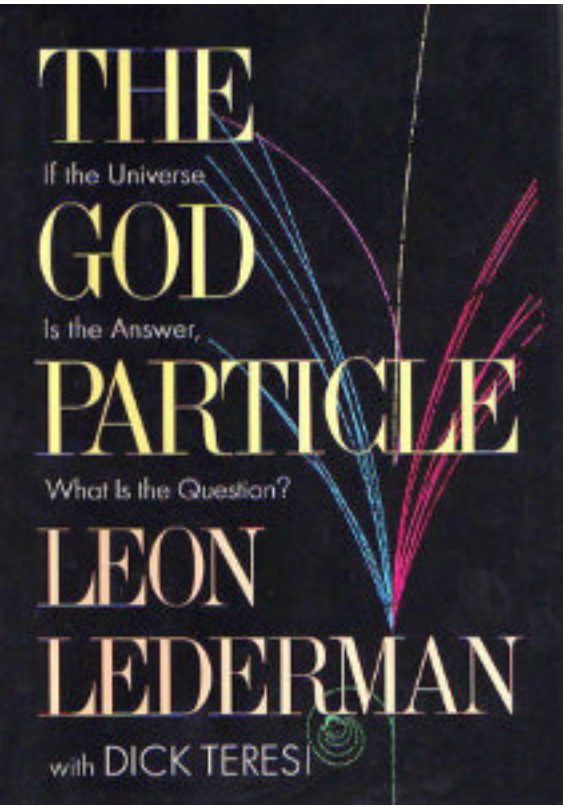
신(神)의 입자
마침내 발견되다

2013 노벨물리학상 해설강연

이화여대 물리학과 안창림

2013 노벨물리학상: Englert and Higgs

신(神)의 입자 [God particle]



Leon Lederman (1988 노벨물리학상)

원제: 빌어먹을 입자
[God particle]

3부작 드라마

1부

대칭성의 깨짐

숨겨진 아름다움을 찾아서

(in search of broken symmetries)

자발적 대칭성의 깨짐

2008 노벨물리학상 해설강연

이화여대 물리학과 안창림

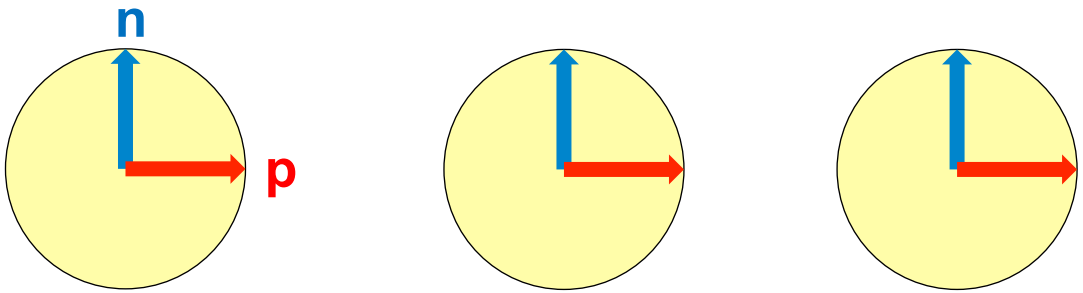
Y. Nambu
2008 Nobel prize

대칭성

Paul Nick

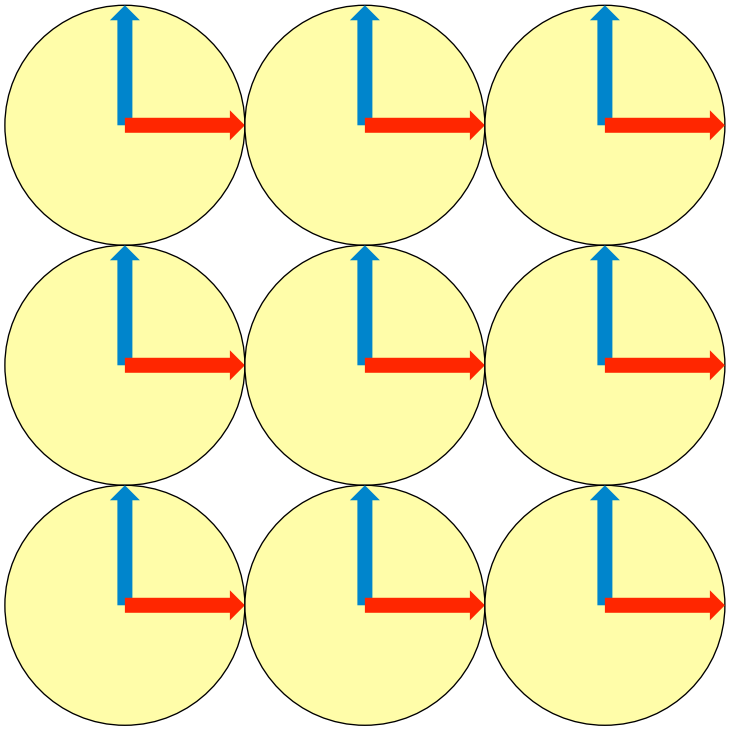
Nick Paul

- 쌍둥이들의 이름바꾸기
- 양성자와 중성자
  - $1.672621636(83)\times10^{-27}$ kg
  - $1.674\,92729(28)\times10^{-27}$ kg
  - 서로 바꾸어 불러도 똑같다



대칭성의 자발적 깨짐

- 양성자와 중성자가 구분가능
- 모든 위치에서 n,p는 결정됨



Paul Nick

AXIAL VECTOR CURRENT CONSERVATION IN WEAK INTERACTIONS*

Yoichiro Nambu
Enrico Fermi Institute for Nuclear Studies and Department of Physics
University of Chicago, Chicago, Illinois
(Received February 23, 1960)

In analogy to the conserved vector current in-
teraction in the beta decay suggested by Feynman
nd Gell-Mann, some speculations have been
nade about a possible conserved axial vector
current.[1-3] One can formally construct an axial
vector nucleon current, which satisfies a con-
tinuity equation,

momenta. Such an attempt has some appeal
view of the apparently modest renormaliza
effect on the axial vector beta decay const
($g_A/g_V \approx 1.25$), although the second appeali
point,[1] namely, the possible forbidding of π-
has now lost its relevance.

The expression (1), unfortunately, can be
easily ruled out experimentally as was no

Goldstone Theorem

연속적인 대칭성이 깨지면 항상 질량이 없는 “골드스톤” 입자가 존재한다.

IL NUOVO CIMENTO Vol. XIX, N. 1 1° Gennaio 1961

Field Theories with «Superconductor» Solutions.

J. GOLDSTONE
CERN - Geneva

(ricevuto l'8 Settembre 1960)

Summary. — The conditions for the existence of non-perturbative type «superconductor» solutions of field theories are examined. A non-covariant canonical transformation method is used to find such solutions for a theory of a fermion interacting with a pseudoscalar boson. A covariant renormalisable method using Feynman integrals is then given. A «superconductor» solution is found whenever in the normal perturbative-type solution the boson mass squared is negative and the coupling constants satisfy certain inequalities. The symmetry properties of such solutions are examined with the aid of a simple model of self-interacting boson fields. The solutions have lower symmetry than the Lagrangian, and contain mass zero bosons.

1. – Introduction.

This paper reports some work on the possible existence of field theories with solutions analogous to the Bardeen model of a superconductor. This possibility has been discussed by NAMBU (1) in a report which presents the general ideas of the theory which will not be repeated here. The present work merely considers models and has no direct physical applications but the nature of these theories seems worthwhile exploring.

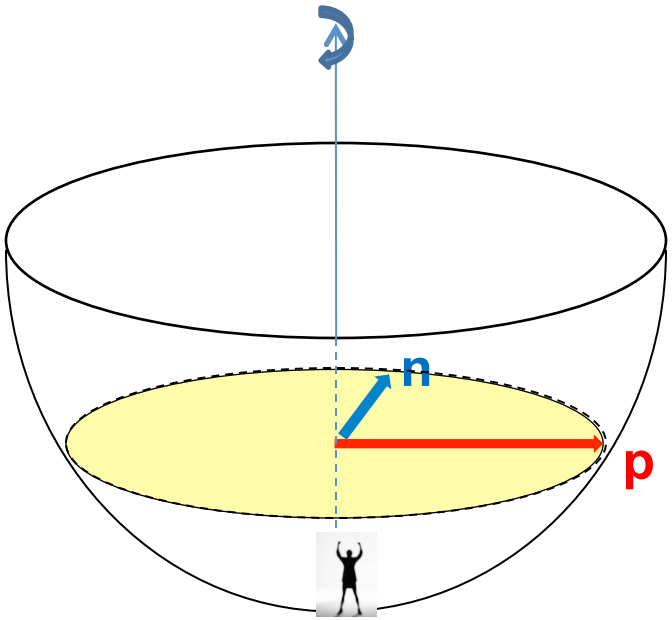
The models considered here all have a boson field in them from the beginning. It would be more desirable to construct bosons out of fermions and this type of theory does contain that possibility (1). The theories of this paper have the dubious advantage of being renormalisable, which at least allows one to find simple conditions in finite terms for the existence of «supercon-

(1) Y. NAMBU: Enrico Fermi Institute for Nuclear Studies, Chicago, Report 60-21.

