Introdução à Física de Partículas

Introduction to particle Physics

(3/3)

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Escola de Professores no CERN em Língua Portuguesa 2014

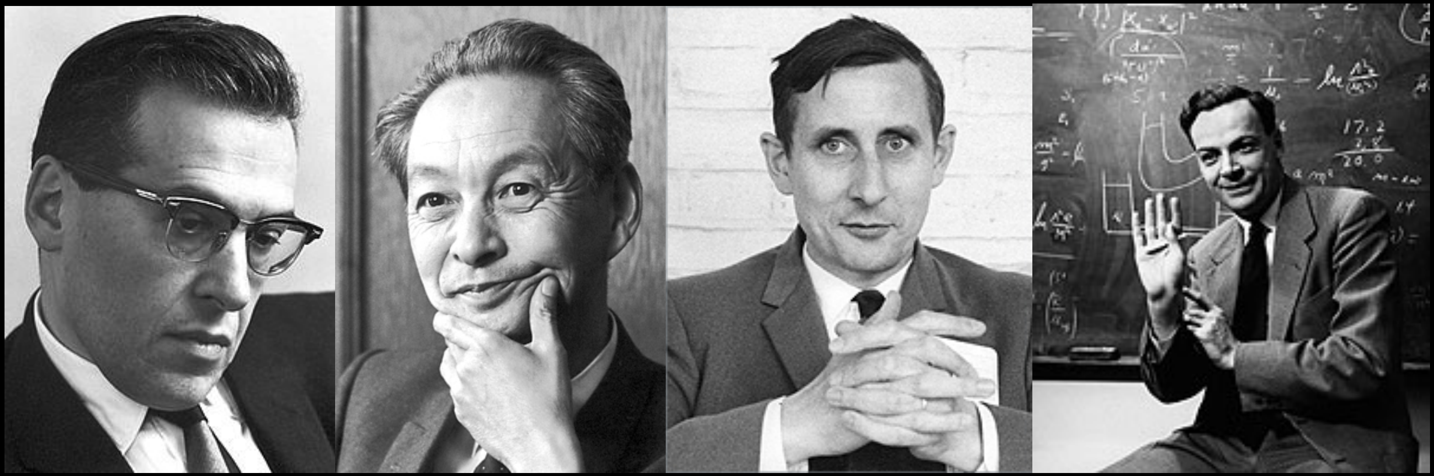
CERN Portuguese Language Teachers Programme 2014

24-29 Agosto, CERN, Genebra

Electrodinâmica quântica

TQC DOS FOTÕES, ELECTRÕES, POSITRÕES E SUAS INTERAÇÕES

ElectroDinâmica Quântica - EDQ (QED)



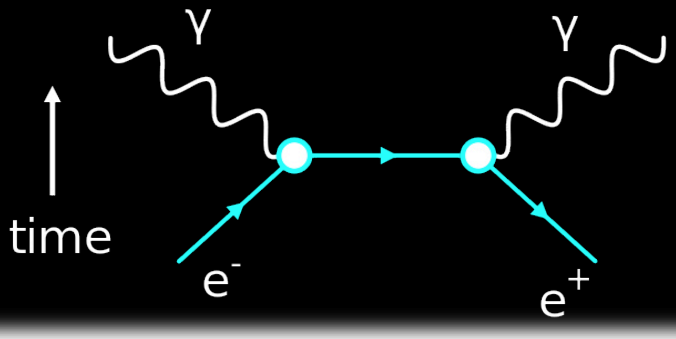
Schwinger Tomonaga Dyson Feynman

The Nobel Prize in Physics 1965 was awarded jointly to Sin-Itiro Tomonaga, Julian Schwinger and Richard P. Feynman "for their fundamental work in quantum electrodynamics, with deep-ploughing consequences for the physics of elementary particles".

Uma arma Universal

1948

Em 1948 Feynman desenvolveu um método "gráfico" que permite calcular processos que envolvem interacções entre particulas elementares.

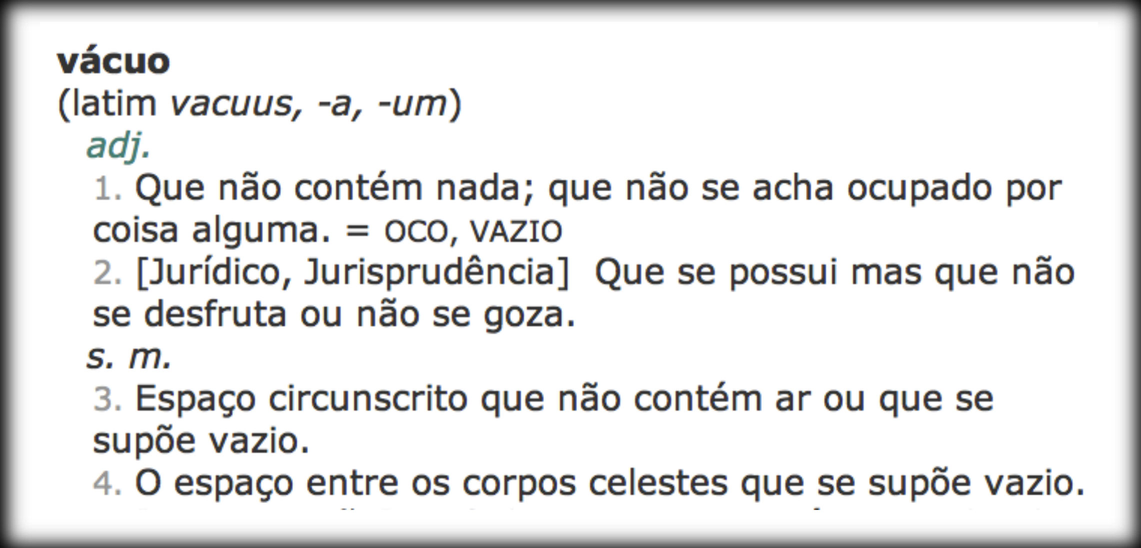


A furgoneta Feynman

Para o diagram acima: $\mathcal{M} = \varepsilon^*_\mu(p_1,\lambda_1)\varepsilon^*_\nu(p_2,\lambda_2)\bar{v}(e^+)(ie\gamma^\nu)\frac{i}{\not{q}-m}(ie\gamma^\mu)u(e^-)$

A TÉCNICA DOS DIAGRAMAS DE FEYNMAN É USADA PARA CALCULAR AS "PROBABILIDADES" DE OCORRÊNCIA DE PROCESSOS ENVOLVENDO PARTÍCULAS ELEMENTARES.

O VÁCUO QUÂNTICO



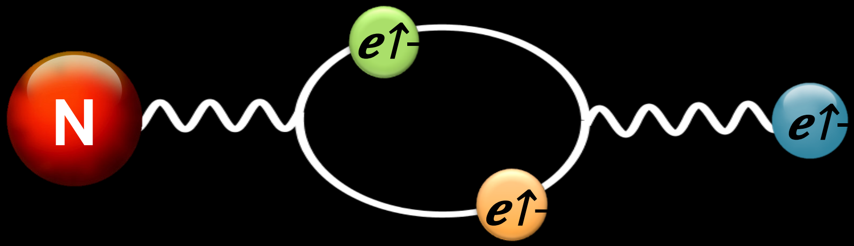
vácuo
(latim *vacuus, -a, -um*)
adj.
1. Que não contém nada; que não se acha ocupado por coisa alguma. = OCO, VAZIO
2. [Jurídico, Jurisprudência] Que se possui mas que não se desfruta ou não se goza.

s. m.
3. Espaço circunscrito que não contém ar ou que se supõe vazio.
4. O espaço entre os corpos celestes que se supõe vazio.

EM FÍSICA QUÂNTICA O VÁCUO ESTÁ LONGE DE SER ESPAÇO VAZIO...

PIH Energia-tempo

2ª Quantização: O campo E.M. pode ser interpretado como um conjunto infinito de osciladores harmónicos cujo estado fundamental tem energia não nula.

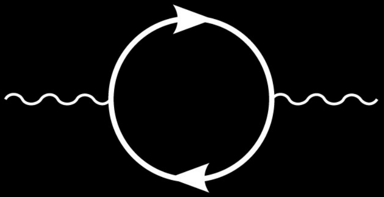


Polarização do vácuo

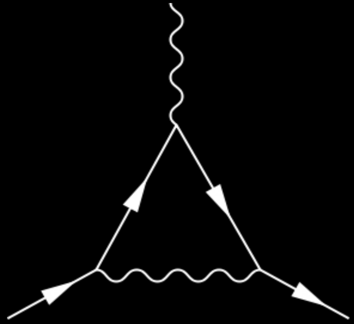
À semelhança da polarização de um dieléctrico.

