Higgs boson: the true story

FESB, July 12, 2022

Goran Senjanović
LMU, Munich&ICTP, Trieste

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Higgs boson discovered @LHC

Crowning achievement of the theory of elementary particle interactions called Standard model, built in ’50 - ‘70s

Hype all over world

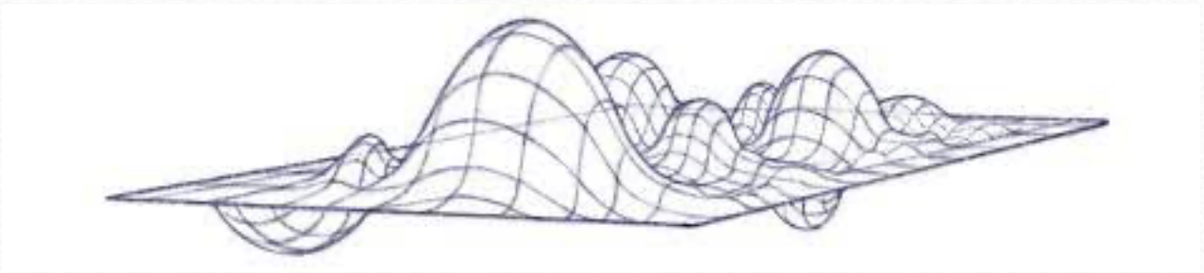
Even called God's particle

- Searched for since the seventies -> Holy Grail

- It proves the existence of the Higgs field - even in empty space

- Higgs field provides the mass for all elementary particles

Particles and fields



particle = wiggles of a field

Belief until ‘60s: vacuum (ground state) carries no wiggles, no energy, no mass, no charge, no nothing

wrong - vacuum permeated with the Higgs field

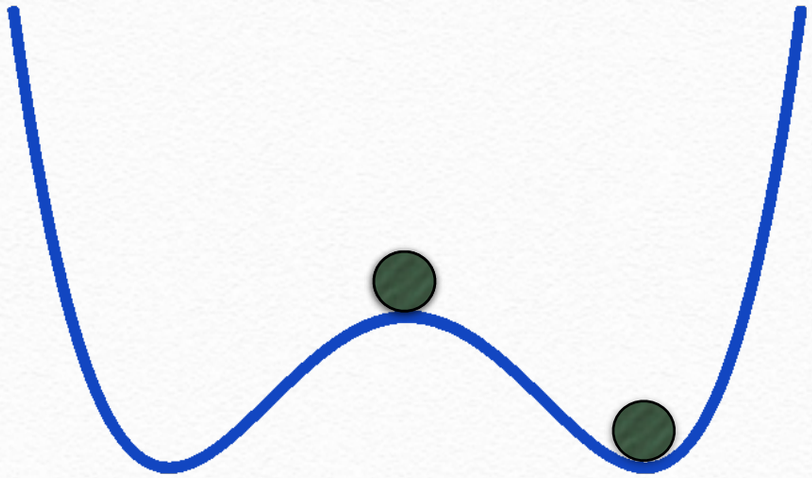
Empty space - like ocean instead of air

Particles that interact with the Higgs field `pick up’ mass from vacuum

Higgs boson = waves in ocean

Left-Right Symmetry: mirror symmetry

Prototype of Higgs mechanism



Spontaneous symmetry breaking

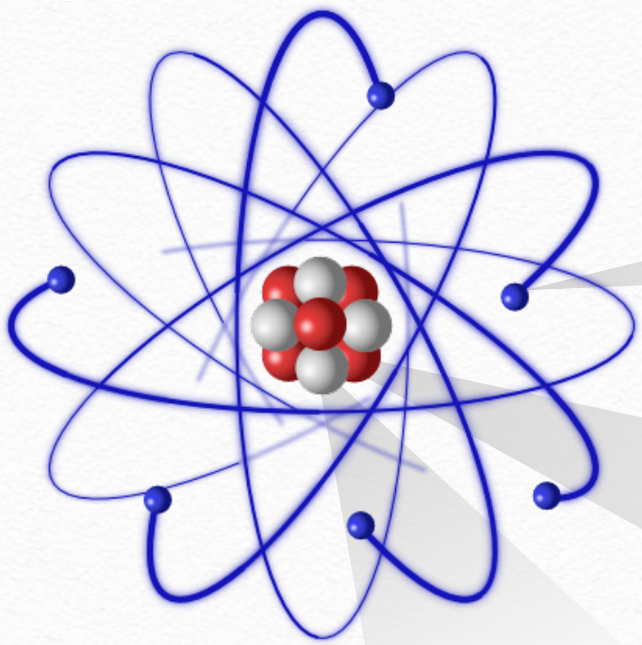
Higgs boson

story of great scientific breakthroughs,
missed opportunities, lack of proper recognition,
endless wait