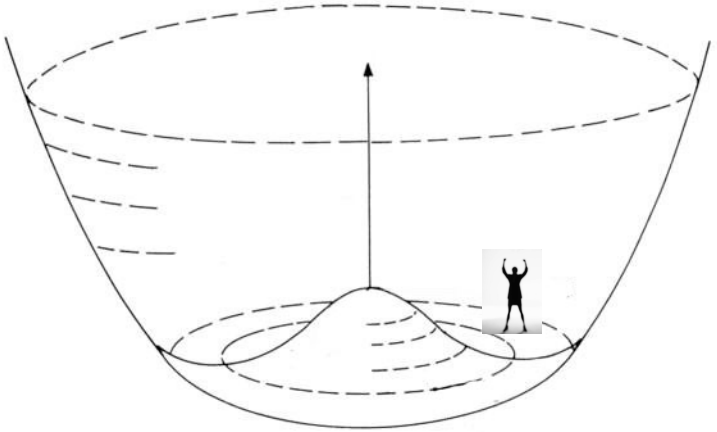
Goldstone boson

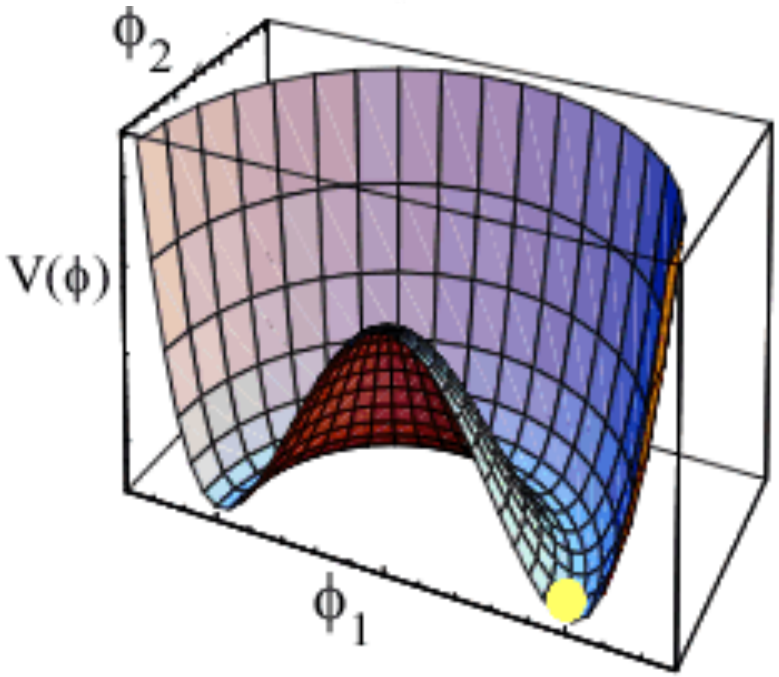
몇달 차이로 노벨상 놓침

With symmetry



Spontaneously broken symmetry

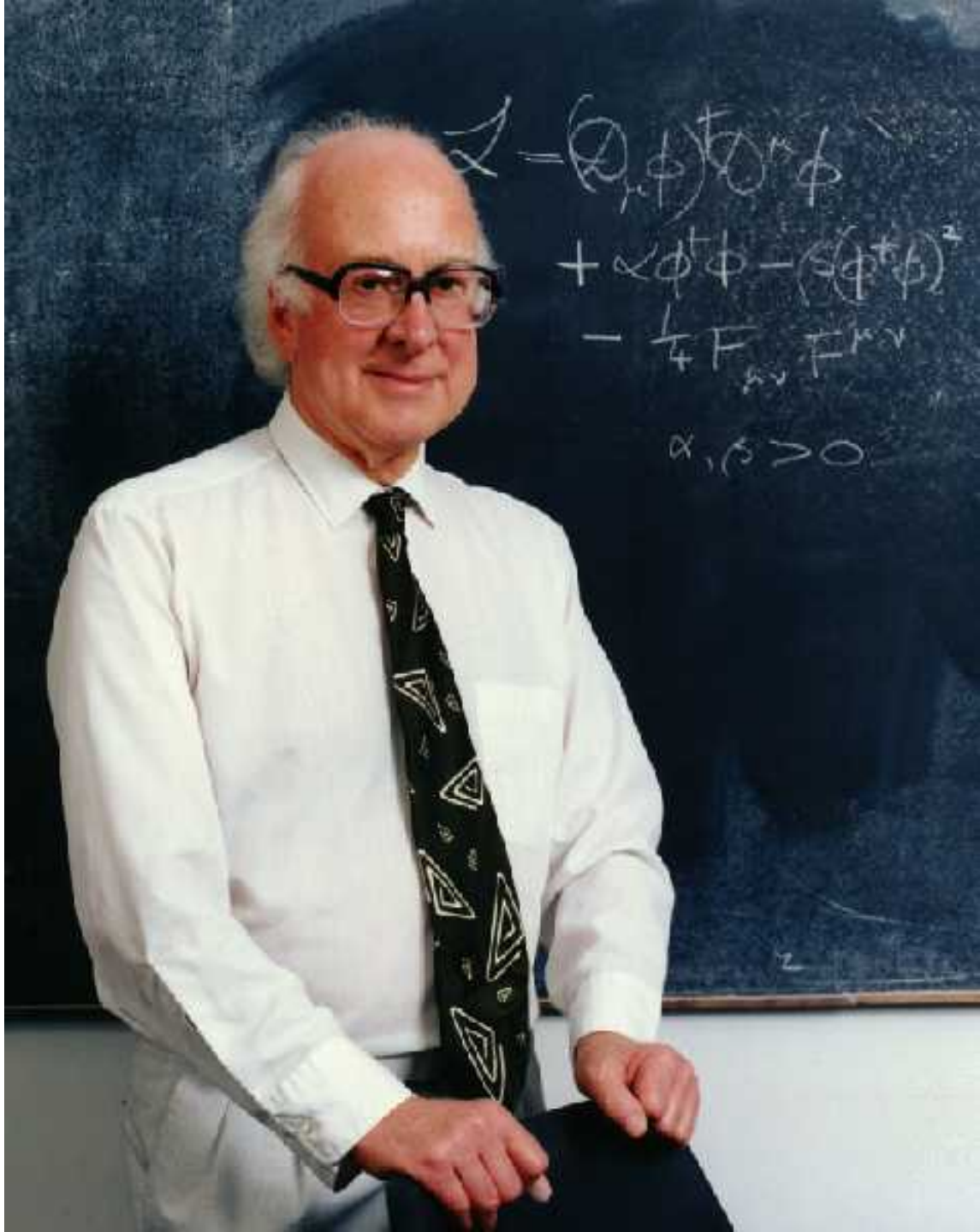




2008년 노벨상해설강연에서의
본인의 예언

P. Higgs

Nobel prize in 2011?



2부

힉스 메카니즘

게이지(gauge) 대칭성

- 가는 곳 마다 쌍둥이의 이름을 멋대로 바꿔불러도 아무 문제가 없다!

서울

Paul Nick

부산

Peter Ben

대구

Jim Bob

광주

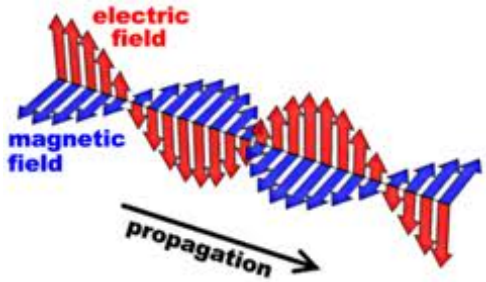
Nick Mike

- 엄마가 따라다니며 알려주면 된다.
- 엄마 = 게이지보존
- 게이지대칭성 → 질량이 없는 게이지보존

게이지보존

- 힘 : 매개입자를 주고받으면서

- 매개입자 : 게이지보존
- (예) 전자기력 : 빛 (photon)
- 종파 (질량없음)



- 원자핵안에서는
  - 강력 : 글루온(gluon)
  - 약력 : Z^0, $W^{\pm}$

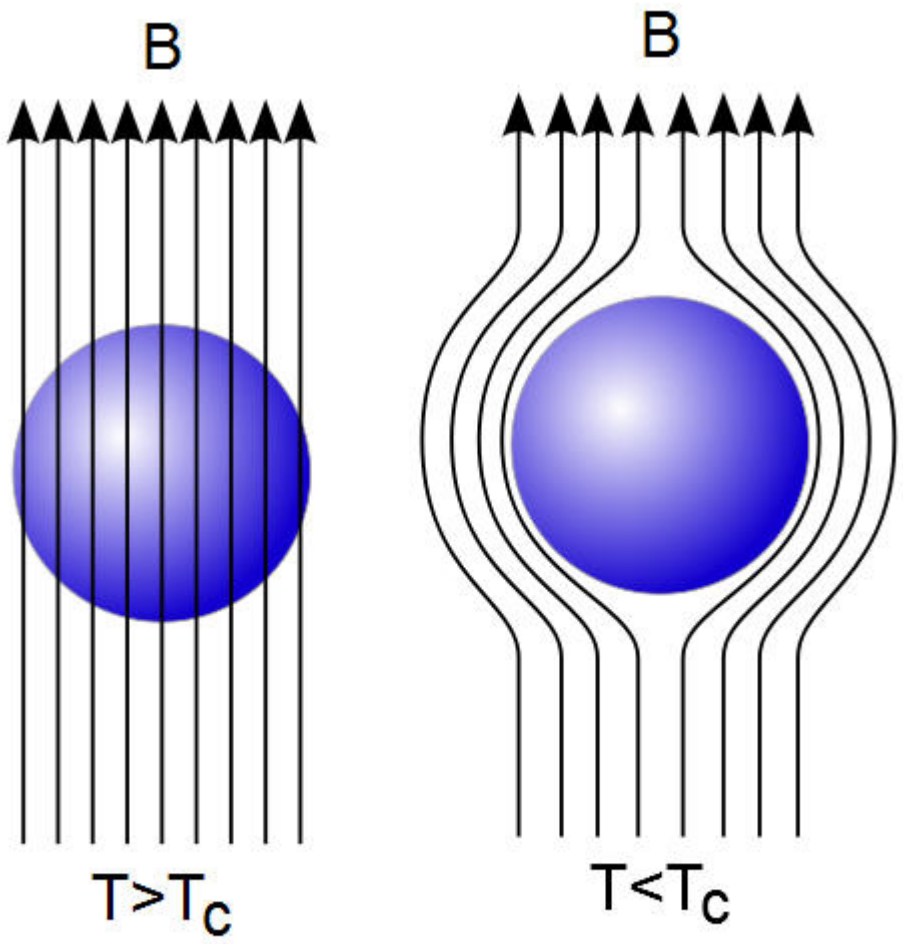
게이지보존

1960년대초의 이론물리학의 난제

1. 왜 골드스톤 보존을 찾을 수 없는가?