O VÁCUO EM QED

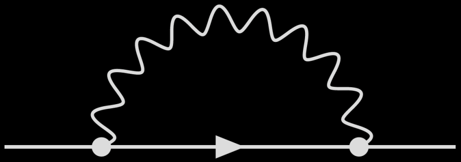
Polarização do vácuo

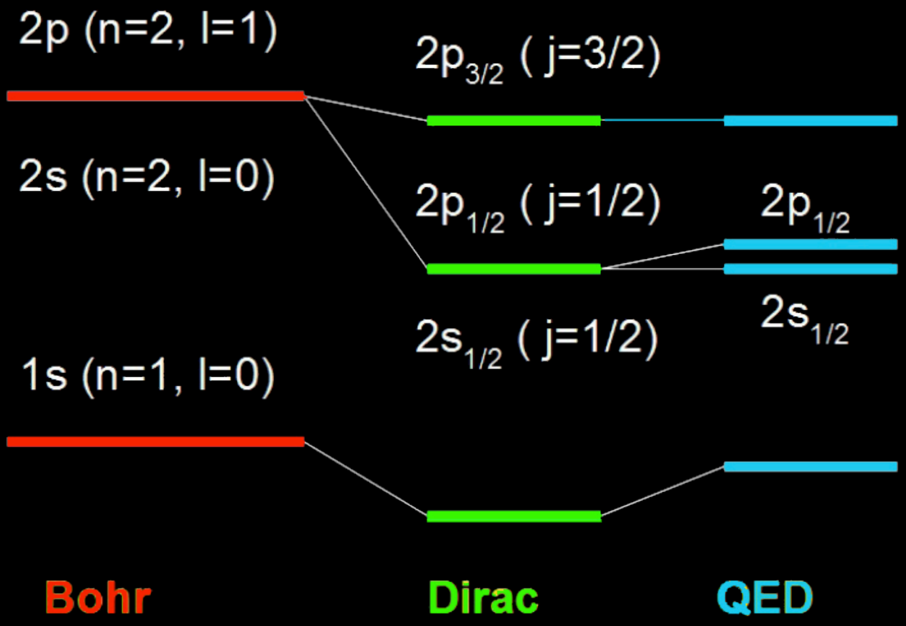


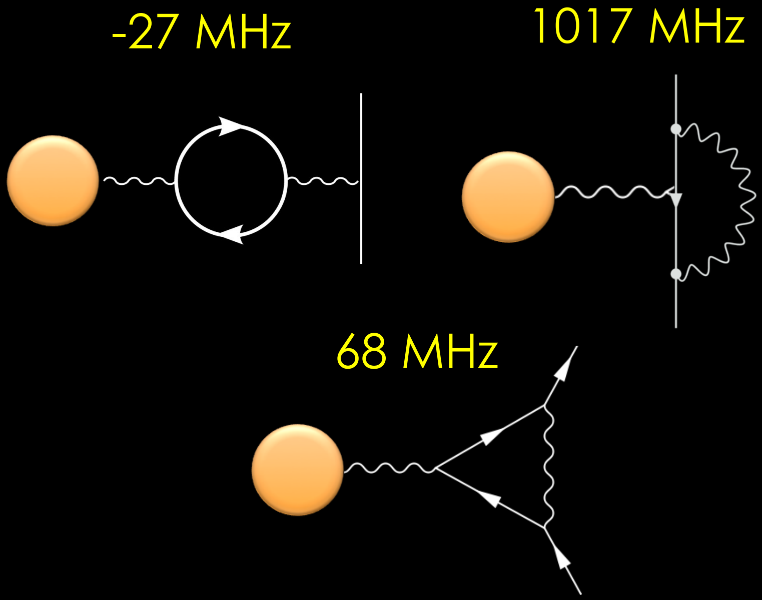
Correcção ao vértice



Correcção à energia própria



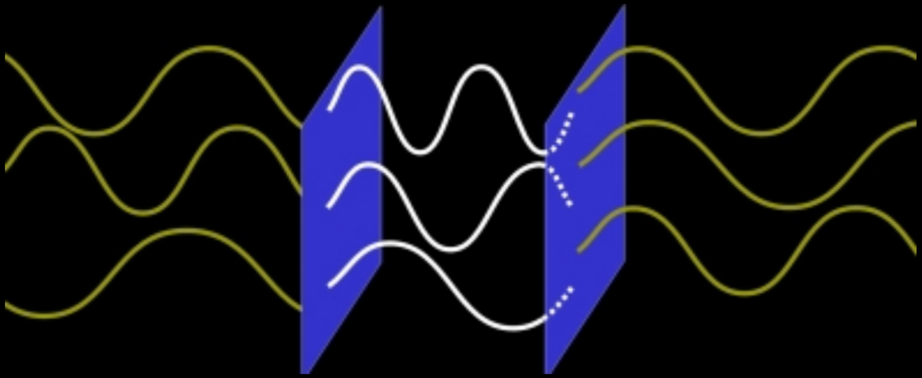




Teoria: 1058 MHz , Exp: 1057.9

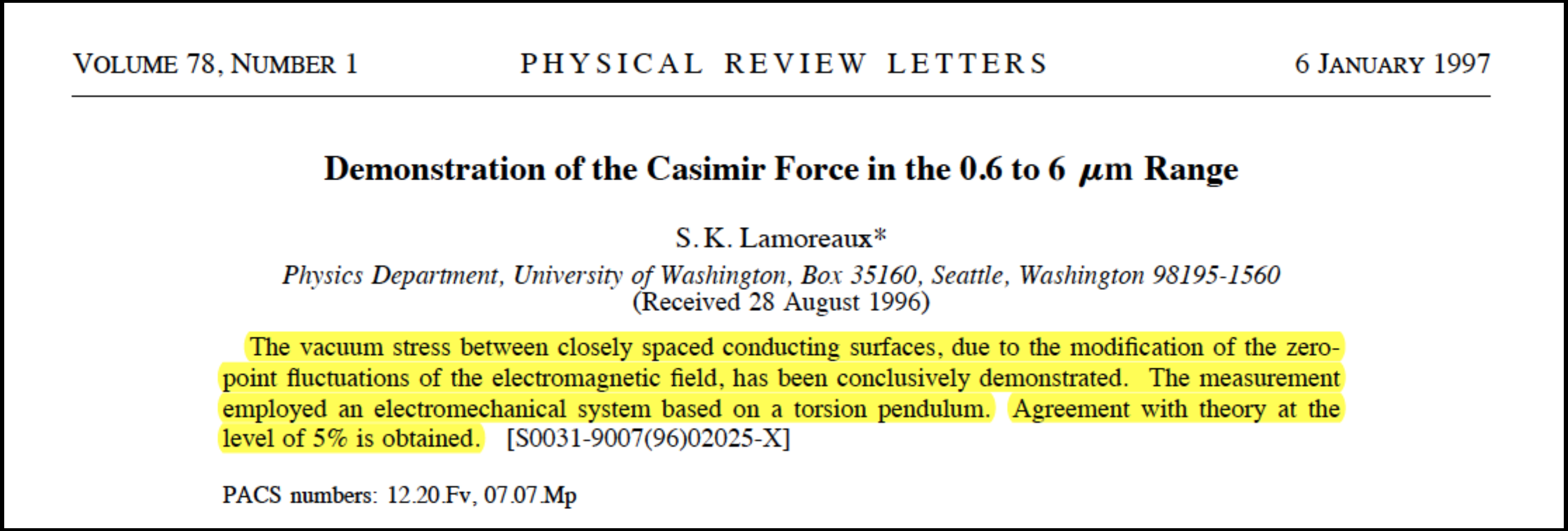
O EFEITO CASIMIR

Segunda Quantização: O campo electromagnético consiste num conjunto de osciladores harmónicos.



CASIMIR (1948):

Estre as placas condutoras só alguns modos dão permitidos.
EFEITO: Força entre as placas condutoras.



VOLUME 78, NUMBER 1 PHYSICAL REVIEW LETTERS 6 JANUARY 1997

Demonstration of the Casimir Force in the 0.6 to 6 μm Range

S. K. Lamoreaux*

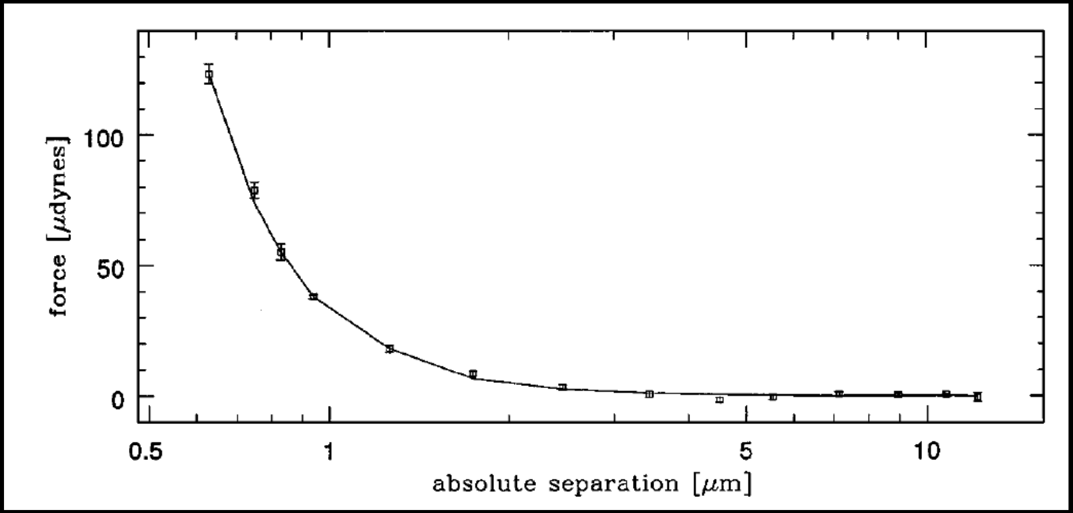
Physics Department, University of Washington, Box 35160, Seattle, Washington 98195-1560

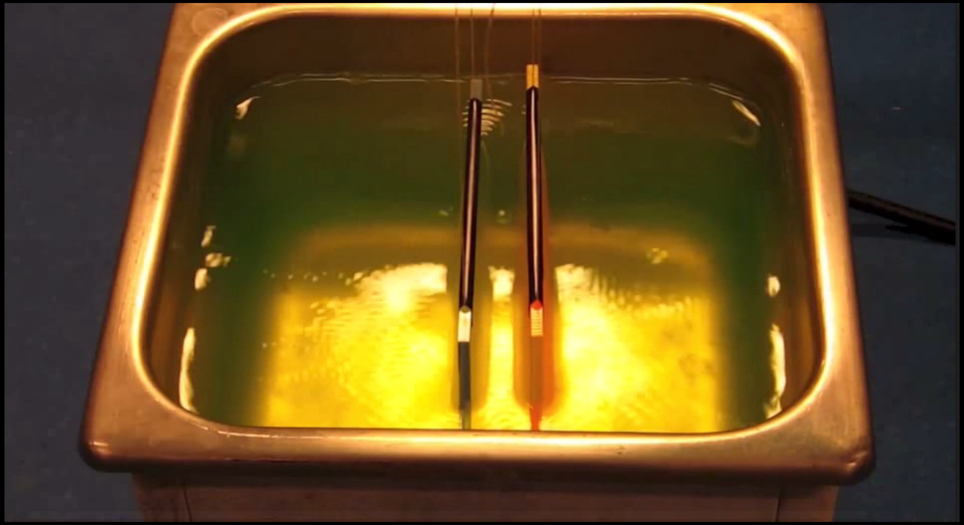
(Received 28 August 1996)

The vacuum stress between closely spaced conducting surfaces, due to the modification of the zero-point fluctuations of the electromagnetic field, has been conclusively demonstrated. The measurement employed an electromechanical system based on a torsion pendulum. Agreement with theory at the level of 5% is obtained. [S0031-9007(96)02025-X]

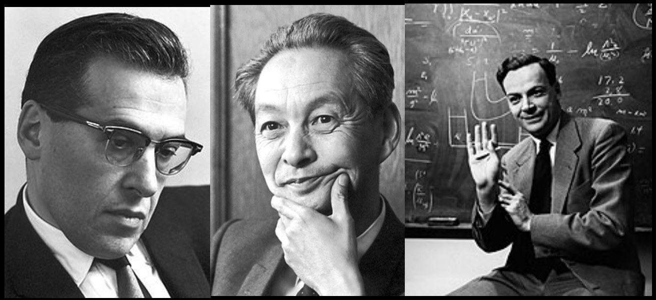
PACS numbers: 12.20.Fv, 07.07.Mp

O EFEITO CASIMIR





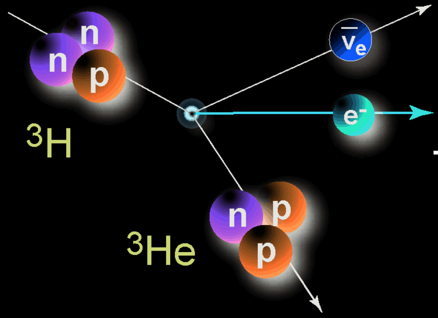
SITUAÇÃO NO FINAL DOS ANOS 40



ELECTRODINÂMICA QUÂNTICA

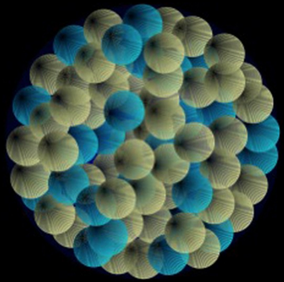
Teoria quântica dos electrões, positrões, fotões e da interacção electromagnética.

(   )



FORÇA FRACA

Teoria do decaimento radioactivo descrita pela interacção de Fermi.



FORÇA FORTE

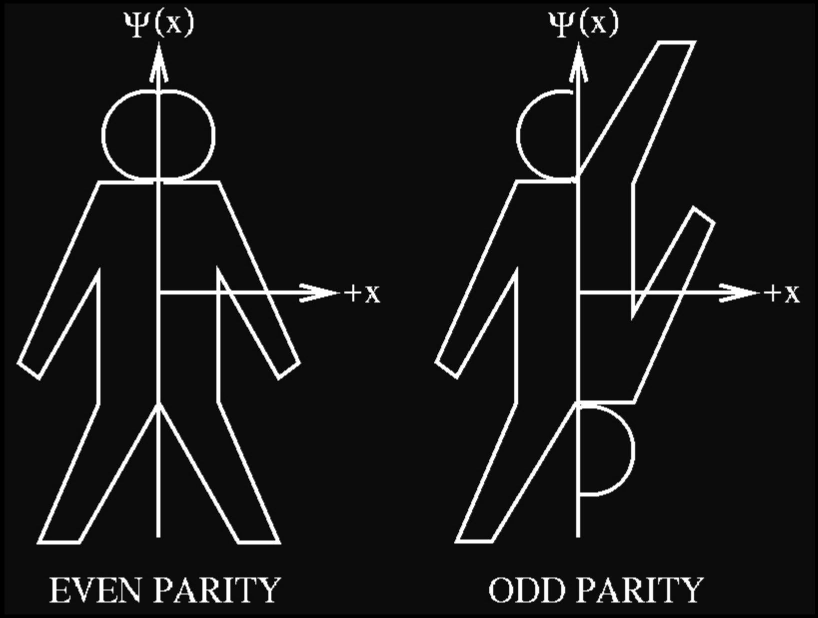
Força responsável pela coesão do núcleo descrita pelo potencial de Yukawa.

