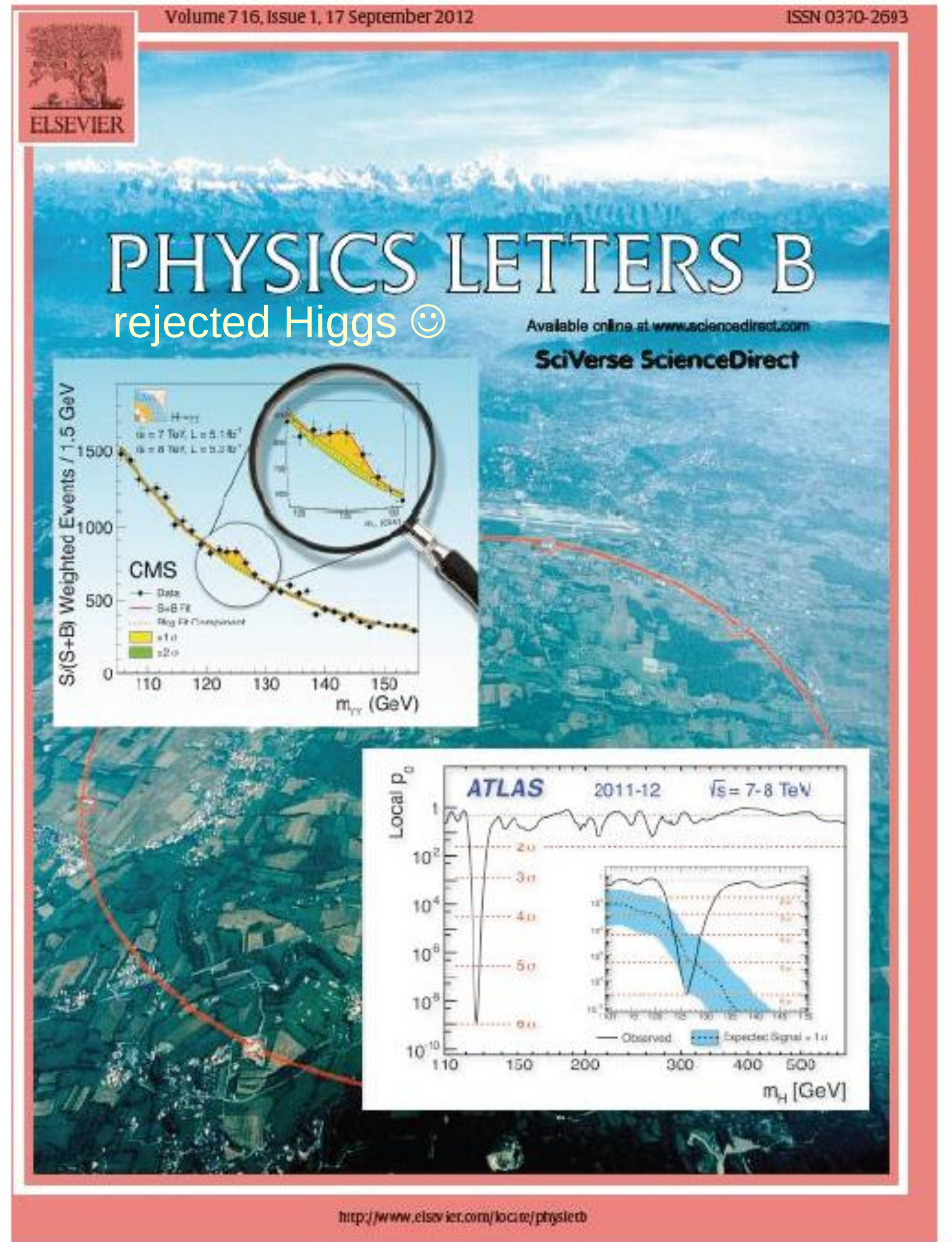




Making Particular History

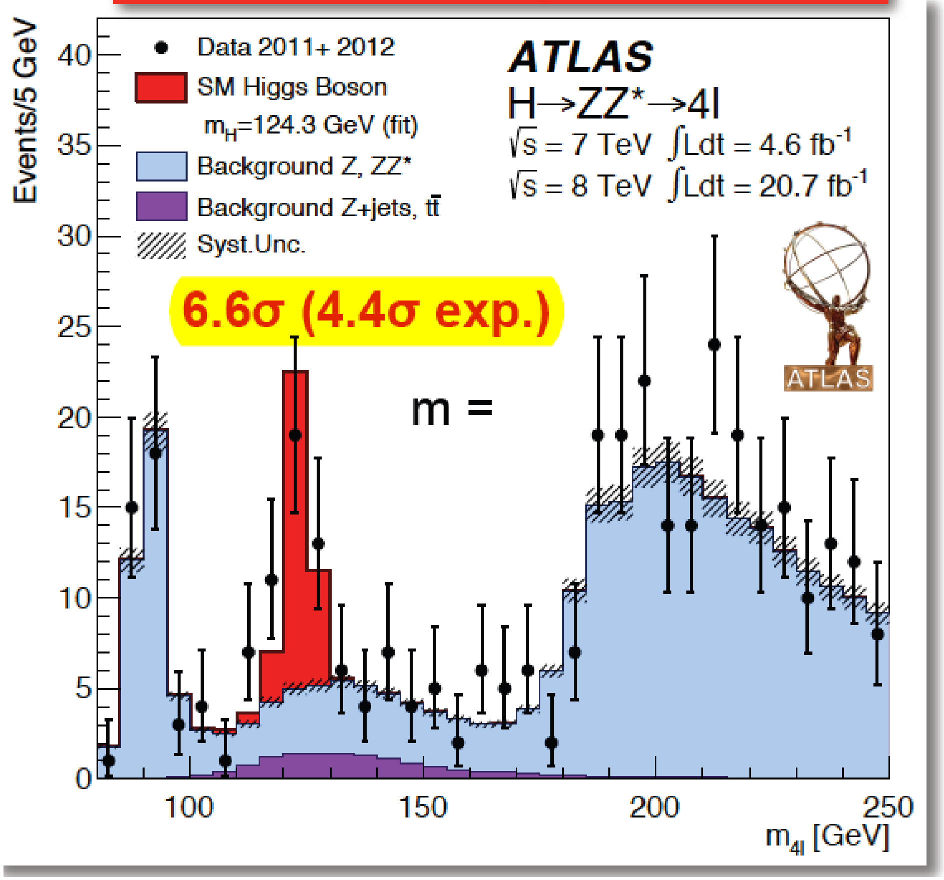




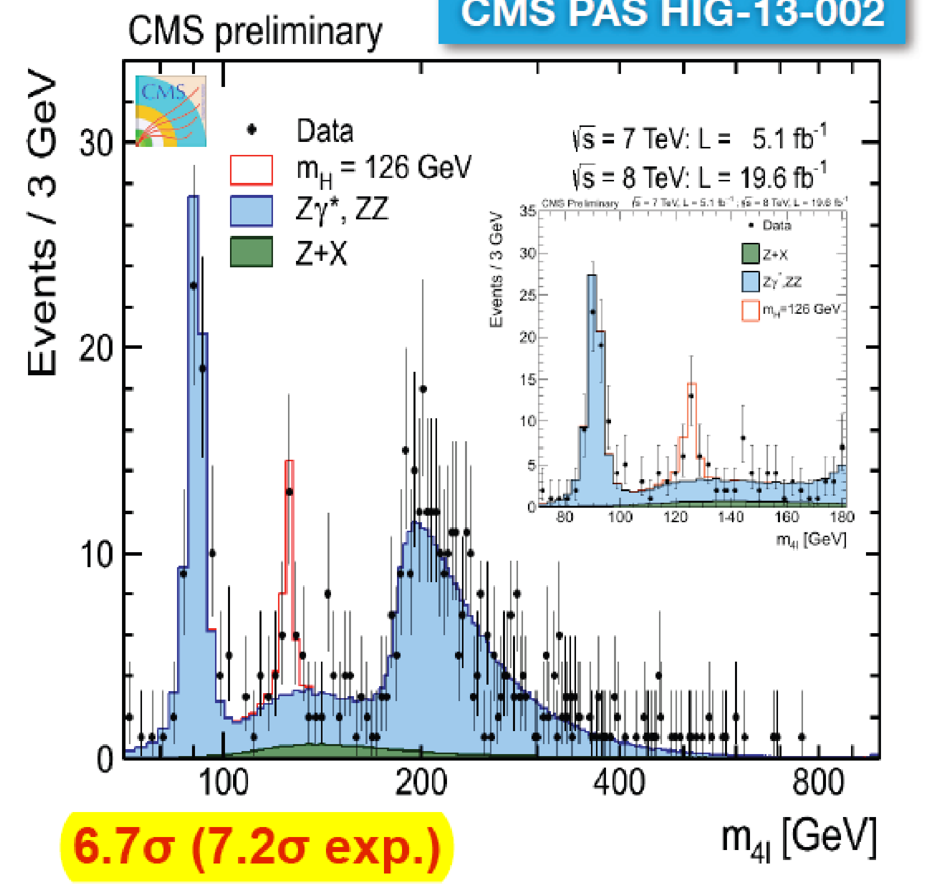


Bumps in the Night

ATLAS Collaboration, arXiv:1307.1427

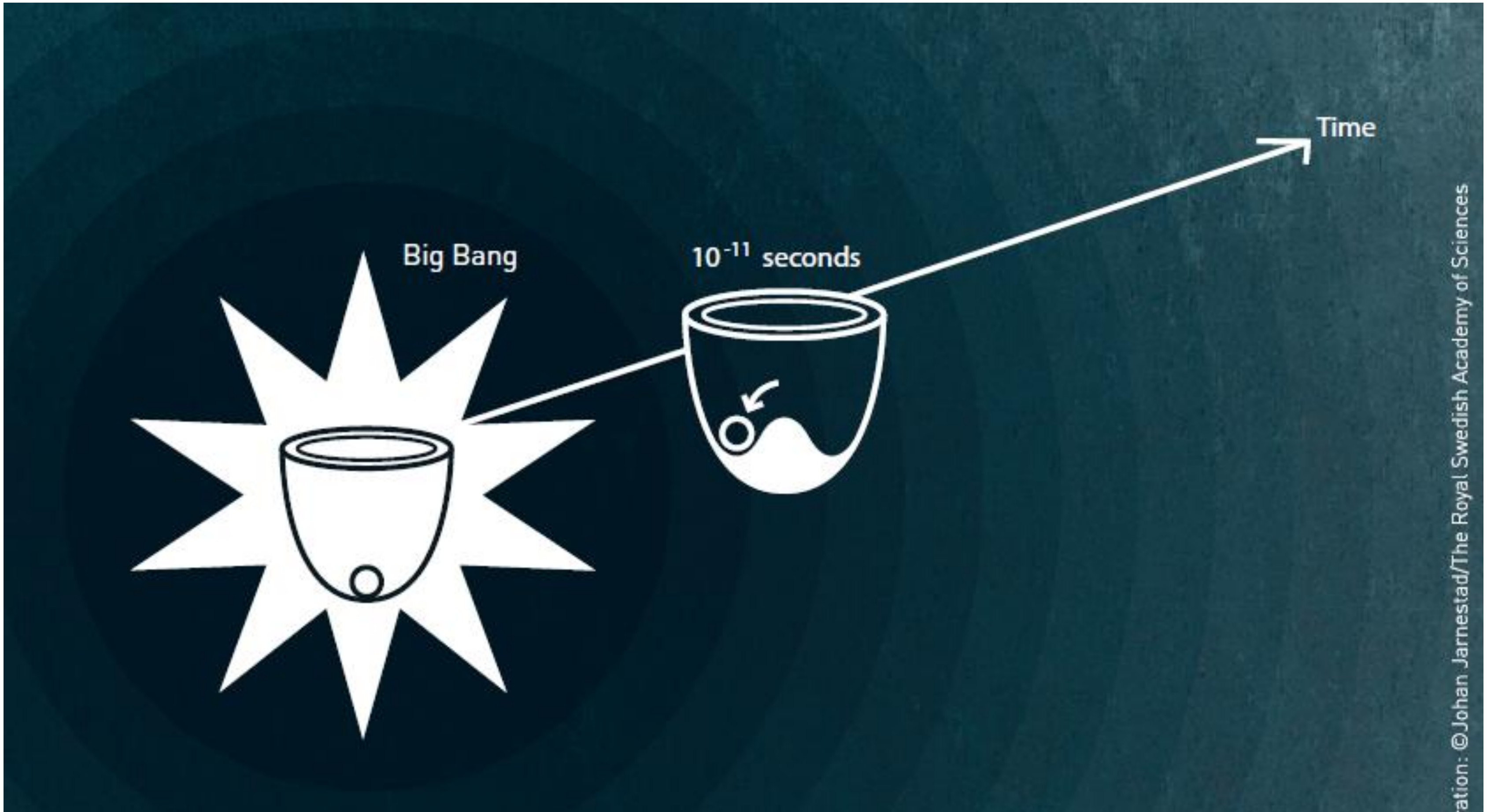


CMS PAS HIG-13-002

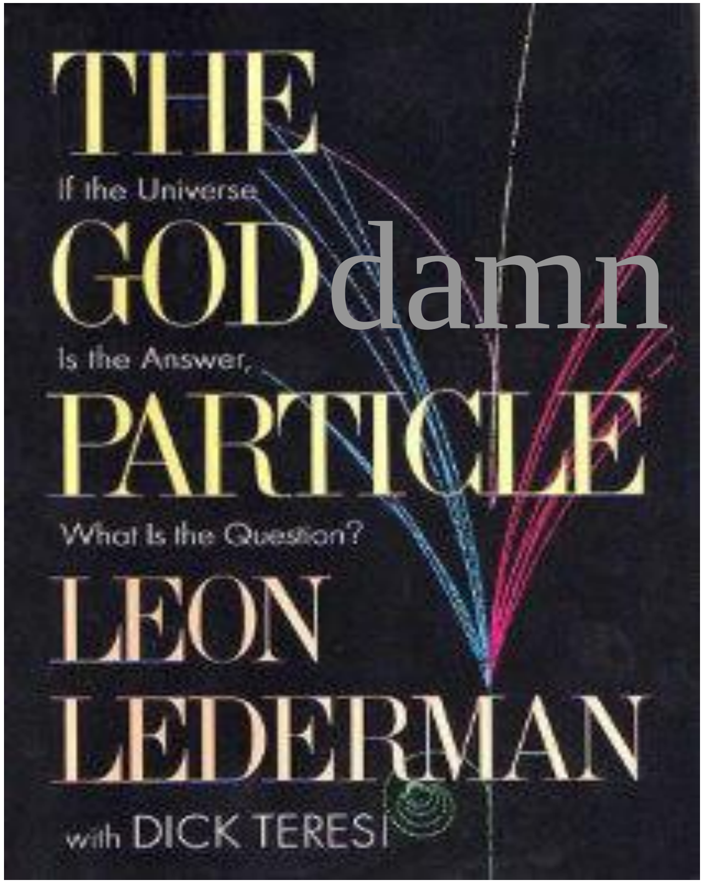


Epilogue

a Field that permeates the Universe



… since the Beginning of Time … ?



- Elusive … till July 4th, 2012
  — 48 yrs stretch
- First "elementary" scalar, ever!
  NOT provided in QED, nor QCD.
- Fermion Mass Generation seem fortuitous: $m_f \sim \lambda_f v$
- Opens a "Can of Worms":
  - Hierarchy Problem
  - Vacuum Stability … etc.

the Squalid State Higgs, 1980

VOLUME 45, NUMBER 8 PHYSICAL REVIEW LETTERS 25 AUGUST 1980

Raman Scattering by Superconducting-Gap Excitations and Their Coupling to Charge-Density Waves

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(Received 24 March 1980)

2*H*-$NbSe_2$ undergoes a charge-density–wave (CDW) distortion at 33 K which induces *A* and *E* Raman-active phonon modes. These are joined in the superconducting state at 2 K by new *A* and *E* Raman modes close in energy to the BCS gap 2Δ. Magnetic fields suppress the intensity of the new modes and enhance that of the CDW-induced modes, thus providing evidence of coupling between the superconducting-gap excitations and the CDW.