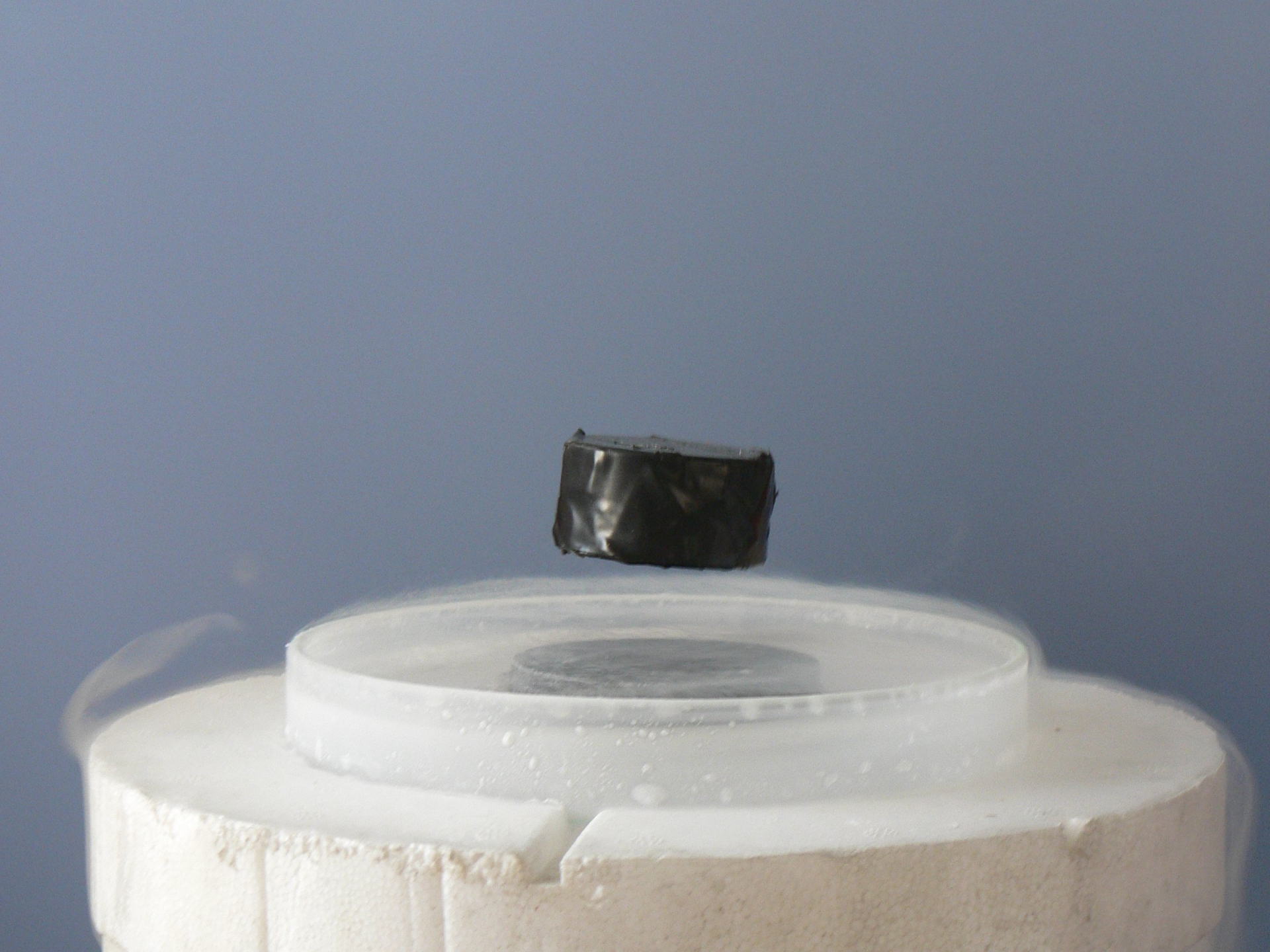
2. 게이지 보존이 질량을 가질 수 있을까?

빛도 질량을 가진다 (마이스너 효과)



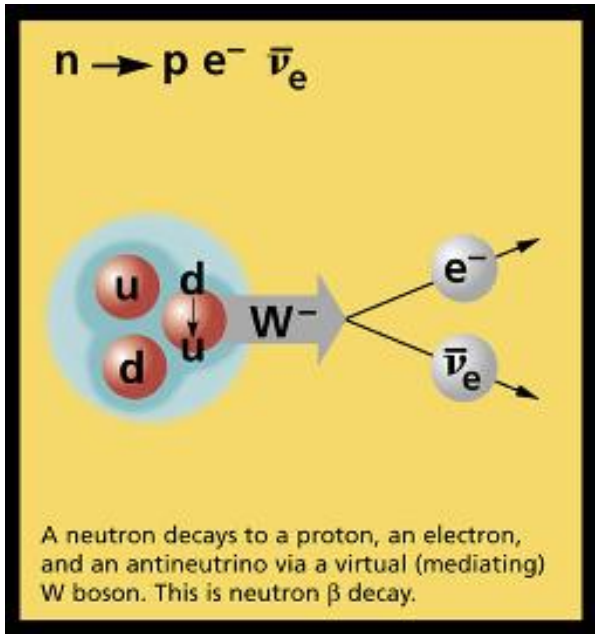
일반 전도체

초전도체



상하이 푸동공항 자기부상열차

베타(β)선 : 약력



약력은 전자기력에 비해 만분의 1정도로 약함

힘을 매개하는 게이지입자가 무겁기 때문

일석이조: 두 난제를 한번에 해결하다

힉스 메카니즘

어떻게 Goldstone Theorem을 피해갈 것인가?

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.

게이지보존이 꼭 질량이 없을 필요는 없다.

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 example exhibiting all of the features of Schwinger's idea. It is also shown that Schwinger's criterion that the vector field $m \neq 0$ implies that the matter spectrum before including the Yang-Mills interaction contains $m=0$, but that the example of superconductivity illustrates that the physical spectrum need not. Some comments on the relationship between these ideas and the zero-mass difficulty in theories with broken symmetries are given.

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 exhib-

gauge 대칭성이 깨질 때는 골드스톤보존이 존재하지 않을 수 있음.

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

(2) The flaw in the argument will then be given, and will be seen to nullify as well the covariant proof.

BROKEN SYMMETRIES AND MASSLESS PARTICLES*

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

cast doubt upon the original theorem. In this they were mistaken. The theorem fails, trivially, in

Goldstone theorem이 여전히 성립한다고 주장

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)

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;

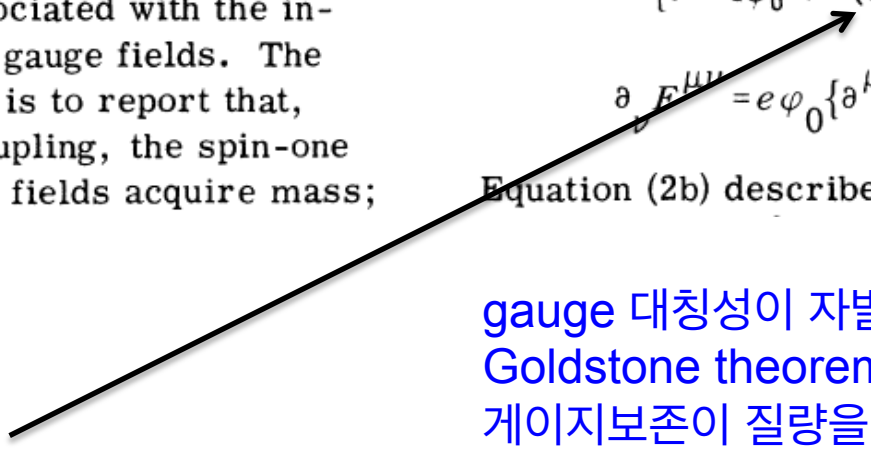
about the "vacuum" solution $\varphi_1(x) = 0$, $\varphi_2(x) = \varphi_0$:

$$\partial^\mu\{\partial_\mu(\Delta\varphi_1) - e\varphi_0 A_\mu\} = 0, \tag{2a}$$

$$\{\partial^2 - 4\varphi_0^2 V''(\varphi_0^2)\}(\Delta\varphi_2) = 0, \tag{2b}$$

$$\partial_\nu F^{\mu\nu} = e\varphi_0\{\partial^\mu(\Delta\varphi_1) - e\varphi_0 A_\mu\}. \tag{2c}$$

Equation (2b) describes waves whose quanta have



덤으로 질량을 갖는 "힉스보존"이 존재함

gauge 대칭성이 자발적으로 깨지면
Goldstone theorem이 성립하지 않고 대신
게이지보존이 질량을 갖음을 이론적으로 입증

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)

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.

gauge 대칭성이 자발적으로 깨지면
게이지보존이 질량을 갖음을 이론적으로 입증

those vector mesons which are coupled to currents that "rotate" the original vacuum are the ones which acquire mass [see Eq. (6)].

We shall then examine a particular model based on chirality invariance which may have a more fundamental significance. Here we begin with a chirality-invariant Lagrangian and introduce both vector and pseudovector gauge fields, thereby guaranteeing invariance under both local phase and local γ_5-phase transformations. In this model the gauge fields themselves may break the γ_5 invariance leading to a mass for the original Fermi field. We shall show in this case

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

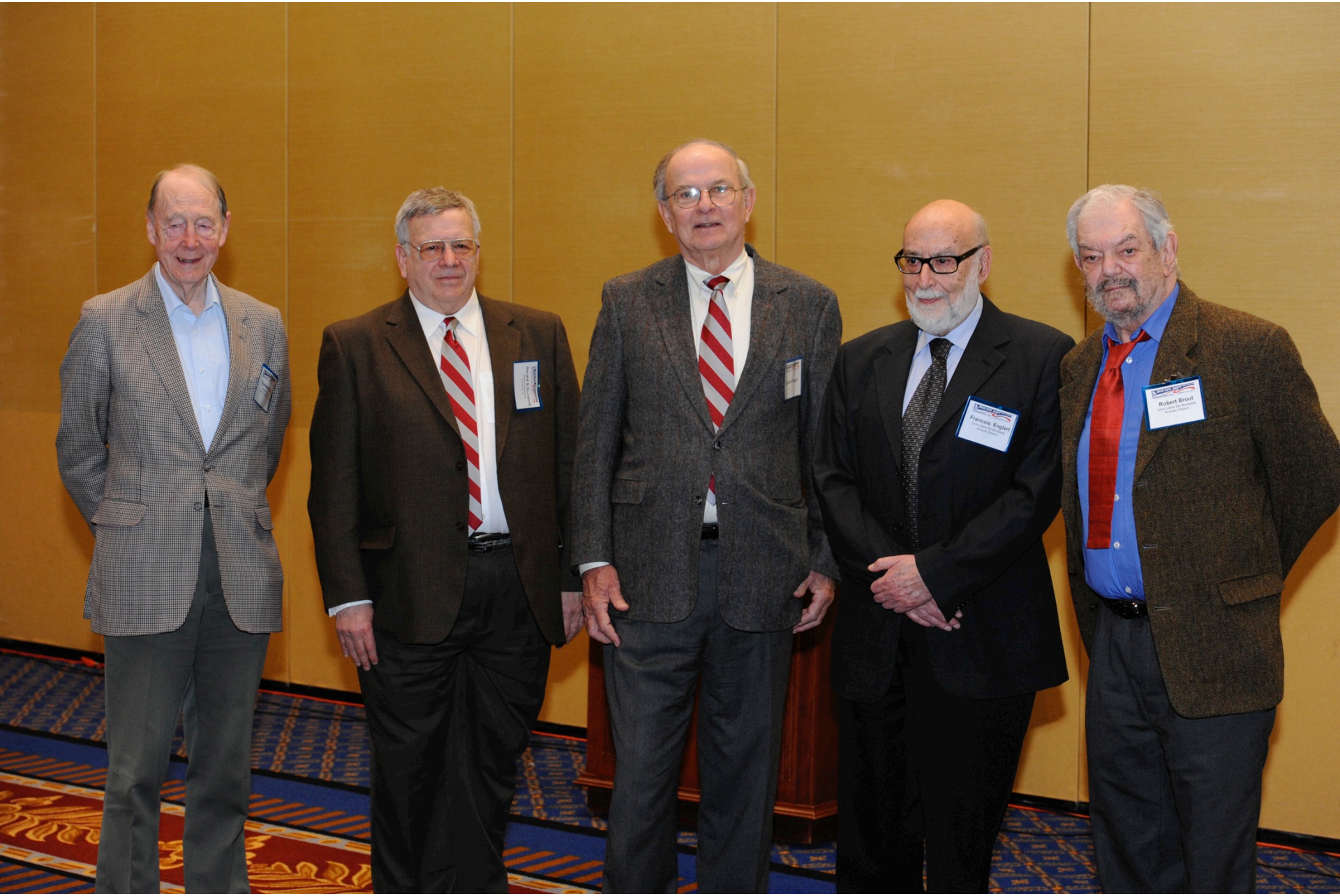
G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

[3]P. W. Higgs, Phys. Letters 12, 132 (1964).
[4]B. Zumino, Phys. Letters 10, 224 (1964).
[5]F. Englert and R. Brout, Phys. Rev. Letters 13, 321 (1964).
[6]P. W. Higgs, to be published.