(   )

PARIDADE

Transformação de paridade P:

Uma dupla transformação de paridade corresponde a não fazer nada…



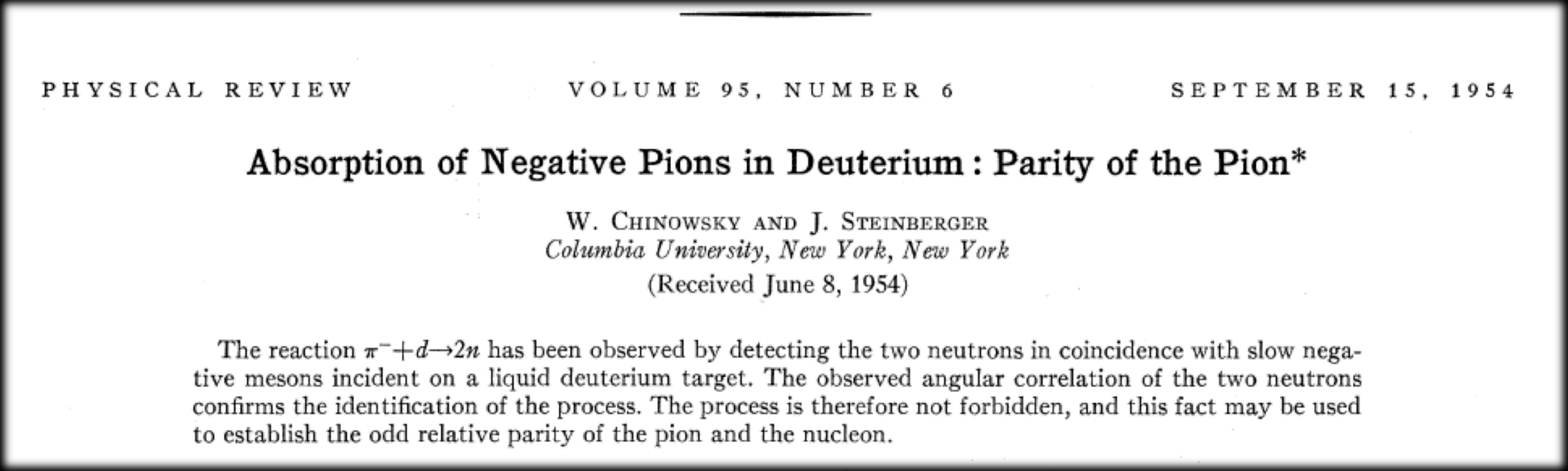
Vector: $\mathrm{P}(\vec{p})=\mathrm{P}(d\vec{r}/dt)=-\vec{p}$

Pseudo-vector: $\vec{L}=\vec{r}\times\vec{p}\ ,\ \vec{S}$

A interacção electromagnética, a força forte e a gravidade são invariantes debaixo de paridade.

1954

Paridade intrínseca: As partículas elementares (e não só) têm uma paridade intrínseca.



PHYSICAL REVIEW VOLUME 95, NUMBER 6 SEPTEMBER 15, 1954

Absorption of Negative Pions in Deuterium: Parity of the Pion*

W. Chinowsky and J. Steinberger
Columbia University, New York, New York

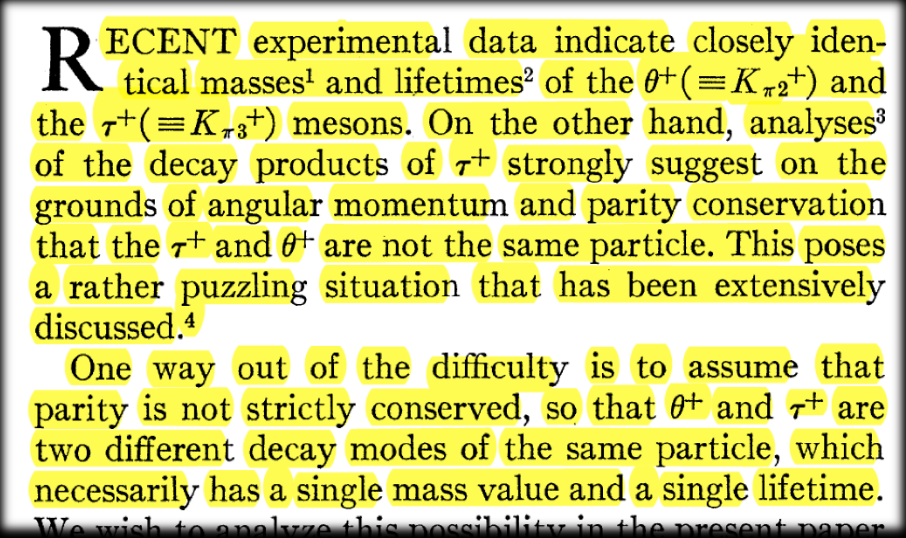
(Received June 8, 1954)

The reaction $\pi^- + d \rightarrow 2n$ has been observed by detecting the two neutrons in coincidence with slow negative mesons incident on a liquid deuterium target. The observed angular correlation of the two neutrons confirms the identification of the process. The process is therefore not forbidden, and this fact may be used to establish the odd relative parity of the pion and the nucleon.

Dalitz (1954): Puzzle $\theta - \tau$ Duas partículas (mesões θ e τ) com a mesma massa decaíam para estados de paridade diferente.

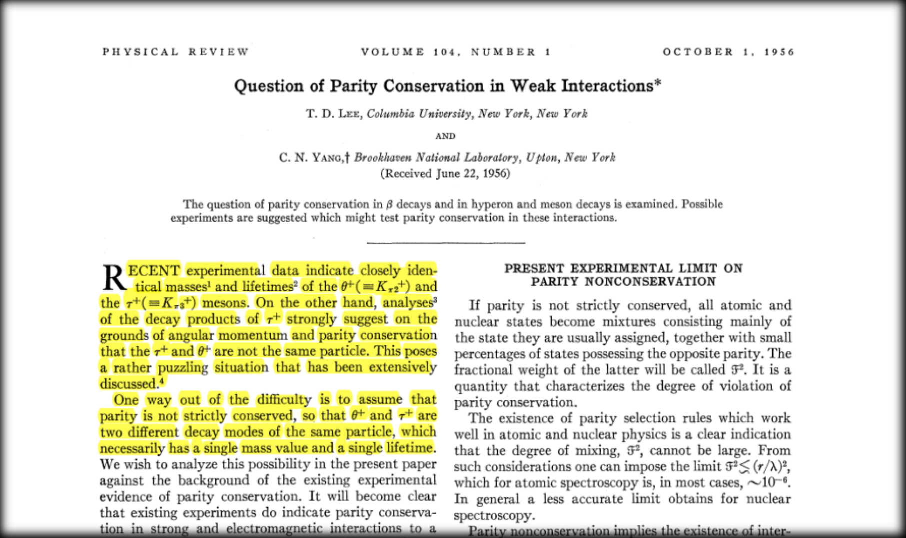
Uma proposta ousada...

1956



RECENT experimental data indicate closely identical masses[1] and lifetimes[2] of the $\theta^+(\equiv K_{\pi 2}^+)$ and the $\tau^+(\equiv K_{\pi 3}^+)$ mesons. On the other hand, analyses[3] of the decay products of τ^+ strongly suggest on the grounds of angular momentum and parity conservation that the τ^+ and θ^+ are not the same particle. This poses a rather puzzling situation that has been extensively discussed.[4]

One way out of the difficulty is to assume that parity is not strictly conserved, so that θ^+ and τ^+ are two different decay modes of the same particle, which necessarily has a single mass value and a single lifetime. We wish to analyze this possibility in the present paper



PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

Question of Parity Conservation in Weak Interactions*

T. D. LEE, *Columbia University, New York, New York*

AND

C. N. YANG,† *Brookhaven National Laboratory, Upton, New York*

(Received June 22, 1956)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.

RECENT experimental data indicate closely identical masses[1] and lifetimes[2] of the $\theta^+(\equiv K_{\pi 2}^+)$ and the $\tau^+(\equiv K_{\pi 3}^+)$ mesons. On the other hand, analyses[3] of the decay products of τ^+ strongly suggest on the grounds of angular momentum and parity conservation that the τ^+ and θ^+ are not the same particle. This poses a rather puzzling situation that has been extensively discussed.[4]

One way out of the difficulty is to assume that parity is not strictly conserved, so that θ^+ and τ^+ are two different decay modes of the same particle, which necessarily has a single mass value and a single lifetime. We wish to analyze this possibility in the present paper against the background of the existing experimental evidence of parity conservation. It will become clear that existing experiments do indicate parity conservation in strong and electromagnetic interactions to a

PRESENT EXPERIMENTAL LIMIT ON PARITY NONCONSERVATION

If parity is not strictly conserved, all atomic and nuclear states become mixtures consisting mainly of the state they are usually assigned, together with small percentages of states possessing the opposite parity. The fractional weight of the latter will be called $\mathfrak{F}^2$. It is a quantity that characterizes the degree of violation of parity conservation.

The existence of parity selection rules which work well in atomic and nuclear physics is a clear indication that the degree of mixing, $\mathfrak{F}^2$, cannot be large. From such considerations one can impose the limit $\mathfrak{F}^2 \lesssim (r/\lambda)^2$, which for atomic spectroscopy is, in most cases, $\sim 10^{-6}$. In general a less accurate limit obtains for nuclear spectroscopy.

Parity nonconservation implies the existence of inter-

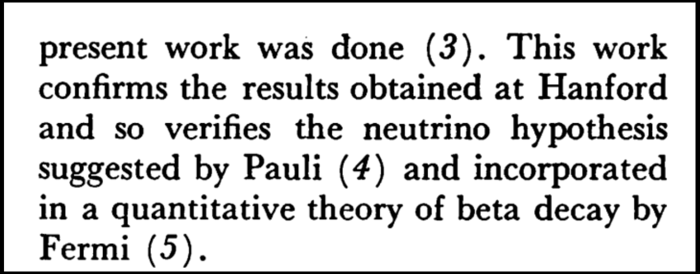
O prémio Nobel da Física foi atríbuido a C. N. Yang e T.D. Lee em 1957;

"for their penetrating investigation of the so-called parity laws which has led to important discoveries regarding the elementary particles"".

26 anos depois: finalmente o neutrino

1956

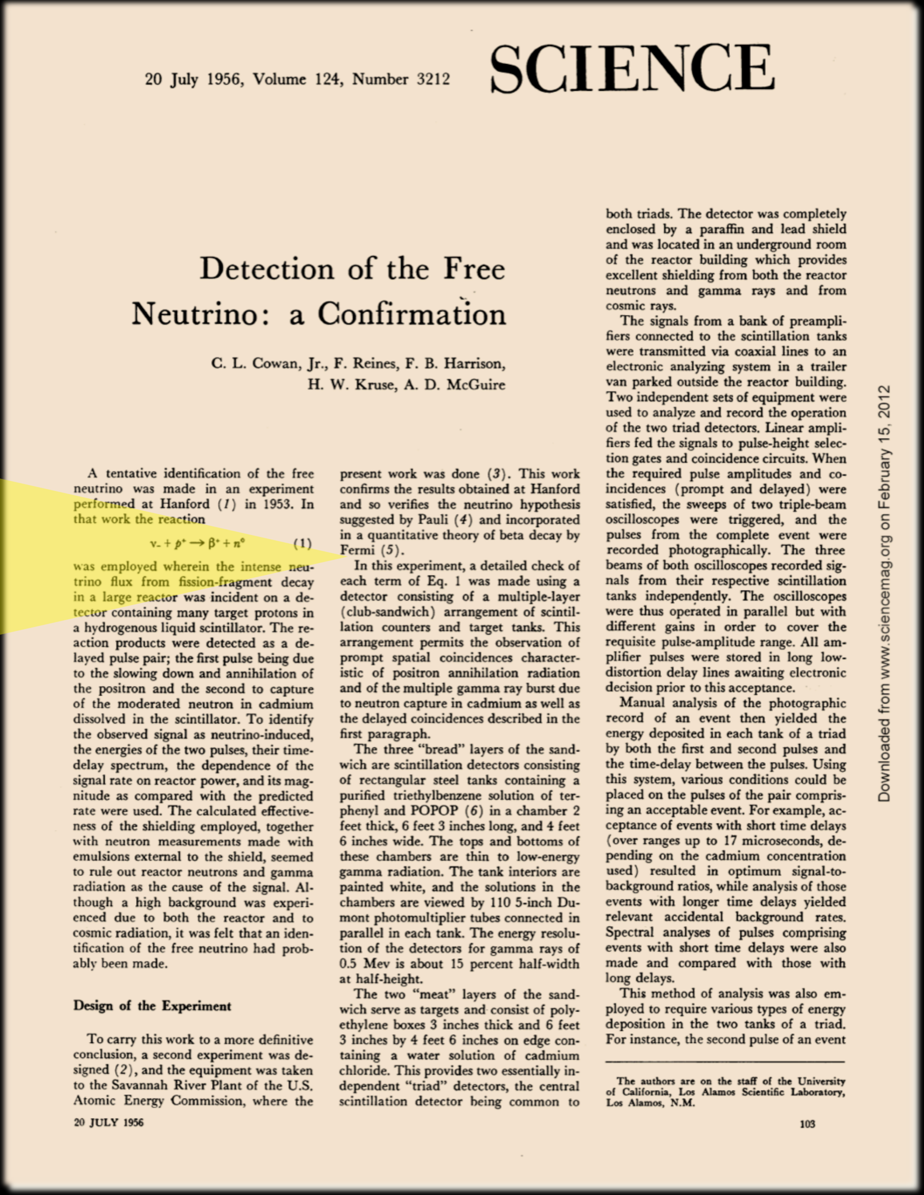
Em 1956 Cowan e Reines detectaram o neutrino do electrão usando como fonte os neutrinos provenientes de um reactor nuclear.



present work was done (*3*). This work confirms the results obtained at Hanford and so verifies the neutrino hypothesis suggested by Pauli (*4*) and incorporated in a quantitative theory of beta decay by Fermi (*5*).