First things first

Matter

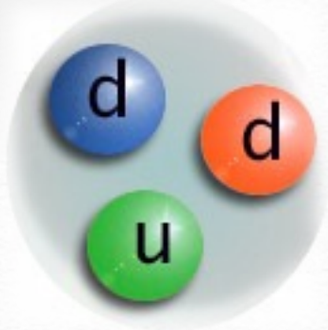
atom



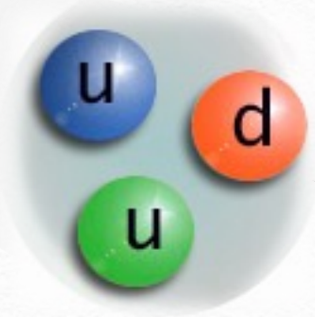
electron

$$m_p \simeq m_n \simeq 1000\, m_e$$

Gell-Mann, Zweig '64



neutron



proton

quarks

Neutrino: special

elusive particle

mean free path = distance travelled before interacting

$$\simeq 10^{19} \text{ cm}$$

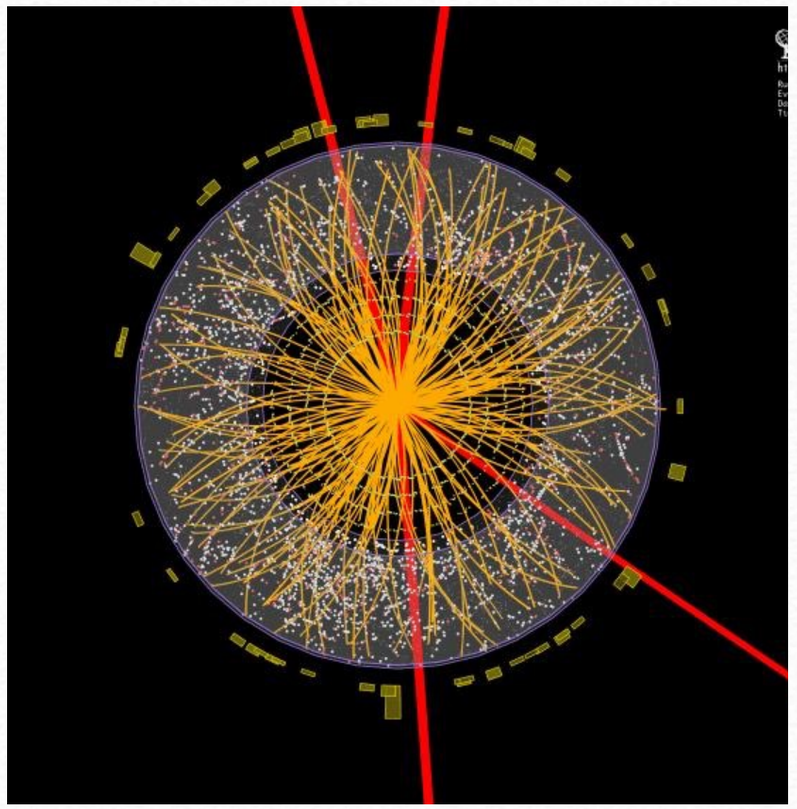
mass less than one millionth of electron mass

How to tell one particle from another?

Example: electron 

Quantum numbers

- electromagentic charge
- spin
- mass...