몇 달 늦는 바람에 노벨상 수상에서 제외됨

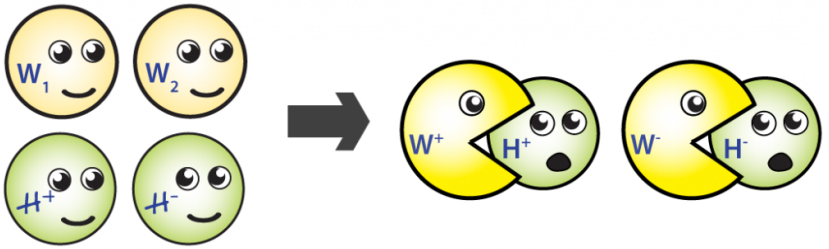
Goldstone : 힉스메카니즘을 발견했으나 동료인 하바드대학의 Coleman교수로부터 말도 안되는 소리라는 질책을 듣고 논문을 발표안함.

“골드스톤보존을 Nambu에게 뺏긴 것은 억울하지 않으나 힉스메카니즘을 힉스에게 뺏긴 것은 너무 억울하다” - J. Goldstone

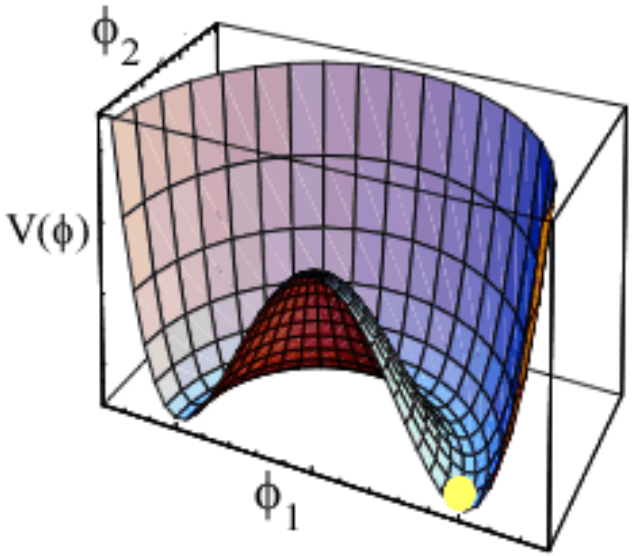

Francois Englert
Robert Brout

힉스장과 힉스보존

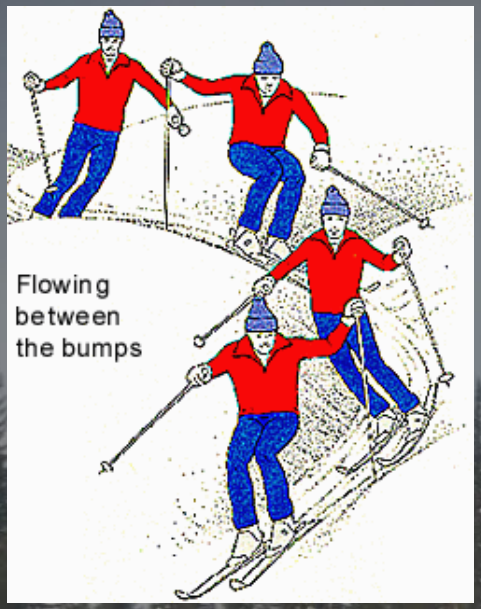
- 우주공간은 힉스장으로 채워져있다.
- “질량이 없는 게이지보존은 골드스톤보존을 먹고 질량이 생긴다”

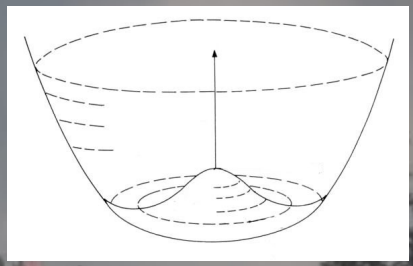


- 게이지보존의 횡파
- 덤으로 힉스보존이 생겨난다.



비유 1. Mogul ski





비유 2


질량이 없는 게이지입자


질량이 생긴 게이지입자


힉스보존

처음엔 학계에서는 완전히 찬밥신세

힉스자신도 이것이 약력에 사용될 줄은 전혀 모름

3부

표준모형의 완성


S. Weinberg
1979년 노벨물리학상

VOLUME 19, NUMBER 21 PHYSICAL REVIEW LETTERS 20 NOVEMBER 1967

A MODEL OF LEPTONS*

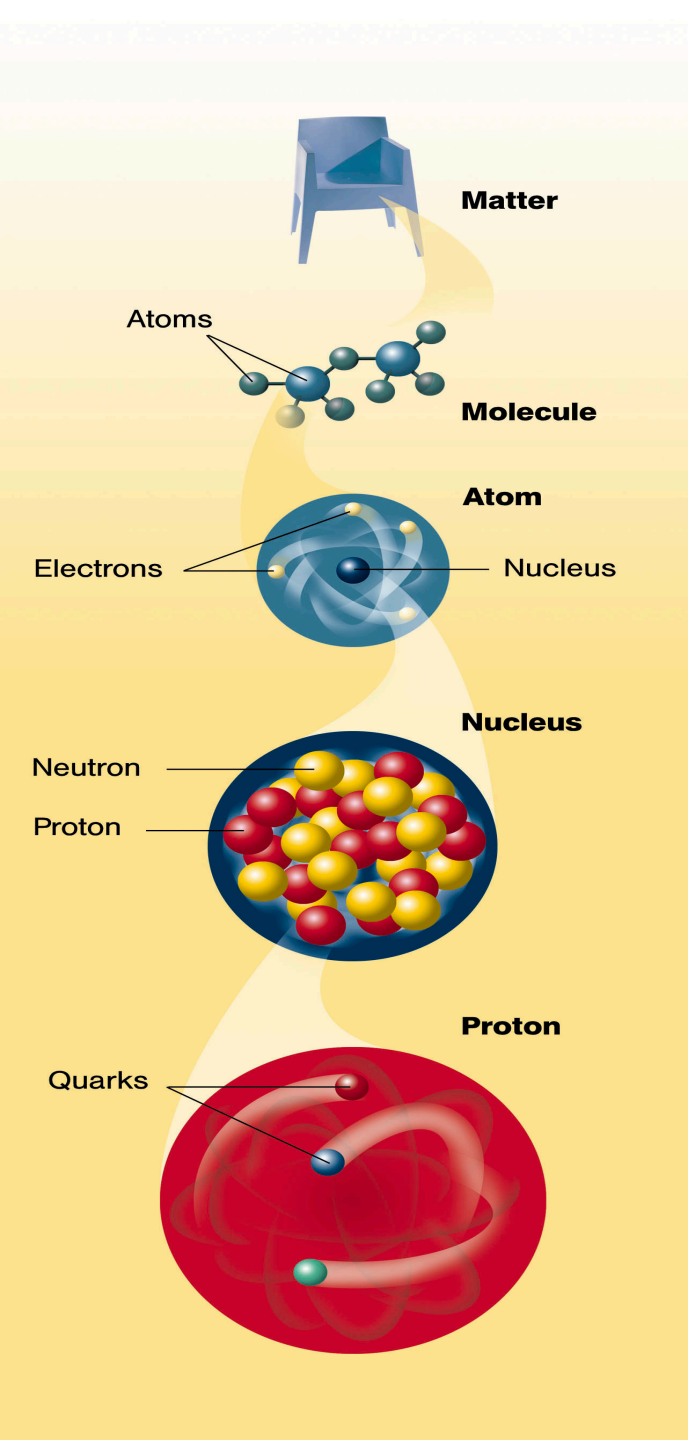
Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

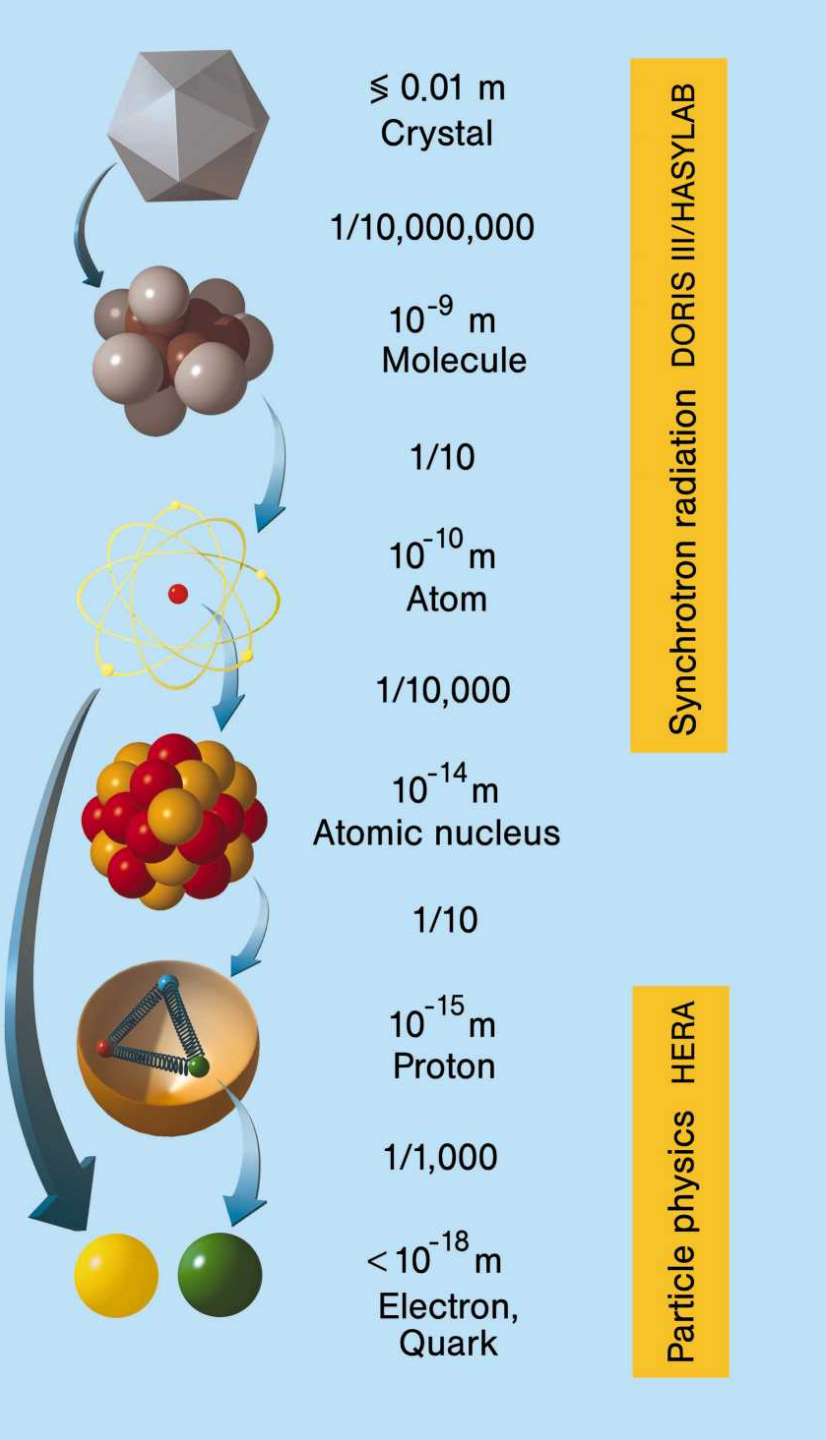
소립자 표준모형의 완성
전자기력과 약력의 통일장이론
모든 입자의 질량은 힉스장에 의해