O prémio Nobel da Física foi atríbuido a F. Reines em 1995;

"for the detection of the neutrino"



20 July 1956, Volume 124, Number 3212 SCIENCE

Detection of the Free Neutrino: a Confirmation

C. L. Cowan, Jr., F. Reines, F. B. Harrison,
H. W. Kruse, A. D. McGuire

A tentative identification of the free neutrino was made in an experiment performed at Hanford (*1*) in 1953. In that work the reaction

$$\nu_- + p^+ \rightarrow \beta^+ + n^0 \qquad (1)$$

was employed wherein the intense neutrino flux from fission-fragment decay in a large reactor was incident on a detector containing many target protons in a hydrogenous liquid scintillator. The reaction products were detected as a delayed pulse pair; the first pulse being due to the slowing down and annihilation of the positron and the second to capture of the moderated neutron in cadmium dissolved in the scintillator. To identify the observed signal as neutrino-induced, the energies of the two pulses, their time-delay spectrum, the dependence of the signal rate on reactor power, and its magnitude as compared with the predicted rate were used. The calculated effectiveness of the shielding employed, together with neutron measurements made with emulsions external to the shield, seemed to rule out reactor neutrons and gamma radiation as the cause of the signal. Although a high background was experienced due to both the reactor and to cosmic radiation, it was felt that an identification of the free neutrino had probably been made.

Design of the Experiment

To carry this work to a more definitive conclusion, a second experiment was designed (*2*), and the equipment was taken to the Savannah River Plant of the U.S. Atomic Energy Commission, where the present work was done (*3*). This work confirms the results obtained at Hanford and so verifies the neutrino hypothesis suggested by Pauli (*4*) and incorporated in a quantitative theory of beta decay by Fermi (*5*).

In this experiment, a detailed check of each term of Eq. 1 was made using a detector consisting of a multiple-layer (club-sandwich) arrangement of scintillation counters and target tanks. This arrangement permits the observation of prompt spatial coincidences characteristic of positron annihilation radiation and of the multiple gamma ray burst due to neutron capture in cadmium as well as the delayed coincidences described in the first paragraph.

The three "bread" layers of the sandwich are scintillation detectors consisting of rectangular steel tanks containing a purified triethylbenzene solution of terphenyl and POPOP (*6*) in a chamber 2 feet thick, 6 feet 3 inches long, and 4 feet 6 inches wide. The tops and bottoms of these chambers are thin to low-energy gamma radiation. The tank interiors are painted white, and the solutions in the chambers are viewed by 110 5-inch Dumont photomultiplier tubes connected in parallel in each tank. The energy resolution of the detectors for gamma rays of 0.5 Mev is about 15 percent half-width at half-height.

The two "meat" layers of the sandwich serve as targets and consist of polyethylene boxes 3 inches thick and 6 feet 3 inches by 4 feet 6 inches on edge containing a water solution of cadmium chloride. This provides two essentially independent "triad" detectors, the central scintillation detector being common to both triads. The detector was completely enclosed by a paraffin and lead shield and was located in an underground room of the reactor building which provides excellent shielding from both the reactor neutrons and gamma rays and from cosmic rays.

The signals from a bank of preamplifiers connected to the scintillation tanks were transmitted via coaxial lines to an electronic analyzing system in a trailer van parked outside the reactor building. Two independent sets of equipment were used to analyze and record the operation of the two triad detectors. Linear amplifiers fed the signals to pulse-height selection gates and coincidence circuits. When the required pulse amplitudes and coincidences (prompt and delayed) were satisfied, the sweeps of two triple-beam oscilloscopes were triggered, and the pulses from the complete event were recorded photographically. The three beams of both oscilloscopes recorded signals from their respective scintillation tanks independently. The oscilloscopes were thus operated in parallel but with different gains in order to cover the requisite pulse-amplitude range. All amplifier pulses were stored in long low-distortion delay lines awaiting electronic decision prior to this acceptance.

Manual analysis of the photographic record of an event then yielded the energy deposited in each tank of a triad by both the first and second pulses and the time-delay between the pulses. Using this system, various conditions could be placed on the pulses of the pair comprising an acceptable event. For example, acceptance of events with short time delays (over ranges up to 17 microseconds, depending on the cadmium concentration used) resulted in optimum signal-to-background ratios, while analysis of those events with longer time delays yielded relevant accidental background rates. Spectral analyses of pulses comprising events with short time delays were also made and compared with those with long delays.

This method of analysis was also employed to require various types of energy deposition in the two tanks of a triad. For instance, the second pulse of an event

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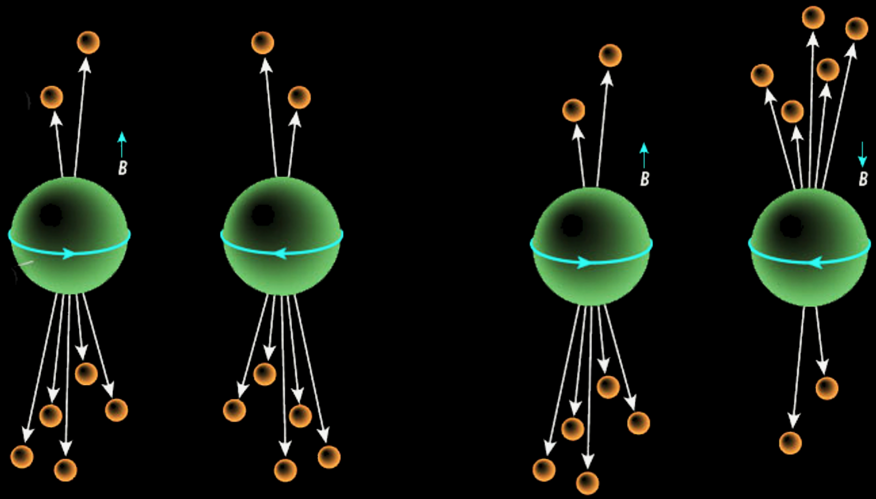
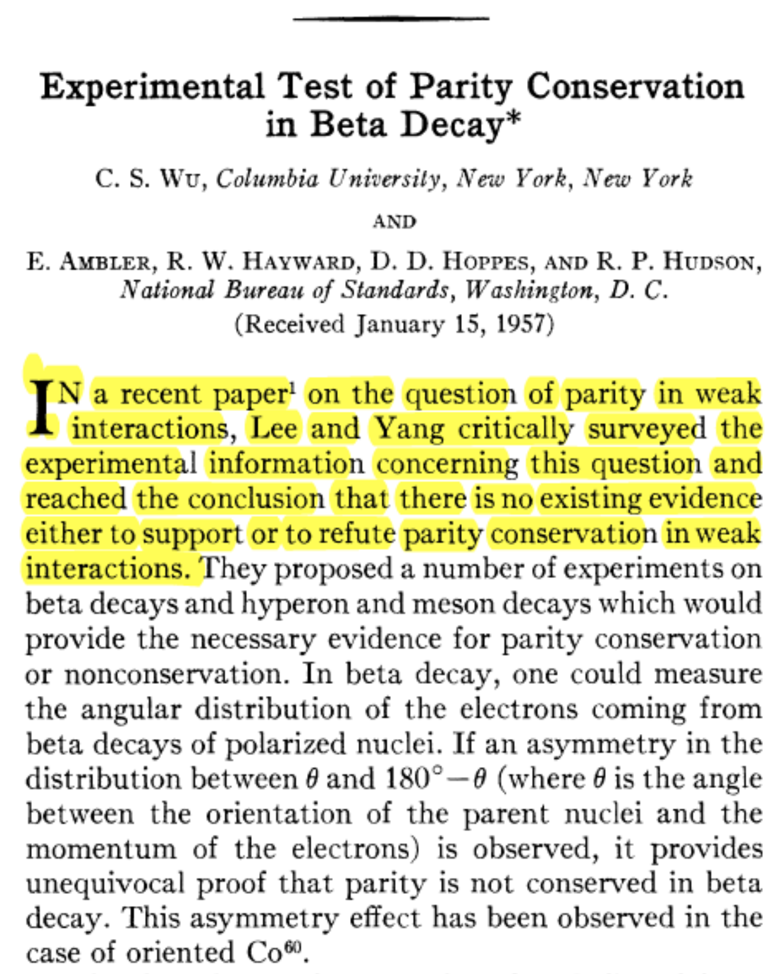
The authors are on the staff of the University of California, Los Alamos Scientific Laboratory, Los Alamos, N.M.

A experiência de Wu: um Nobel não dado?

1957



Em 1957 Wu obtém a prova experimental de que a paridade não é conservada pela interacção fraca.



Experimental Test of Parity Conservation in Beta Decay*

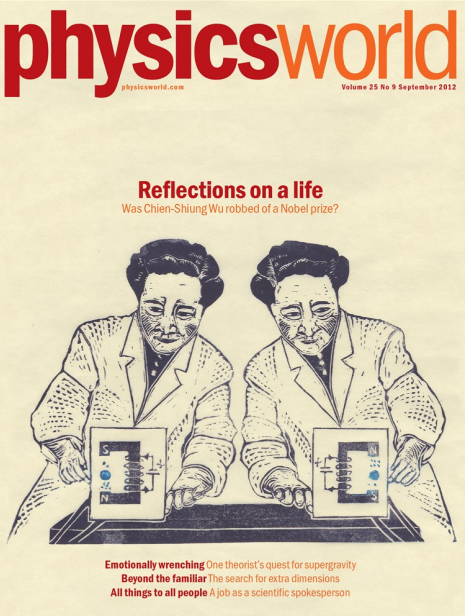
C. S. Wu, *Columbia University, New York, New York*

AND

E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, *National Bureau of Standards, Washington, D. C.*

(Received January 15, 1957)

In a recent paper[1] on the question of parity in weak interactions, Lee and Yang critically surveyed the experimental information concerning this question and reached the conclusion that there is no existing evidence either to support or to refute parity conservation in weak interactions. They proposed a number of experiments on beta decays and hyperon and meson decays which would provide the necessary evidence for parity conservation or nonconservation. In beta decay, one could measure the angular distribution of the electrons coming from beta decays of polarized nuclei. If an asymmetry in the distribution between θ and $180°-\theta$ (where θ is the angle between the orientation of the parent nuclei and the momentum of the electrons) is observed, it provides unequivocal proof that parity is not conserved in beta decay. This asymmetry effect has been observed in the case of oriented Co^{60}.