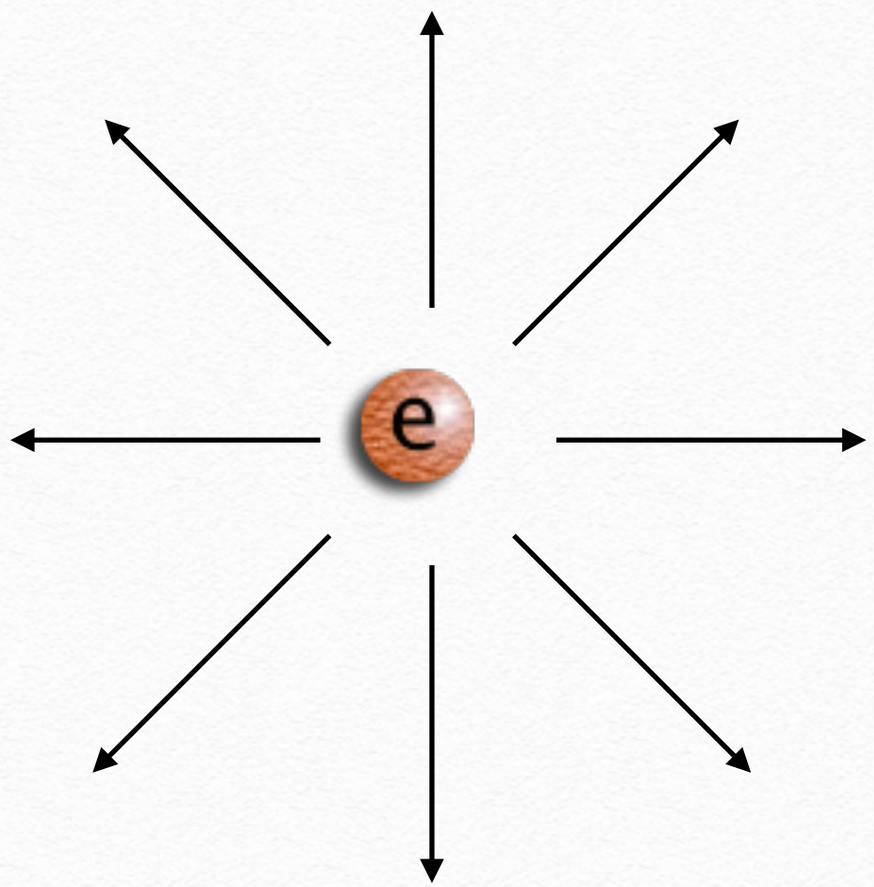


Charge

charges

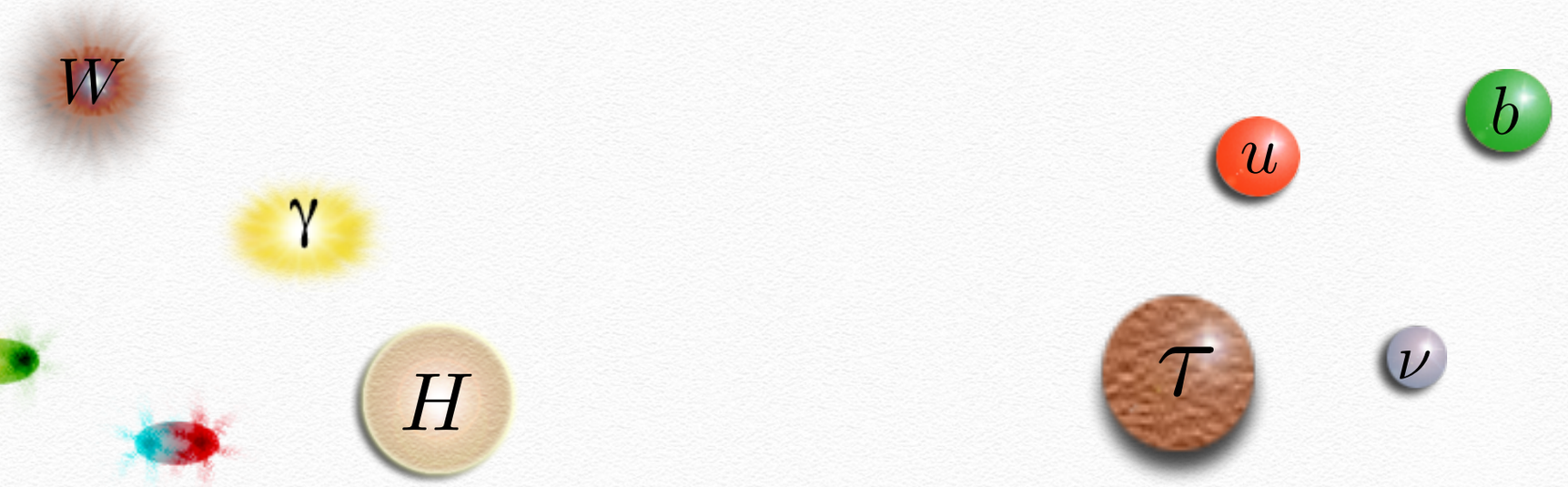
interactions

electric



electromagnetic field

Spin  intrinsic angular momentum



bosons

fermions

Spin = integer number

Spin = half integer number

Bose-Einstein statistics

Fermi-Dirac statistics

Quantum Electro Dynamics (QED)