인용횟수: 8633회

[3]P. W. Higgs, Phys. Letters 12, 132 (1964), Phys. Rev. Letters 13, 508 (1964), and Phys. Rev. 145, 1156 (1966); F. Englert and R. Brout, Phys. Rev. Letters 13, 321 (1964); G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble, Phys. Rev. Letters 13, 585 (1964).

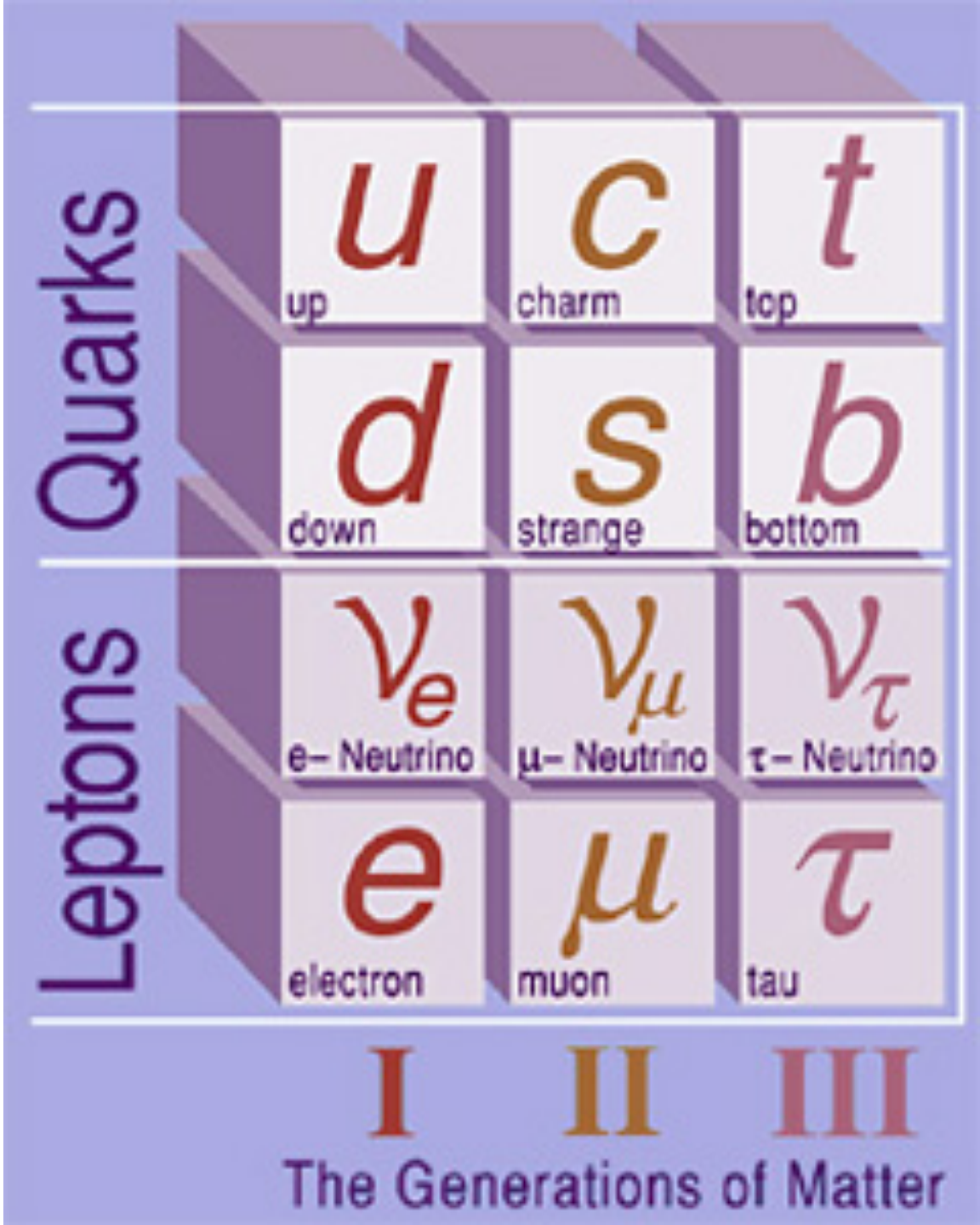
물질의 궁극적 구조


Matter
Atoms
Molecule
Atom
Electrons
Nucleus
Nucleus
Neutron
Proton
Proton
Quarks


≤ 0.01 m
Crystal
1/10,000,000
10-9 m
Molecule
1/10
10-10 m
Atom
1/10,000
10-14 m
Atomic nucleus
1/10
10-15 m
Proton
1/1,000
< 10-18 m
Electron,
Quark
Synchrotron radiation DORIS III/HASYLAB
Particle physics HERA

현대판
원소주기율표

페르미온 (Fermion)



가장 기본적인 힘

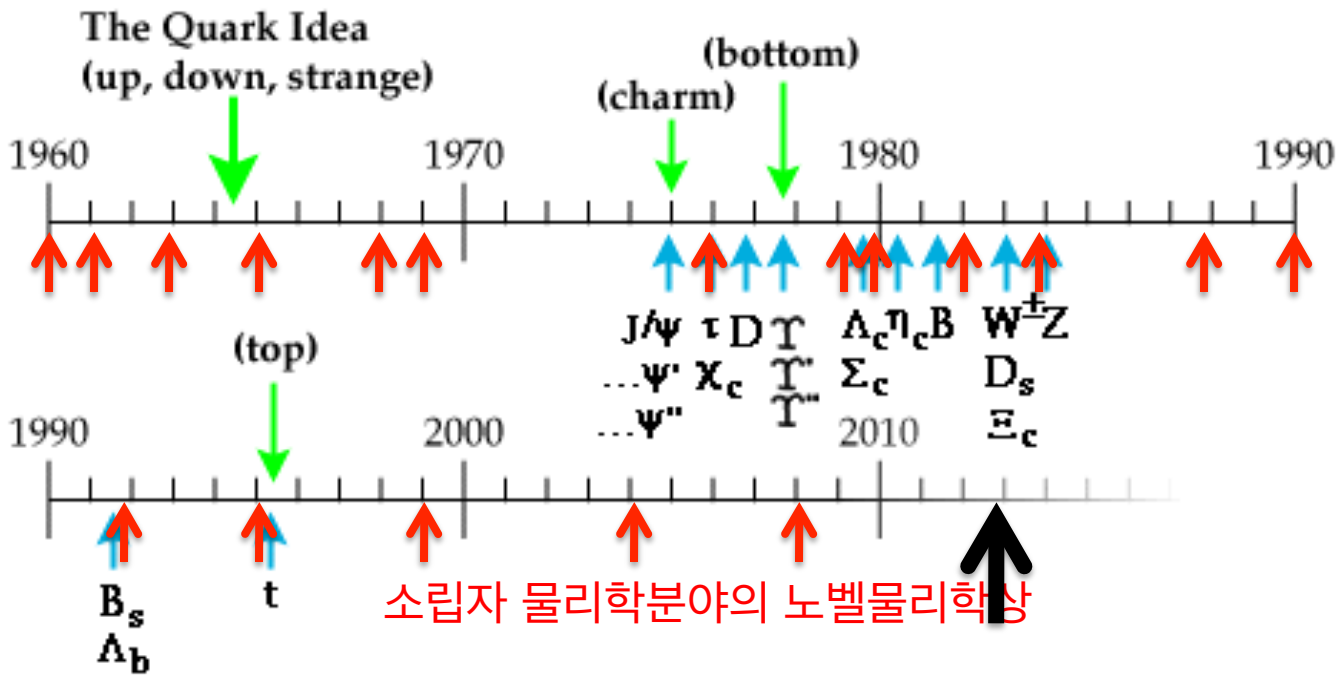
게이지 보존

	Gravity	Weak (Electroweak)	Electromagnetic	Strong
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons

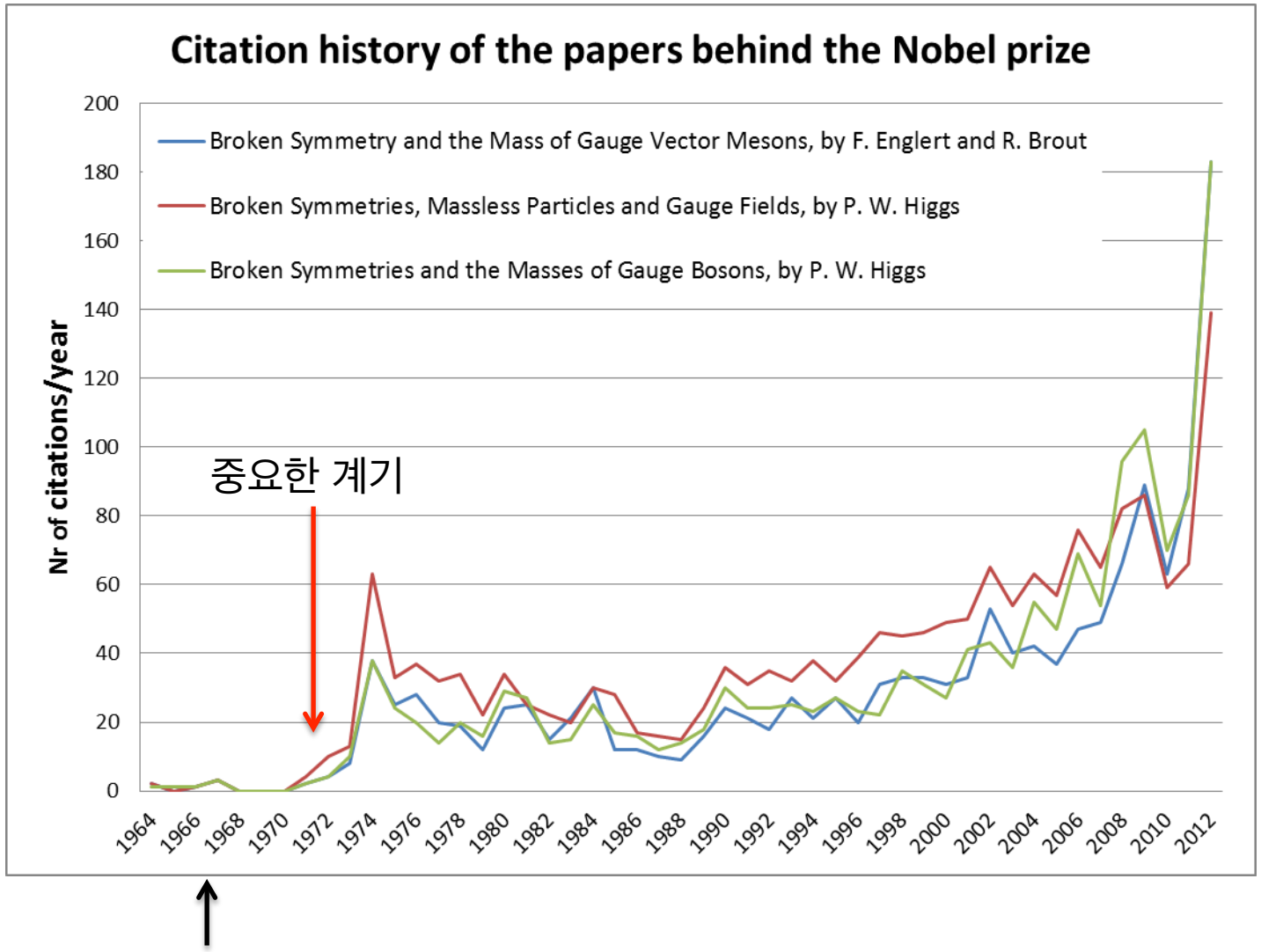
β선 γ선 α선

그리고 …

H^0


The Quark Idea
(up, down, strange)
(charm)
(bottom)
1960
1970
1980
1990
J/ψ τ D ϒ Λc ηc B W± Z
...ψ' χc ϒ' Σc Ds
...ψ'' ϒ''
(top)
1990
2000
2010
Bs
Λb
t
Ξc
소립자 물리학분야의 노벨물리학상

Higgs논문의 인용빈도수

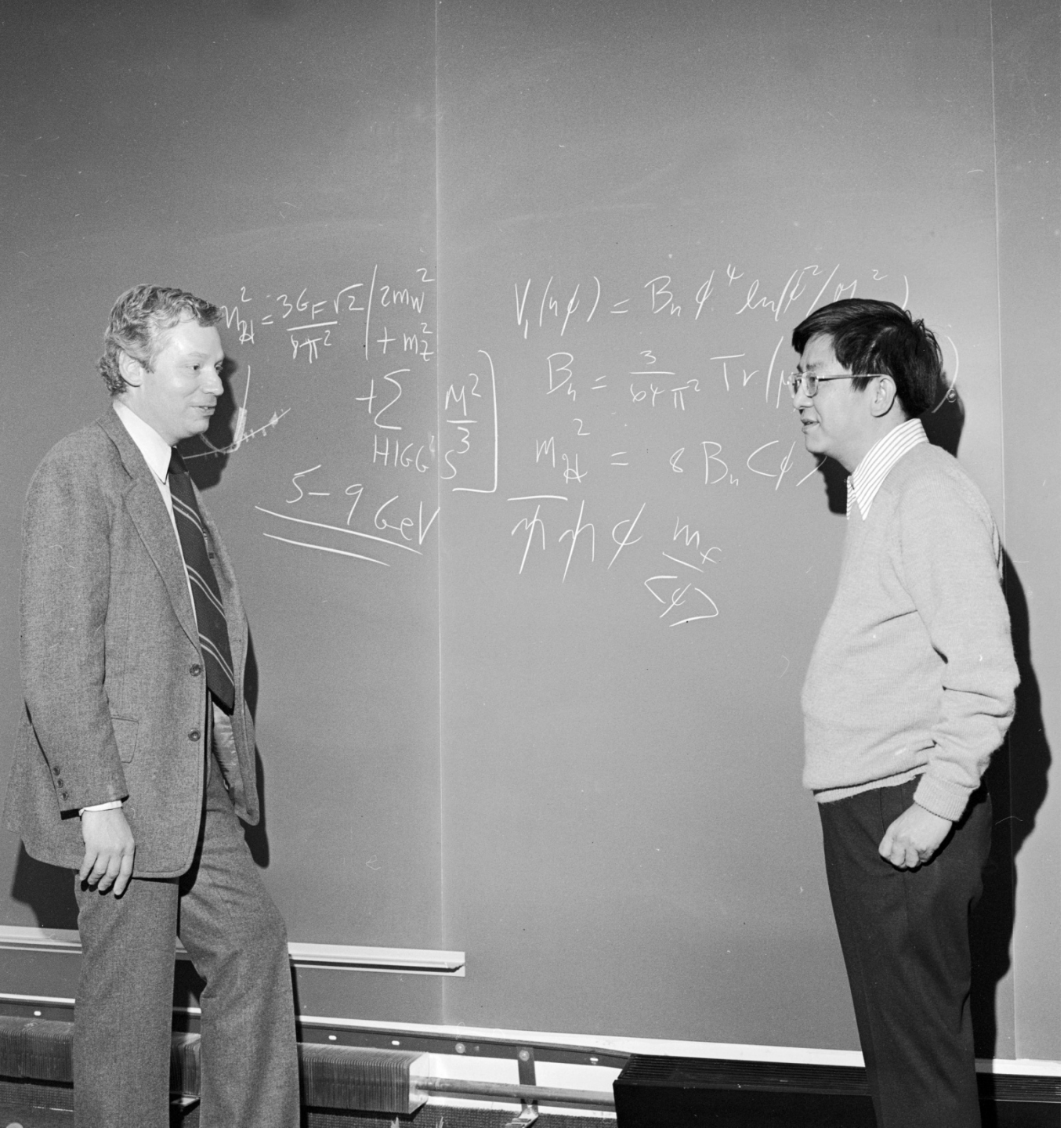


[2218 회]

[2572 회]

[2439 회]

이휘소 (Benjamin W. Lee) 교수


$m_H^2 = \frac{3G_F\sqrt{2}}{8\pi^2}\left[2m_W^2 + m_Z^2 + \sum_{\text{HIGGS}} \frac{M^2}{3}\right]$
5 – 9 GeV
$V_1(\phi) = B_n \phi^4 \ln(\phi^2/\mu^2)$
$B_n = \frac{3}{64\pi^2} \mathrm{Tr}$
$m_H^2 = 8 B_n \langle\phi\rangle^2$
$\pi\hbar c$
m_c
$\langle\phi\rangle$

이휘소의 두번

- 1971년 ‘t Hooft & Veltma
  표준모형의 재규격화 증명
  - 1999년 노벨상
  - 이휘소 박사의 노력으로 이 증명(
    계에 알려짐
- 1972년 Higgs와 만남

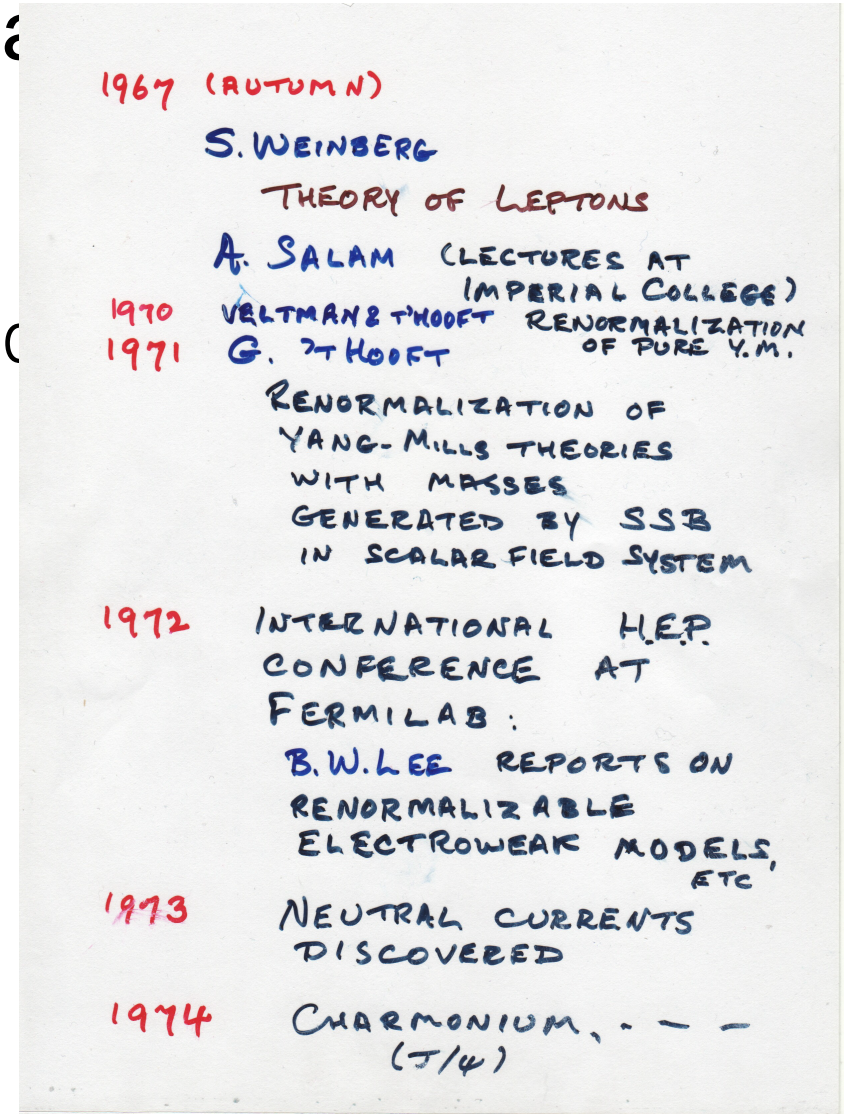
In 1972, Ben Lee, …, then plastered my name over everything connected with spontaneous symmetry breaking, and other people were relegated to a foot note.
“이휘소가 대칭성이 깨지는 현상과 관련된 모든 것에 내 이름을 붙이기 시작하면서 나는 떴고 다른 사람들은 각주 정도로 격하되었다.”