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Volume 25 No 9 September 2012

Reflections on a life

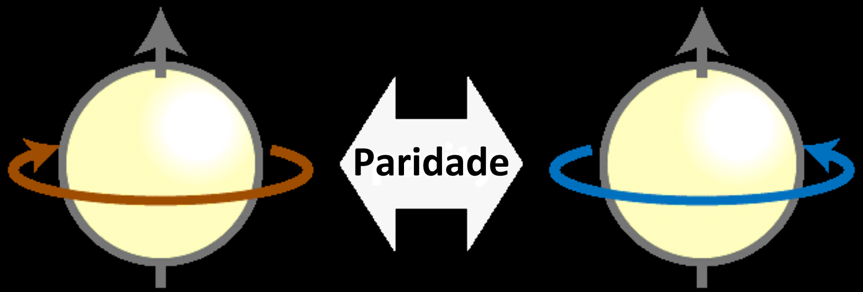
Was Chien-Shiung Wu robbed of a Nobel prize?

Emotionally wrenching One theorist's quest for supergravity

Beyond the familiar The search for extra dimensions

All things to all people A job as a scientific spokesperson

PARIDADE E HELICIDADE



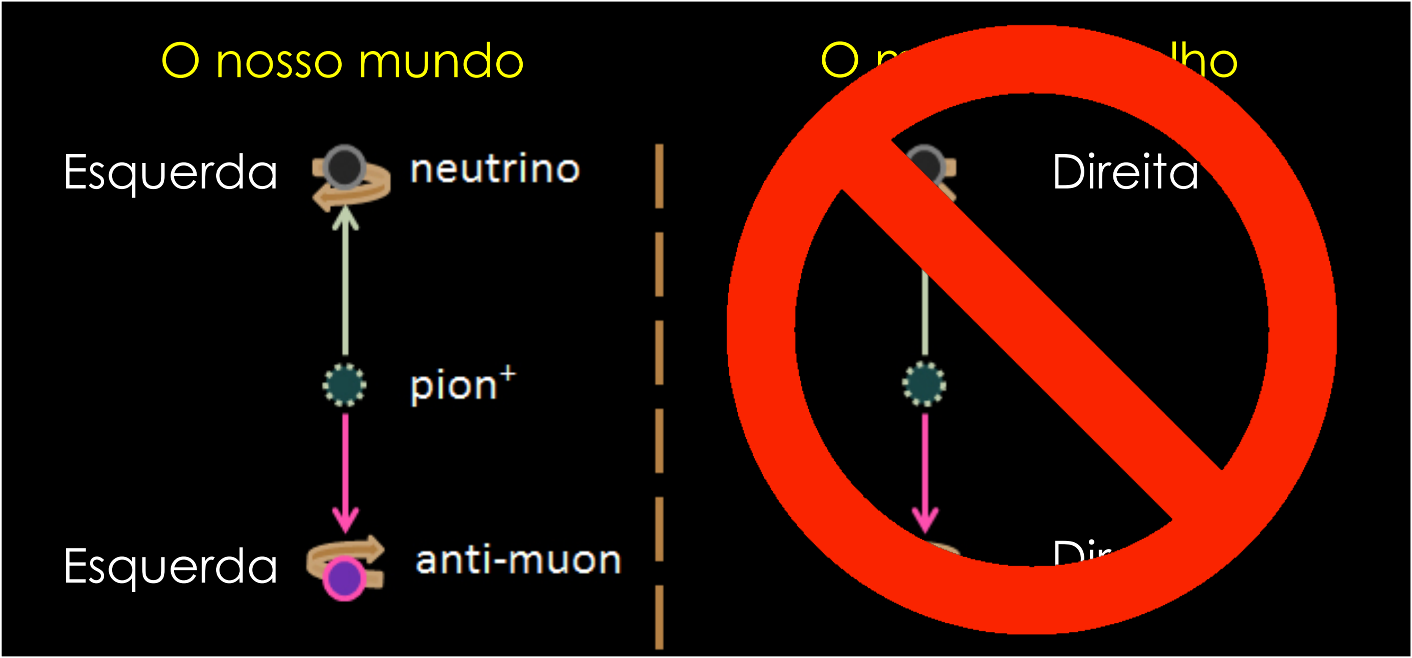
Esquerda

Direita

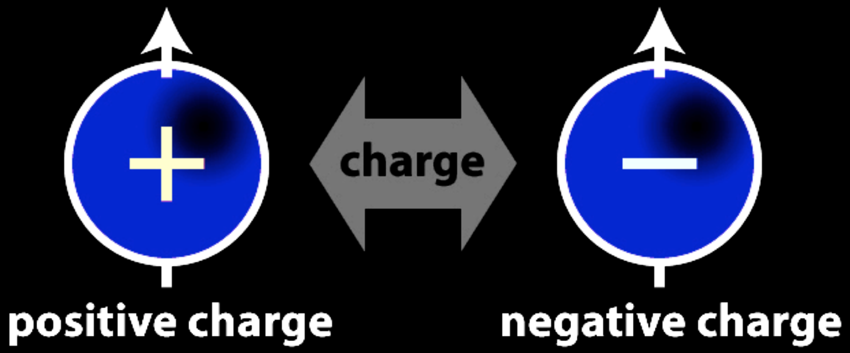
HELICIDADE:

h=1 : Direita

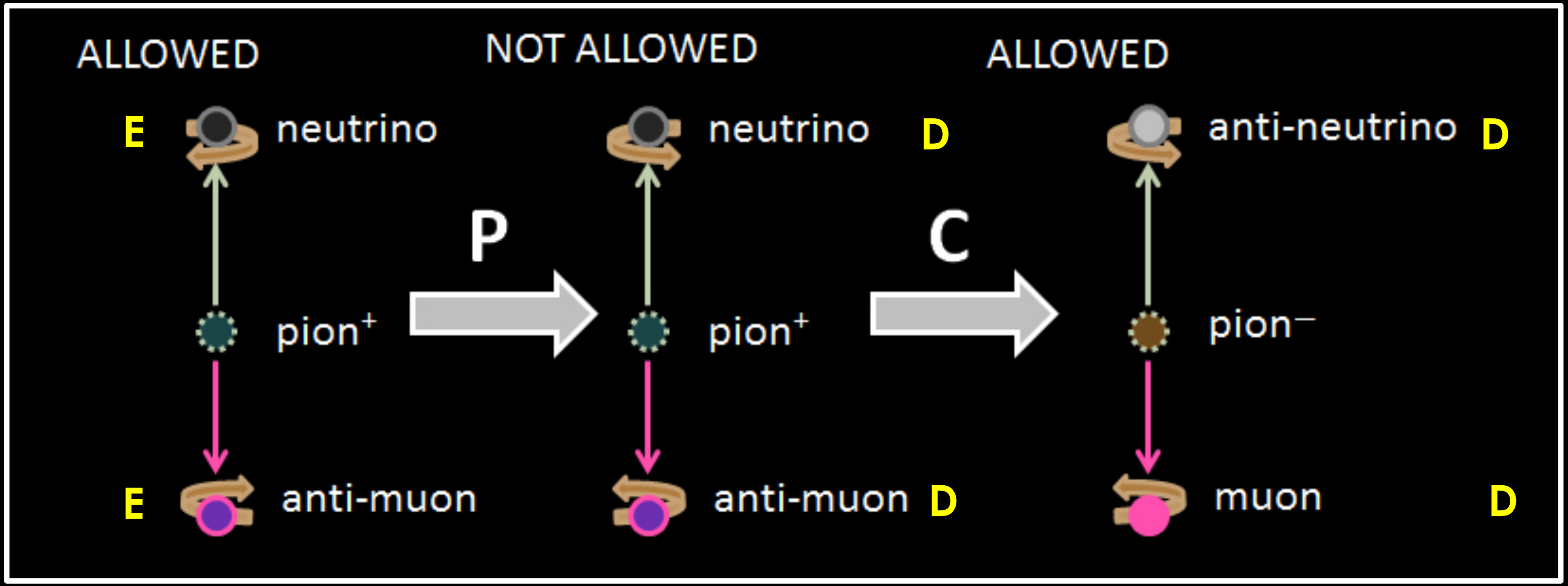
h=-1 : Esquerda



SIMETRIAS C (conjugação de carga) E CP



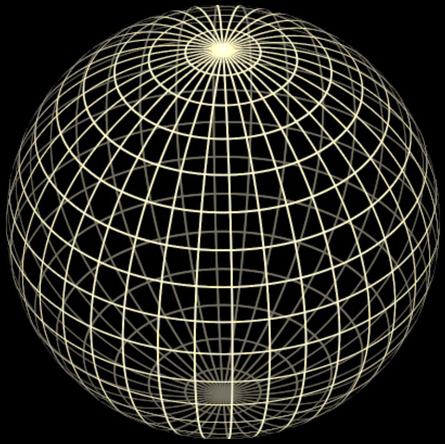
A conjugação de carga transforma uma partícula na sua antipartícula



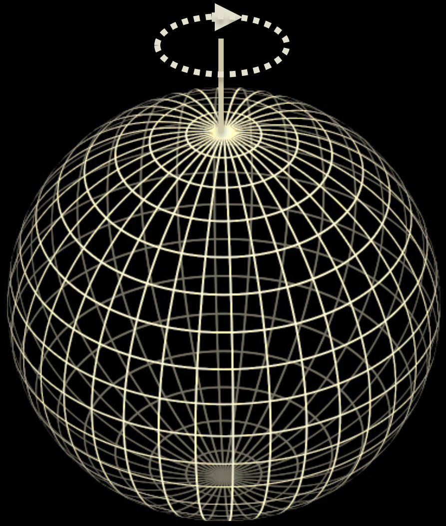
TALVEZ CP SEJA CONSERVADA…

TRANSFORMAÇÕES GLOBAIS E LOCAIS

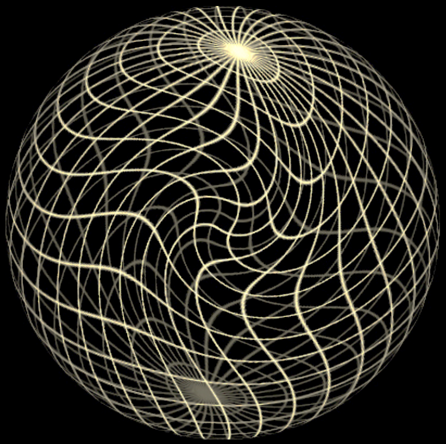
Esfera original

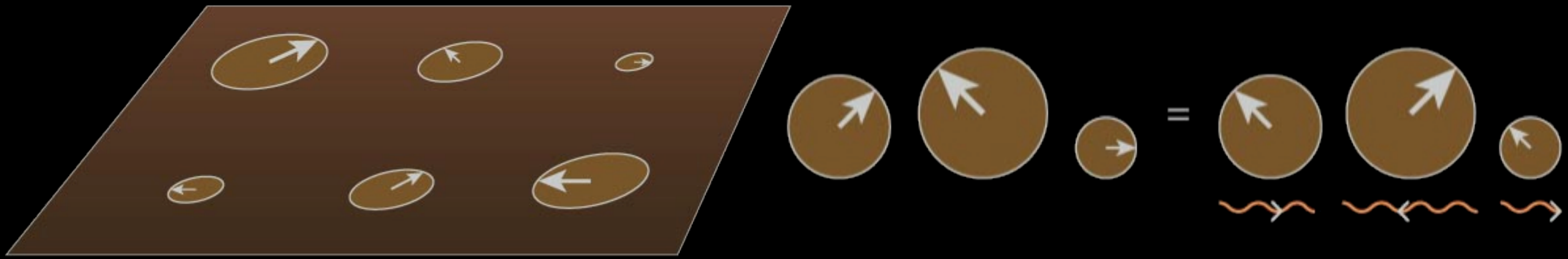


Transformação global



Transformação local





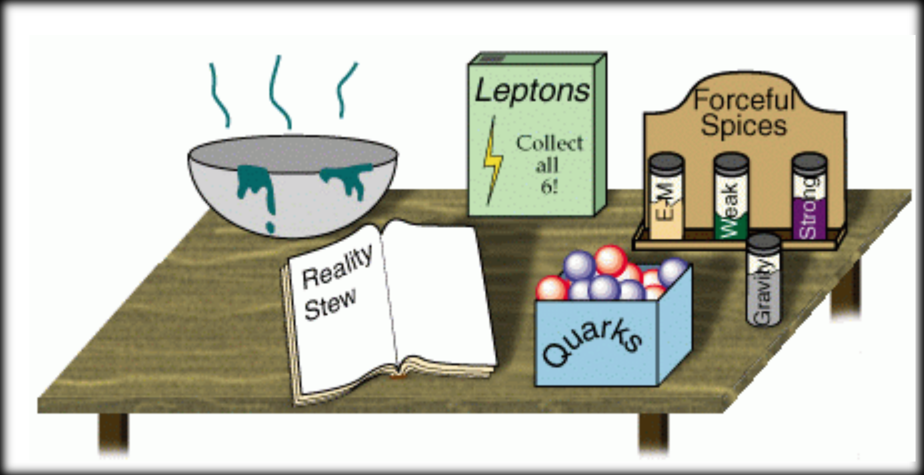
Os bosões de gauge (e respectivas forças) surgem como consequência de impôr invariância debaixo de simetrias locais