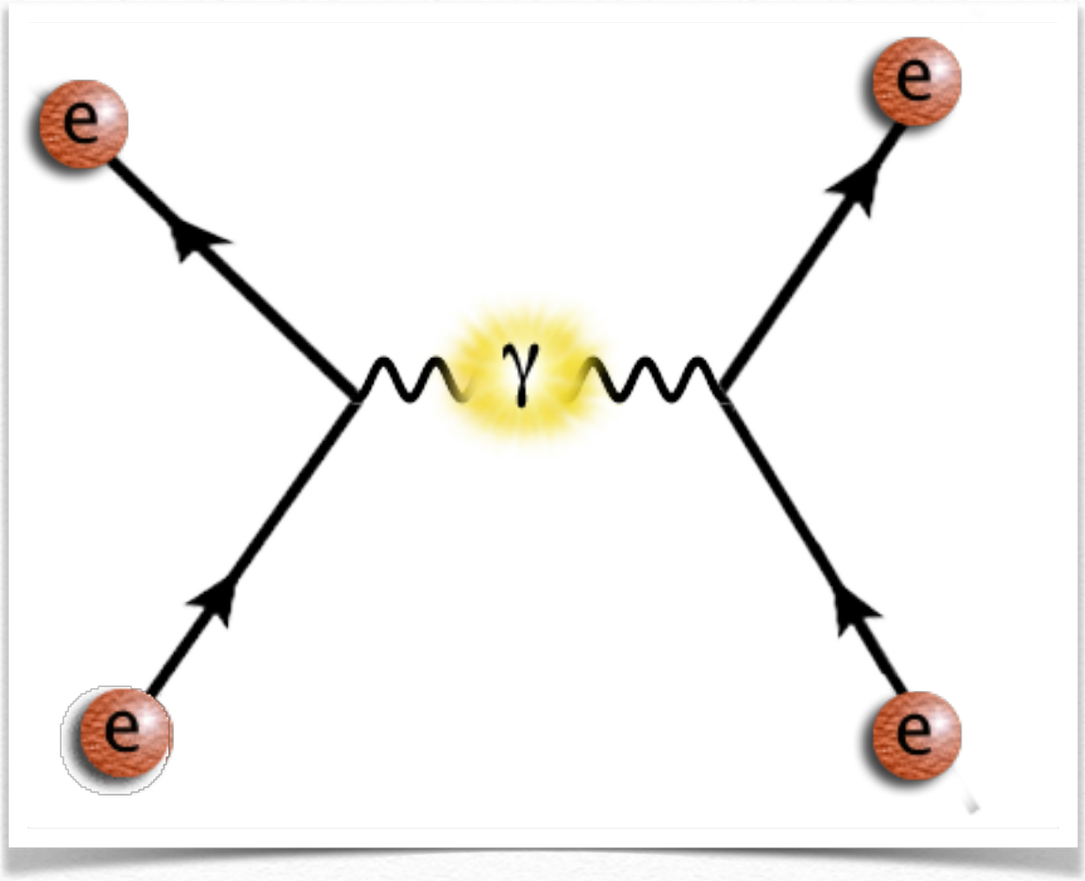
$$\mathcal{H}_{em} = e\, J^{\mu}_{em}\, A_{\mu}$$

messenger = photon (s=1)