My Life as a Boson

Peter Higgs

School of Physics and Astronomy, University of Edinburgh, James Clerk Maxwell Building, King’s Buildings Mayfield Road Edinburgh EH9 3JZ, Scotland

Based on a talk presented at Kings College London, Nov. 24th, 2010



A Historical Profile of the Higgs Boson

John Ellis[a], Mary K. Gaillard[b] and Dimitri V. Nanopoulos[c]

However, the seminal papers on spontaneous breaking of gauge symmetries and electroweak unification were largely ignored by the particle physics community until the renormalizability of spontaneously-broken gauge theories was demonstrated by 't Hooft and Veltman [8]. These ideas then joined the mainstream very rapidly, thanks in particular to a series of influential papers by B. W. Lee and collaborators [27, 28].

4 A Phenomenological Profile of the Higgs Boson

B. W. Lee also carries much of the responsibility for calling the Higgs boson the Higgs boson, mentioning repeatedly 'Higgs scalar fields' in a review talk at the International Conference on High-Energy Physics in 1972 [29]. However, in the early 1970s there were

이휘소교수는 현대 물리학의 가장 중요한 3부작 드라마의 실질적인 연출자였음.

힉스입자의 발견

50년이나 걸린 이유

- 질량을 정확히 몰랐다.
- 질량 = 125 GeV/c^2 = 2.2×10^{-25} kg
  - top quark 다음으로 가장 무거운 입자
  - 수소원자의 130배
  - 강력한 가속기가 필요
- 수명이 엄청 짧다 : 1.56×10^{-22} s
  - 정밀한 검출기가 필요

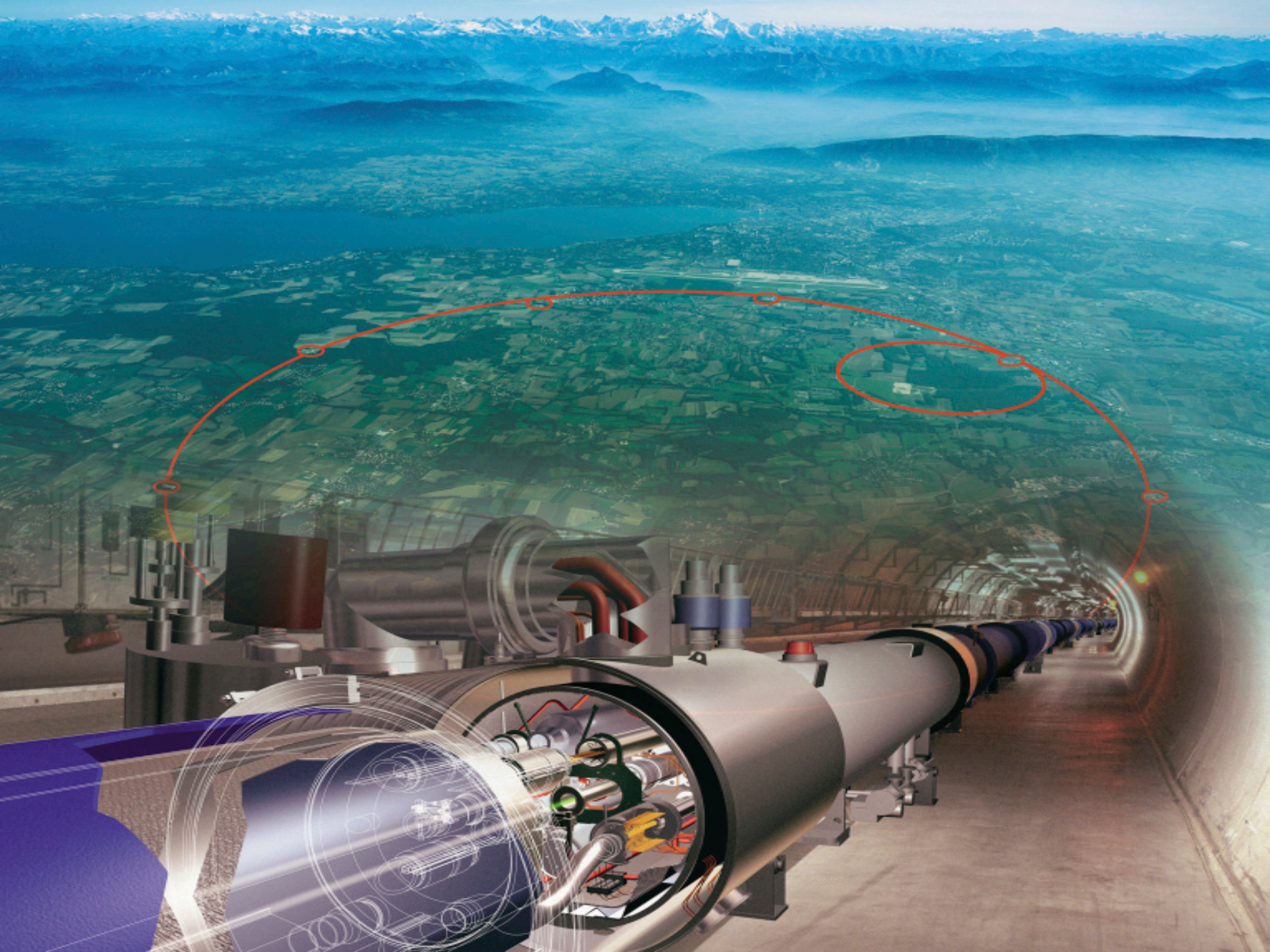
- Before LHC

- CERN의 LHC가속기

125.3 ± 0.4 (stat) ± 0.5 (sys) GeV/c^2
126.0 ± 0.4 (stat) ± 0.4 (sys) GeV/c^2

Large Hadron Collider (LHC)

- 유럽공동 입자물리연구소 (www가 발명된 곳)
- 길이: 27km (스위스와 프랑스)
- 건설비용: 10조원
- 연구참가진: 한국포함 100여개 국가에서 만명 이상 참가



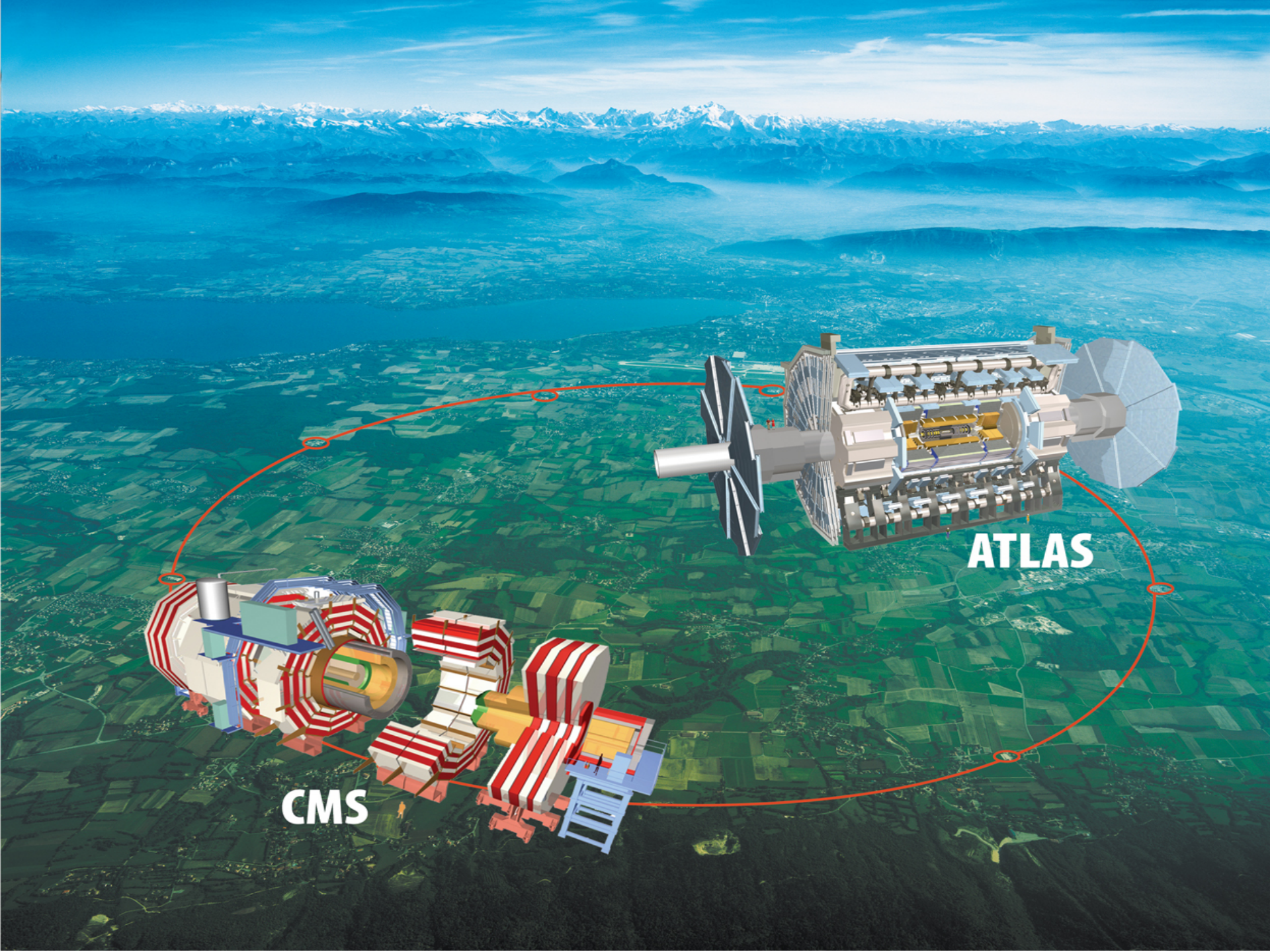
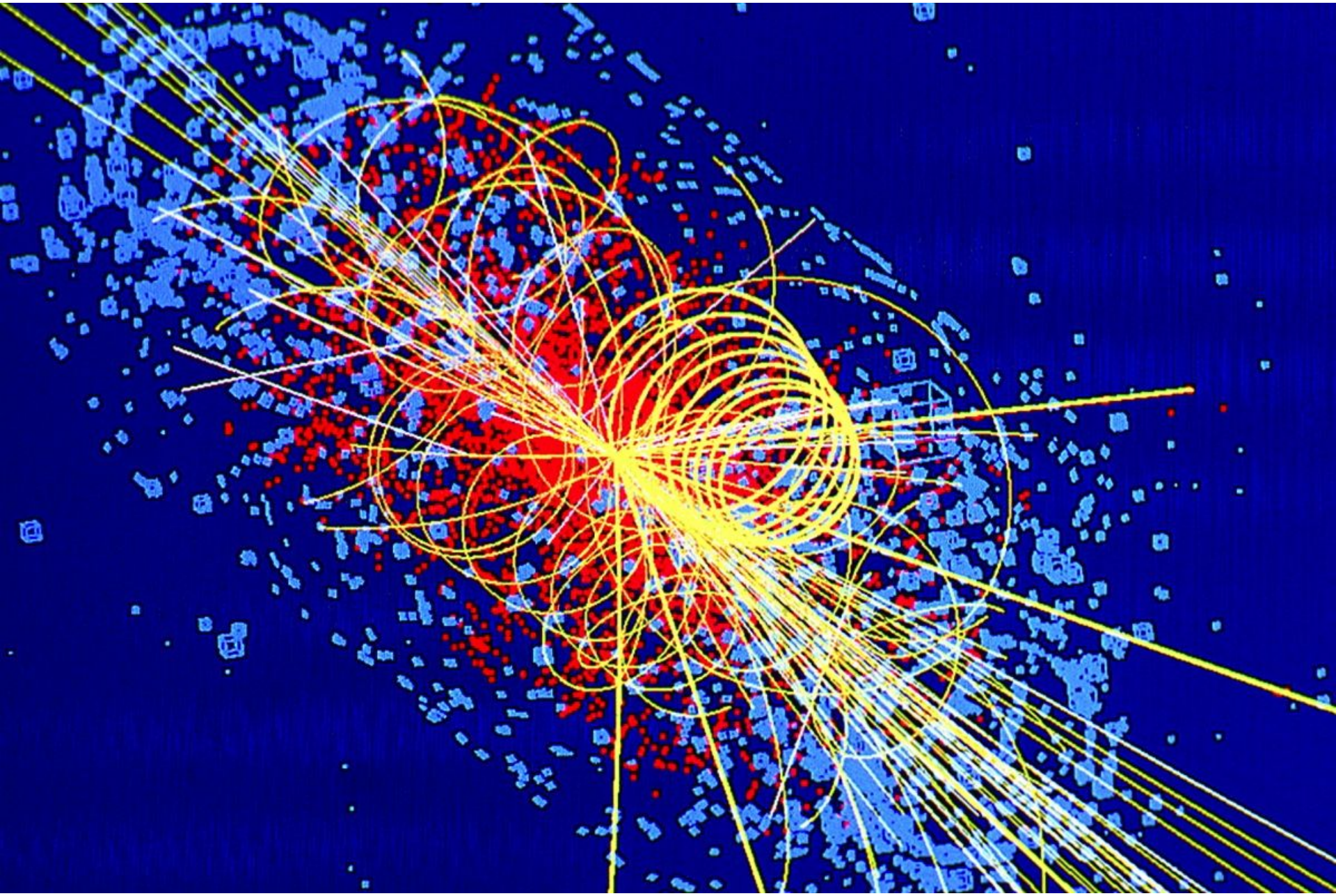