O MODELO PADRÃO: A RECEITA

O GRUPO DE SIMETRIA DO MODELO PADRÃO É:

$$SU(2)_L \times U(1)_Y$$

Glashow Weinberg Salam



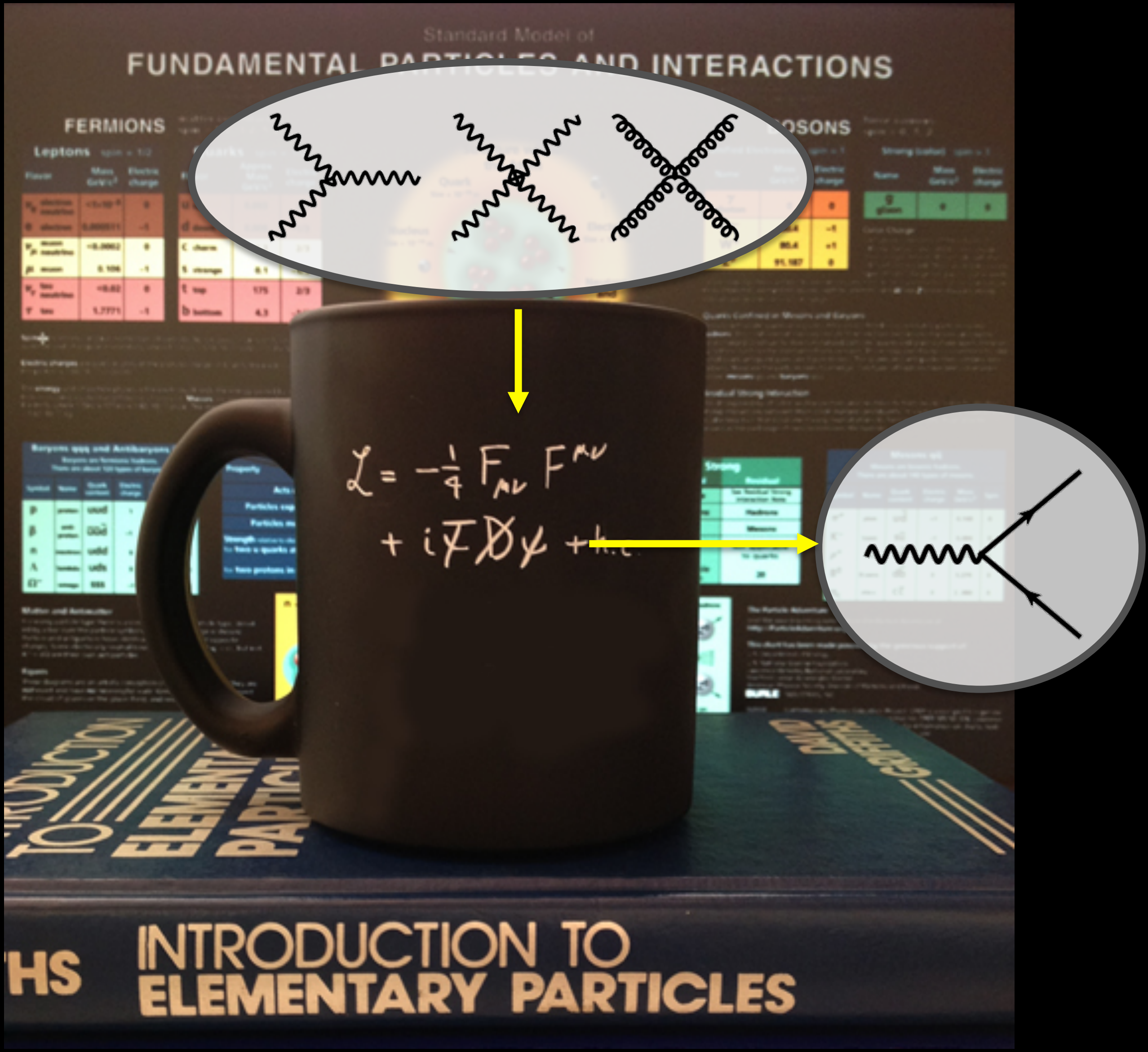
1) Distribua as partículas elementares pelas "representações" do grupo de simetria.

2) Escreva todas as interacções que são invariantes debaixo do grupo de simetria local.

RESULTADO: Teoria que descreve a interacção dos quarks, leptões e bosões de gauge.

mas… Todas as partículas têm massa nula !

Até agora a chávena do CERN é assim:



1964

O mecanismo ABEGHHK'tH

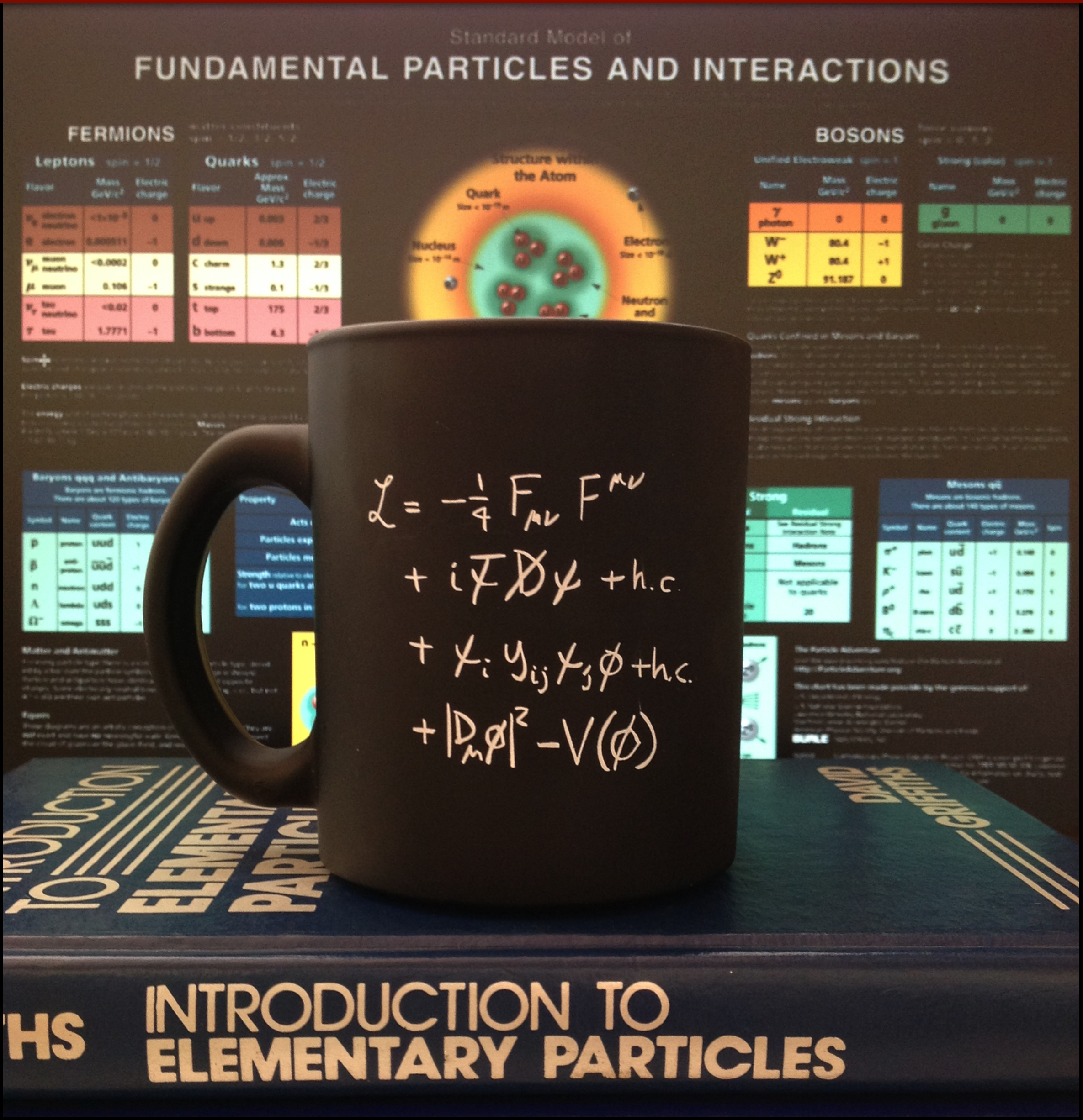
Anderson, Brout, Englert, Guralnik, Hagen, Higgs, Kibble and ‘t Hooft

Φ

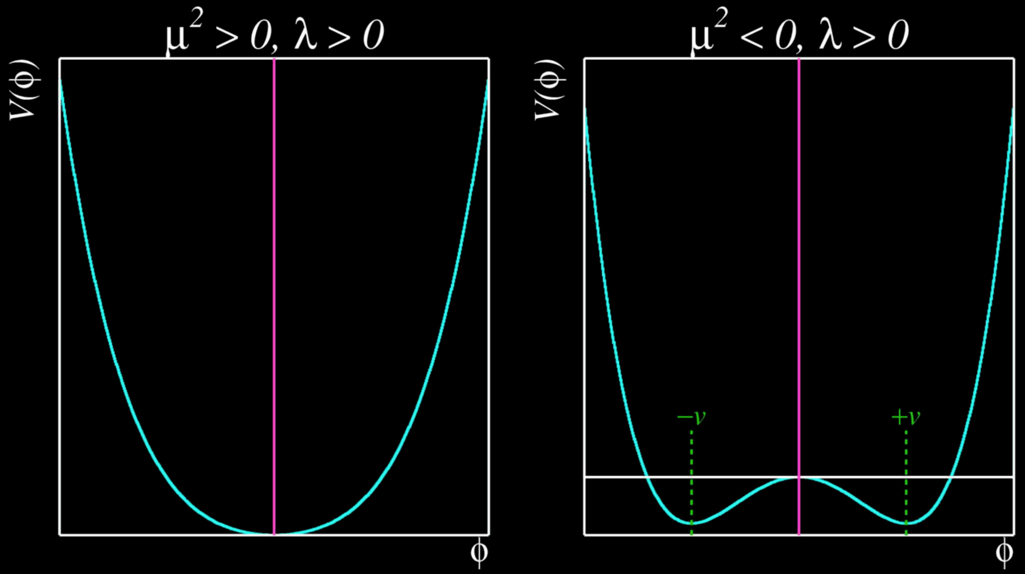
Como funciona então o mecanismo ABEGHHK'tH?

O CAMPO DE HIGGS...

A chávena CERN depois de introduzir o Φ



O MECANISMO DE HIGGS



$$V(\phi) = \mu^2 |\phi|^2 + \lambda |\phi|^4$$

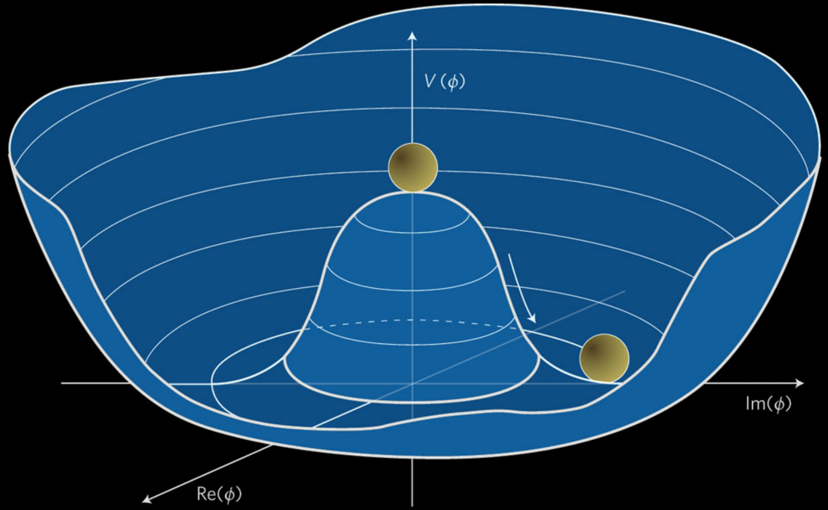
"NO VÁCUO": $v = \sqrt{-\frac{\mu^2}{2\lambda}}$

Essencial para o mecanismo de Higgs funcionar.