$$J^{em}_{\mu} = \bar{f} Q^{em} \gamma_{\mu} f$$

mass=0  long range force

Feynman 1948



Feynman, Schwinger, Tomonaga, Dyson …

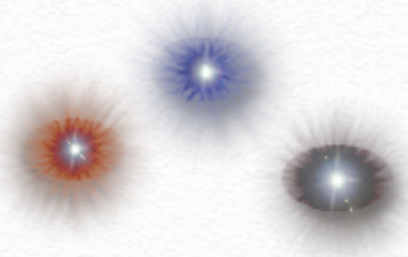
Standard Model of all Interactions

- electromagnetic

photon

U(1) gauge theory

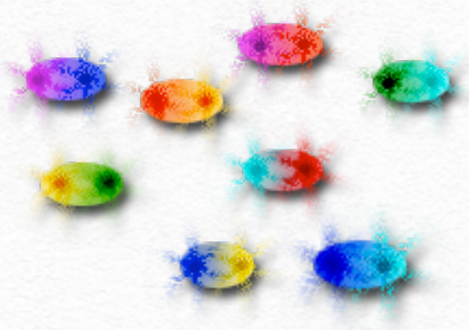
- weak



W+, W-, Z

SU(2) gauge theory

- strong



gluons

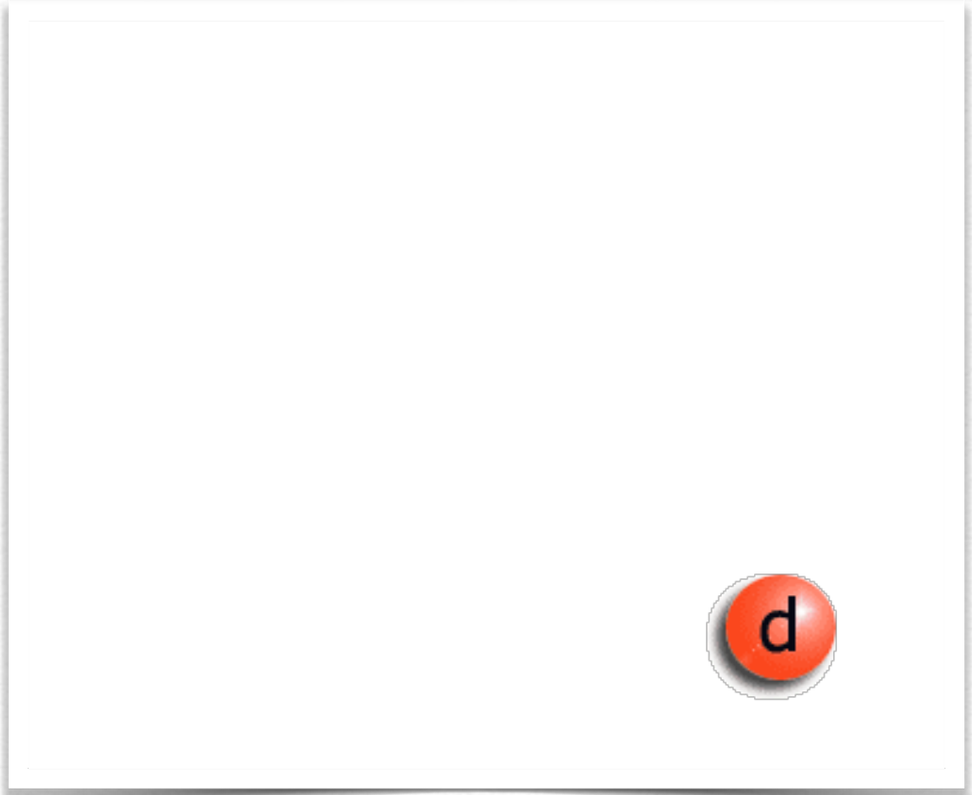
SU3) gauge theory

Messengers = gauge bosons
(s=1)