ATLAS
CMS


photo M.Hoch
CMS



- 끝 -

새로운 문제의 시작!

표준모형의 심각한 문제점들

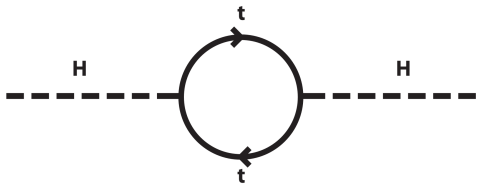
- 자연스럽지 못하다
- 붕괴직전의 우주
- 암흑물질

Naturalness problem

- 재규격화: 양자효과에 의해 물리상수값이 무한대가 되는데 이를 잘 다루어 유한하게 하는 방법
- 보존(스칼라)입자는 재규격화에 심각한 문제

$$M_H = M_H^0 + \Lambda$$

무한대



- $M^0_H \rightarrow -\infty$ & 무한대−무한대 = 125

125=
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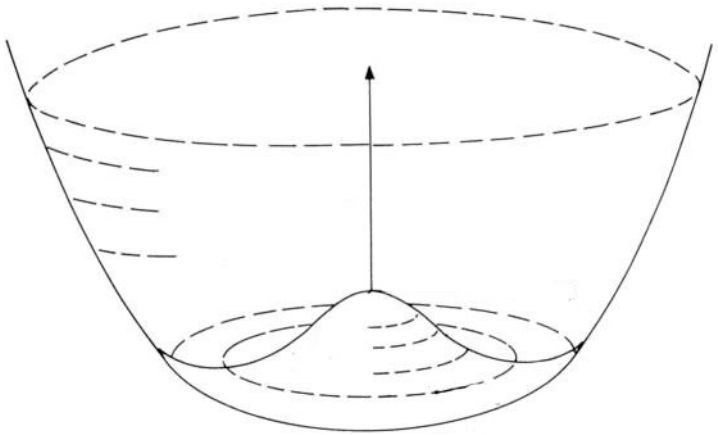
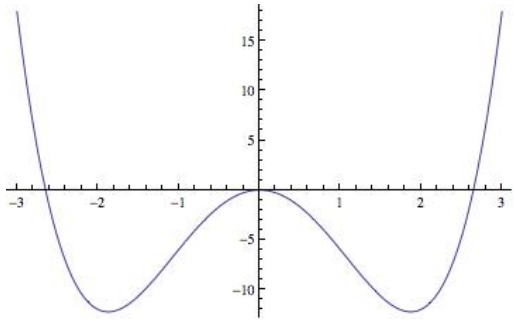
이렇게 정밀하게 상수값이미리 정해져있었다는 것은 부자연스럽다.

우주는 붕괴직전!

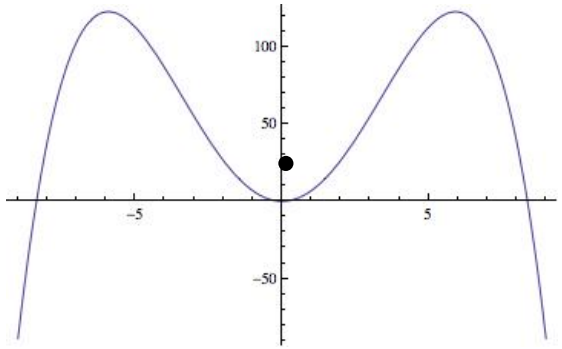


$$V(x) = -\alpha x^2 + \beta x^4$$



- 재규격화
- 양자터널링효과
- 우주가 붕괴

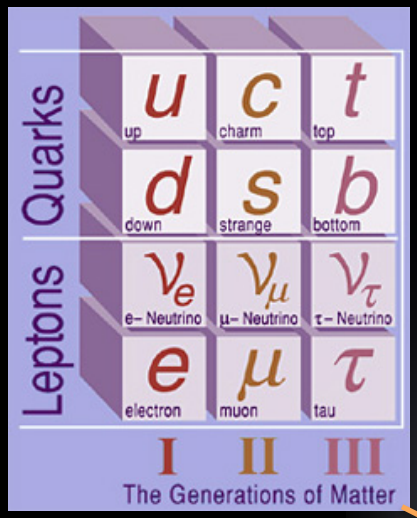
$$V(x) = \alpha' x^2 - \beta' x^4$$



- 힉스의 질량 > 130 GeV : “우주는 안전”
- 힉스의 질량 < 130 GeV : “우주는 붕괴”

힉스질량 = 125 GeV

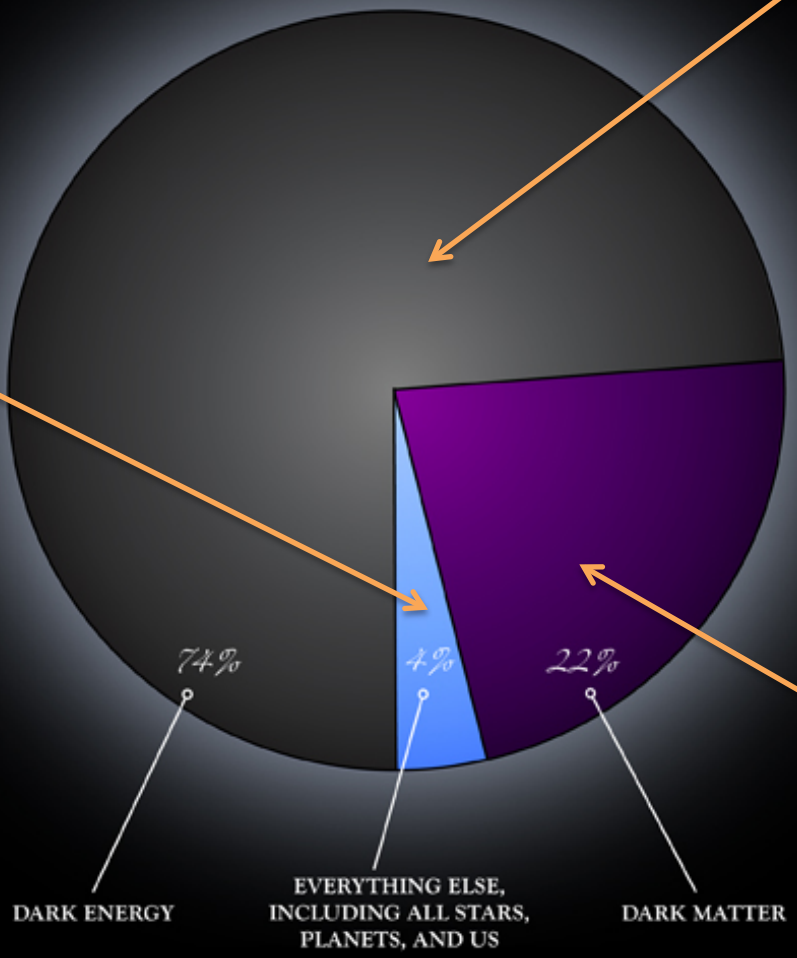
- 결국 우주의 붕괴는 시간 문제
  - 힉스의 질량 < 110 GeV : 이미 우주는 없어졌어야.
  - 힉스의 질량 = 125 GeV : 몇 십억년 남았음



우주의 구성비율

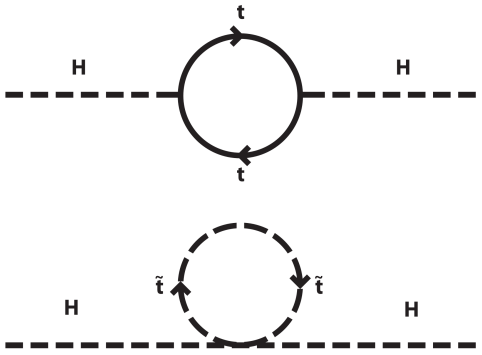
2011년 노벨
물리학상

암흑물질
새로운 입자?



21세기에 규명될 새로운 이론들

- 초대칭성 (supersymmetry)
  - 페르미온←→보존
  - Higgs보존→Higgsino = 암흑물질



- 새로운 힘 (Technicolor)
  - 힉스보존 = 새로운 페르미온들로 만들어진 입자
  - 우주에는 보존입자들은 존재하지 않는다

- 숨겨진 차원 (extra dimension)
  - 우리가 사는 공간은 10차원
  - 초끈이론 (superstring theory)

이번에도 모든 문제들을 한꺼번에 해결될까?

미래의 힉스를 기다리며 …

[보너스] 힉스를 통해 배우는 노벨상 받는 법

- 남보다 먼저 할 것
- 권위자(지도교수)의 훼방을 극복할 것
- 운이 좋을 것
- 오래 살 것
- 노벨상 수상자만이 훌륭한 과학자는 아님

- 끝 -