A simetria é quebrada espontâneamente!!

Os bosões de gauge (W e Z) e os fermiões adquirem massa!

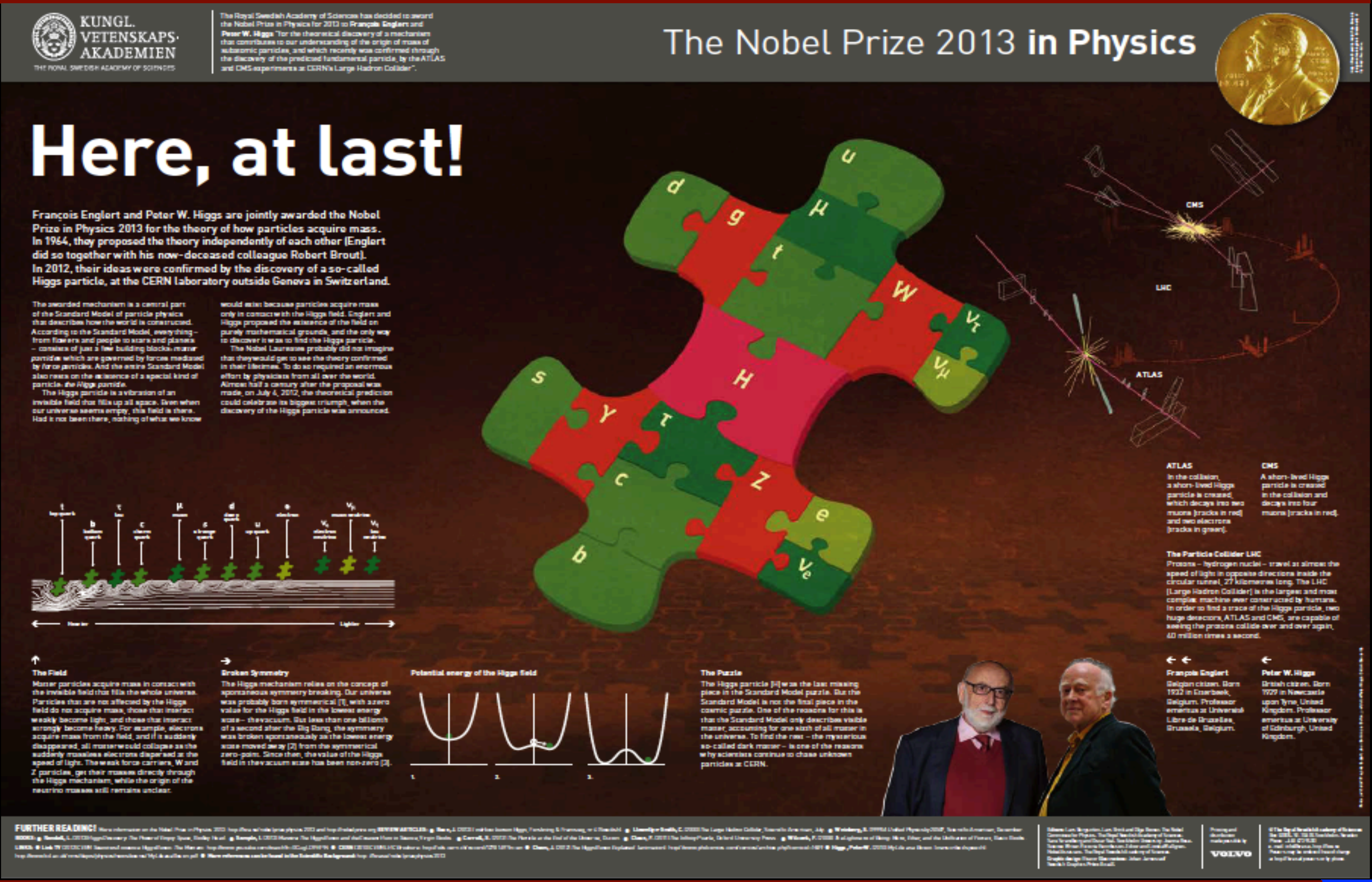
E... O FOTÃO PERMANECE SEM MASSA!!!



UMA ANALOGIA PARA O MECANISMO DE HIGGS

https://www.youtube.com/watch?v=joTKd5j3mzk

PRÉMIO NOBEL DA FÍSICA 2013



KUNGL. VETENSKAPS·AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2013 to **François Englert** and **Peter W. Higgs** "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider".

The Nobel Prize 2013 **in Physics**

Here, at last!

François Englert and Peter W. Higgs are jointly awarded the Nobel Prize in Physics 2013 for the theory of how particles acquire mass. In 1964, they proposed the theory independently of each other (Englert did so together with his now-deceased colleague Robert Brout). In 2012, their ideas were confirmed by the discovery of a so-called Higgs particle, at the CERN laboratory outside Geneva in Switzerland.

The awarded mechanism is a central part of the Standard Model of particle physics that describes how the world is constructed. According to the Standard Model, everything – from flowers and people to stars and planets – consists of just a few building blocks: *matter particles* which are governed by forces mediated by *force particles*. And the entire Standard Model also rests on the existence of a special kind of particle: *the Higgs particle*.

The Higgs particle is a vibration of an invisible field that fills up all space. Even when our universe seems empty, this field is there. Had it not been there, nothing of what we know would exist because particles acquire mass only in contact with the Higgs field. Englert and Higgs proposed the existence of the field on purely mathematical grounds, and the only way to discover it was to find the Higgs particle.

The Nobel Laureates probably did not imagine that they would get to see the theory confirmed in their lifetimes. To do so required an enormous effort by physicists from all over the world. Almost half a century after the proposal was made, on July 4, 2012, the theoretical prediction could celebrate its biggest triumph, when the discovery of the Higgs particle was announced.

ATLAS
In the collision, a short-lived Higgs particle is created, which decays into two muons (tracks in red) and two electrons (tracks in green).

CMS
A short-lived Higgs particle is created in the collision and decays into four muons (tracks in red).

The Particle Collider LHC
Protons – hydrogen nuclei – travel at almost the speed of light in opposite directions inside the circular tunnel, 27 kilometres long. The LHC (Large Hadron Collider) is the largest and most complex machine ever constructed by humans. In order to find a trace of the Higgs particle, two huge detectors, ATLAS and CMS, are capable of seeing the protons collide over and over again, 40 million times a second.

The Field
Matter particles acquire mass in contact with the invisible field that fills the whole universe. Particles that are not affected by the Higgs field do not acquire mass, those that interact weakly become light, and those that interact strongly become heavy. For example, electrons acquire mass from the field, and if it suddenly disappeared, all matter would collapse as the suddenly massless electrons dispersed at the speed of light. The weak force carriers, W and Z particles, get their masses directly through the Higgs mechanism, while the origin of the neutrino masses still remains unclear.

Broken Symmetry
The Higgs mechanism relies on the concept of spontaneous symmetry breaking. Our universe was probably born symmetrical (1), with a zero value for the Higgs field in the lowest energy state – the vacuum. But less than one billionth of a second after the Big Bang, the symmetry was broken spontaneously as the lowest energy state moved away (2) from the symmetrical zero-point. Since then, the value of the Higgs field in the vacuum state has been non-zero (3).

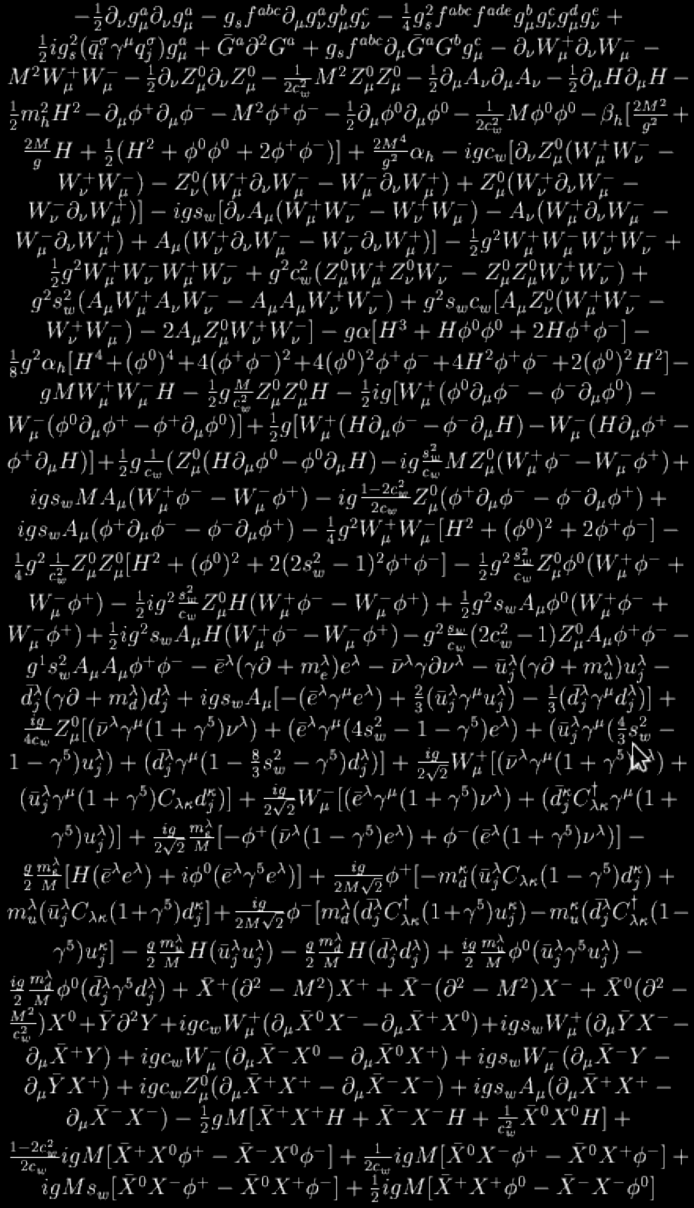
The Puzzle
The Higgs particle (H) was the last missing piece in the Standard Model puzzle. But the Standard Model is not the final piece in the cosmic puzzle. One of the reasons for this is that the Standard Model only describes visible matter, accounting for one sixth of all matter in the universe. To find the rest – the mysterious so-called dark matter – is one of the reasons why scientists continue to chase unknown particles at CERN.

François Englert
Belgian citizen. Born 1932 in Etterbeek, Belgium. Professor emeritus at Université Libre de Bruxelles, Brussels, Belgium.

Peter W. Higgs
British citizen. Born 1929 in Newcastle upon Tyne, United Kingdom. Professor emeritus at University of Edinburgh, United Kingdom.

FURTHER READING!

O LAGRANGIANO DO MODELO STANDARD



$$\begin{gathered}
-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
\frac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu\partial_\mu A_\nu - \frac{1}{2}\partial_\mu H\partial_\mu H - \\
\frac{1}{2}m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} + \\
\frac{2M}{g}H + \frac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - \\
W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - \\
W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
\frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
g^2s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \\
\frac{1}{8}g^2\alpha_h[H^4+(\phi^0)^4+4(\phi^+\phi^-)^2+4(\phi^0)^2\phi^+\phi^-+4H^2\phi^+\phi^-+2(\phi^0)^2H^2] - \\
gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - \\
W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \\
\phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + \\
igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + \\
igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2W^+_\mu W^-_\mu[H^2+(\phi^0)^2+2\phi^+\phi^-] - \\
\frac{1}{4}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2+(\phi^0)^2+2(2s_w^2-1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \frac{1}{2}ig^2s_wA_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial+m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial+m_u^\lambda)u^\lambda_j - \\
\bar{d}^\lambda_j(\gamma\partial+m_d^\lambda)d^\lambda_j + igs_wA_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \\
\frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2 - \\
1-\gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1-\frac{8}{3}s_w^2-\gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + \\
(\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+ \\
\gamma^5)u^\lambda_j)] + \frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \\
\frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_jC_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + \\
m_u^\lambda(\bar{u}^\lambda_jC_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_jC^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_jC^\dagger_{\lambda\kappa}(1- \\
\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m_u^\lambda}{M}H(\bar{u}^\lambda_ju^\lambda_j) - \frac{g}{2}\frac{m_d^\lambda}{M}H(\bar{d}^\lambda_jd^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5u^\lambda_j) - \\
\frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5d^\lambda_j) + \bar{X}^+(\partial^2-M^2)X^+ + \bar{X}^-(\partial^2-M^2)X^- + \bar{X}^0(\partial^2 - \\
\frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2Y + igc_wW^+_\mu(\partial_\mu\bar{X}^0X^- - \partial_\mu\bar{X}^+X^0) + igs_wW^+_\mu(\partial_\mu\bar{Y}X^- - \\
\partial_\mu\bar{X}^+Y) + igc_wW^-_\mu(\partial_\mu\bar{X}^-X^0 - \partial_\mu\bar{X}^0X^+) + igs_wW^-_\mu(\partial_\mu\bar{X}^-Y - \\
\partial_\mu\bar{Y}X^+) + igc_wZ^0_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) + igs_wA_\mu(\partial_\mu\bar{X}^+X^+ - \\
\partial_\mu\bar{X}^-X^-) - \frac{1}{2}gM[\bar{X}^+X^+H + \bar{X}^-X^-H + \frac{1}{c_w^2}\bar{X}^0X^0H] + \\
\frac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + \\
igMs_w[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0]
\end{gathered}$$

O MECANISMO DE HIGGS

Algumas previsões da teoria:

$$M_Z \cos\theta_W = M_W \,, \quad \sin^2\theta_W = 1 - M_W^2/M_Z^2$$

$$M_W^2 \sin^2\theta_W = \frac{e^2}{4\pi\sqrt{2}\, G_F}$$

Os bosões W e Z foram descobertos no CERN em 1983.

$$M_W = 80.385 \pm 0.015 \text{ GeV}$$

$$M_Z = 91.1876 \pm 0.086 \text{ GeV}$$

O detector gargamelle

O prémio Nobel da Física foi atríbuido a Rubbia e Van De Meer em 1984;

"for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction"

O NOBEL PARA O MODELO PADRÃO

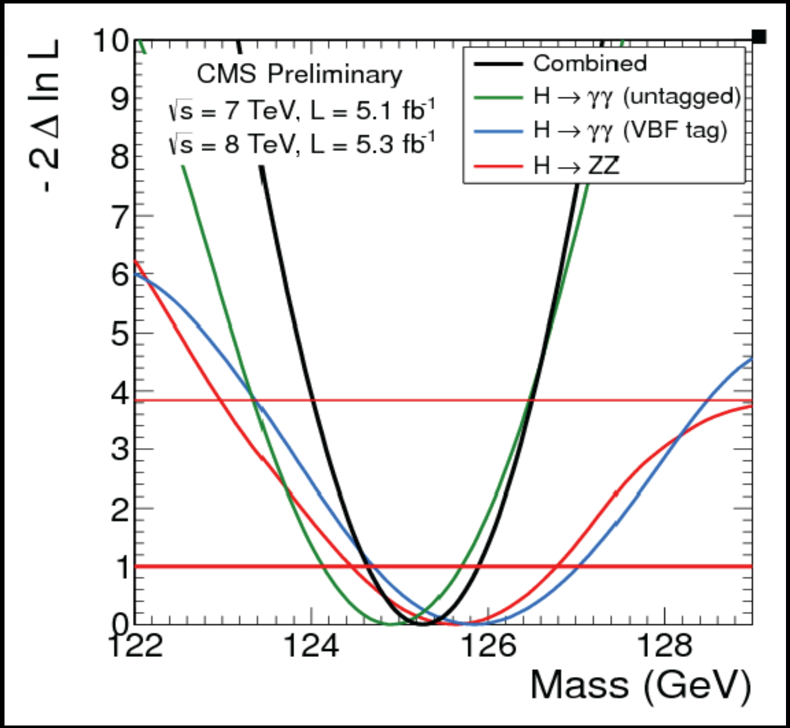
O prémio Nobel da Física foi atríbuido a Glashow, Weinberg e Salam em 1979;

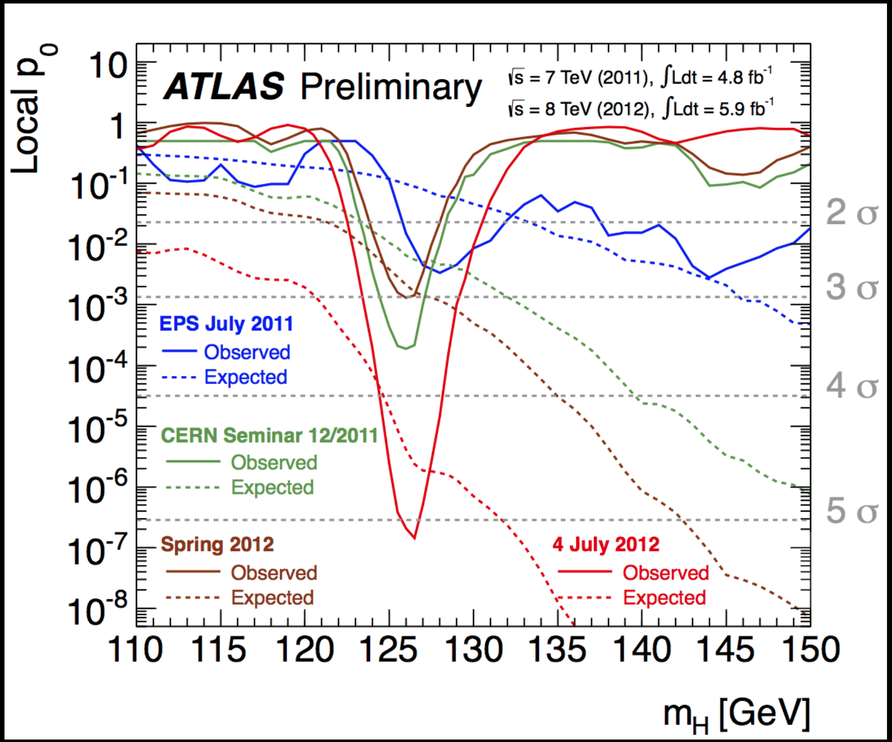
"for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, the prediction of the weak neutral current".

Até ao dia 4 de Julho de 2012 não se sabia nada sobre o que estava por detrás da quebra de simetria electrofraca.

Até que...

BORN ON THE 4TH OF JULY





"The discovery of a particle consistent with the Higgs boson opens the way to more detailed studies, … , and is likely to shed light on other mysteries of our Universe."

Rolf Heuer, CERN D.G., Press Release July 4, 2012

"We are reaching into the fabric of the Universe at the level never done before… We are in the edge of a new exploration."

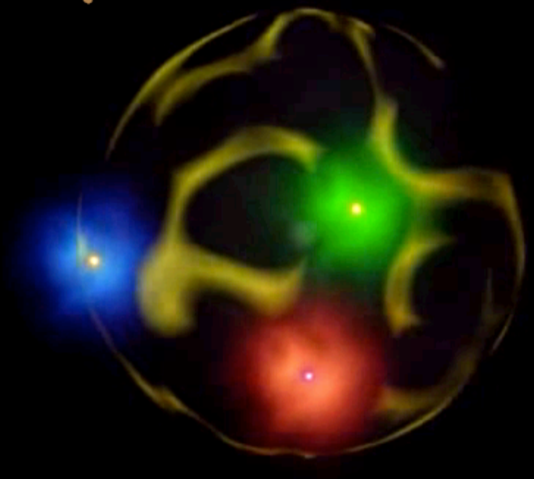
Joe Incandela, CMS spokesperson, Press Conference, July 4, 2012

O ACONTECIMENTO CIENTÍFICO MAIS MEDIÁTICO

“ENTÃO A MASSA VEM TODA DO HIGGS?”

Protão p = uud: $2\,m_u + m_d = 11\ \mathrm{MeV}$

$$m_p = 938\ \mathrm{MeV}$$

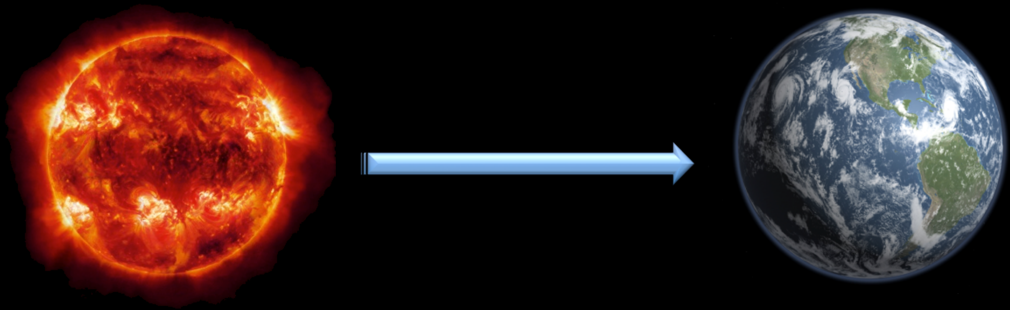


Só 1% da massa do protão é devida à massa em repouso dos quarks, ou seja…

Apenas uma infima parte da massa é devida ao mecanismo de Higgs…

1964: MISTÉRIO DOS NEUTRINOS DESAPARECIDOS

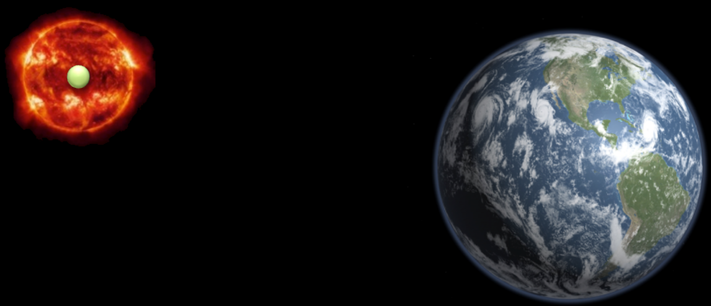
Bachall



Davis

- O número de neutrinos que saem do Sol está mal calculado, OU
- A experiência está errada.

OSCILAÇÕES DE NEUTRINOS



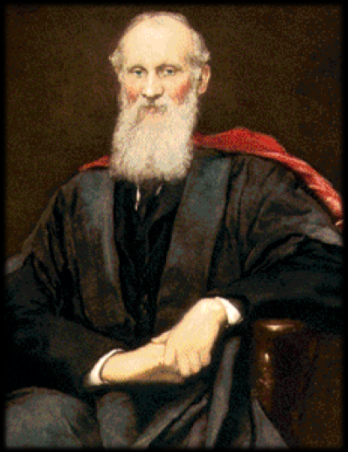
$$P = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2}{4E}L\right)$$

$$\Delta m^2 = m_2^2 - m_1^2$$

E AGORA?

O QUE DIRIA KELVIN AGORA?

"Twentieth first-Century Clouds over the electroweak theory"



"A beleza e a clareza da teoria electrofraca está obscurecida por algumas núvens"

As núvens do Pedro:

- Matéria escura e energia escura
- Porque existe mais matéria que anti-matéria no Universo?
- Porquê 3 famílias?;
- Problema da Hierarquia;
- Porque é que as massas das partículas elementares são o que são;
- Porque é que os neutrinos são muito mais leves do que os leptões carregados e os quarks;
- Será que as 3 (ou 4) forças se unificam a alguma escala?;
- Será que as partículas elementares são mesmo elementares?;

“We are in the edge of a new exploration.”

filipe.joaquim@tecnico.ulisboa.pt

ALGUNS LIVROS (Os mais actuais em inglês)