Weak interaction: messenger W boson

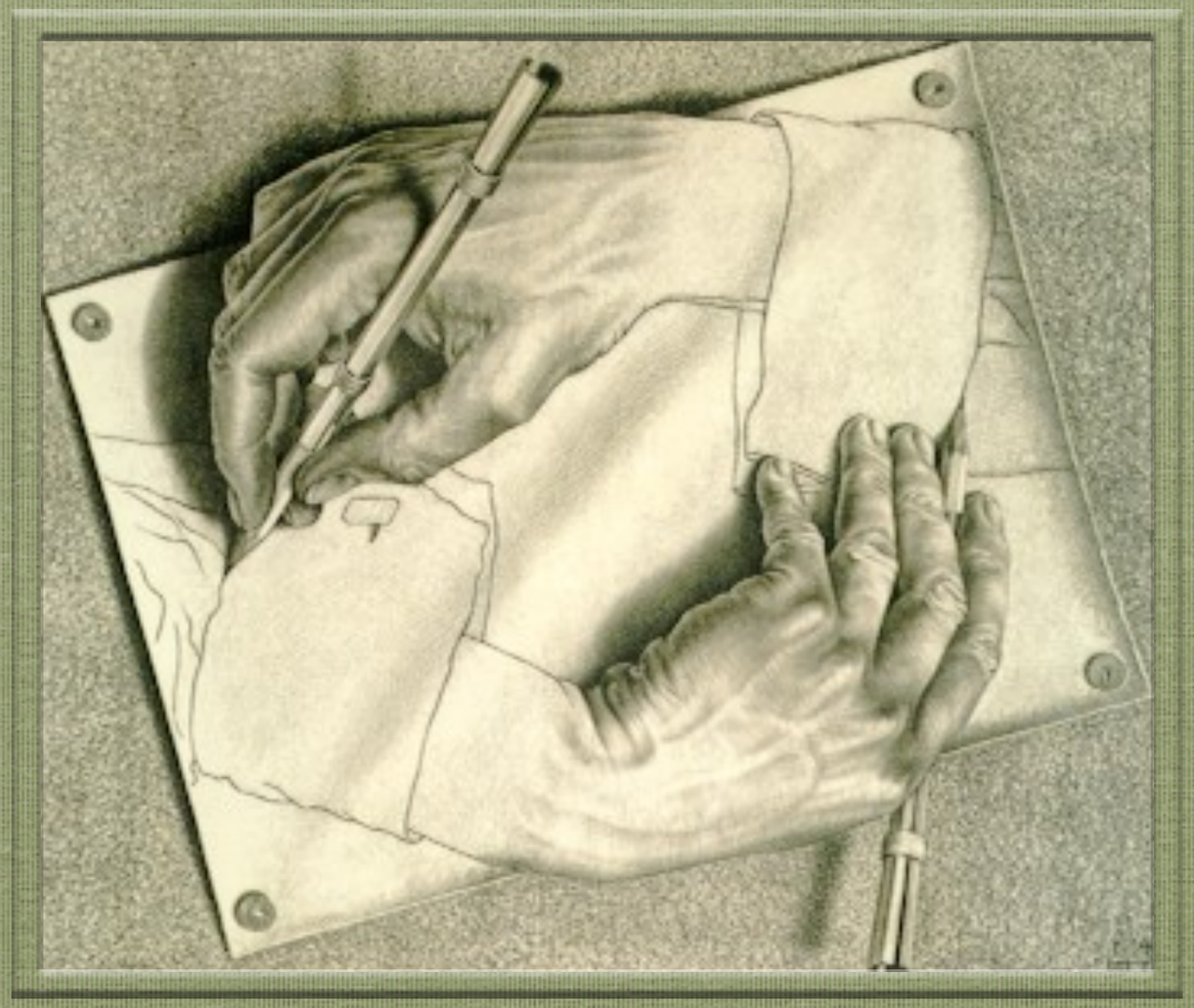
$$d \to u + e + \bar{\nu}$$

weak interaction
messenger: W

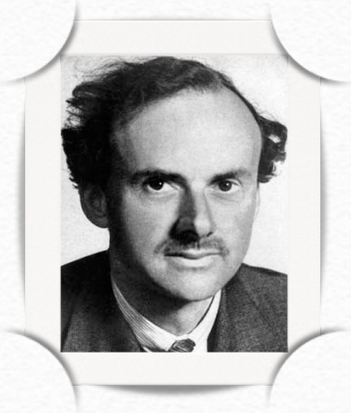


heavy $M_W = 80\, m_p$  short range force

The issue of parity
and
origin of mass



Anti particles



Paul Dirac

Dirac 1928 $(i\,\gamma^\mu \partial_\mu - m)\psi = 0$ ➡ spin

⬇ $\psi = \psi^*$

$\bar{e}$ positron (anti electron)  *Anderson 1932*

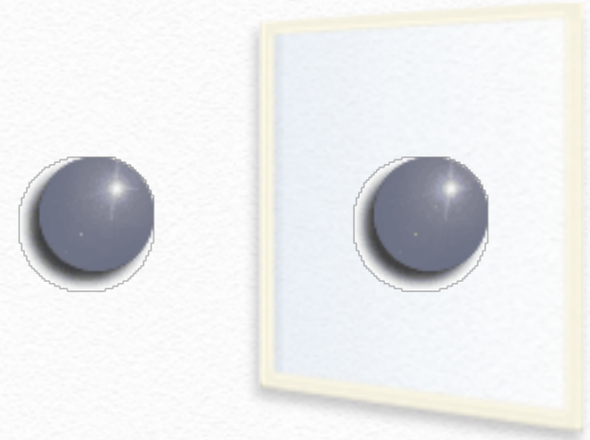
. . .

Left and right particles

chirality (handedness):

intrinsic particle property just like mass, spin….

Left-handed (L) and right-handed (R) electrons, quarks



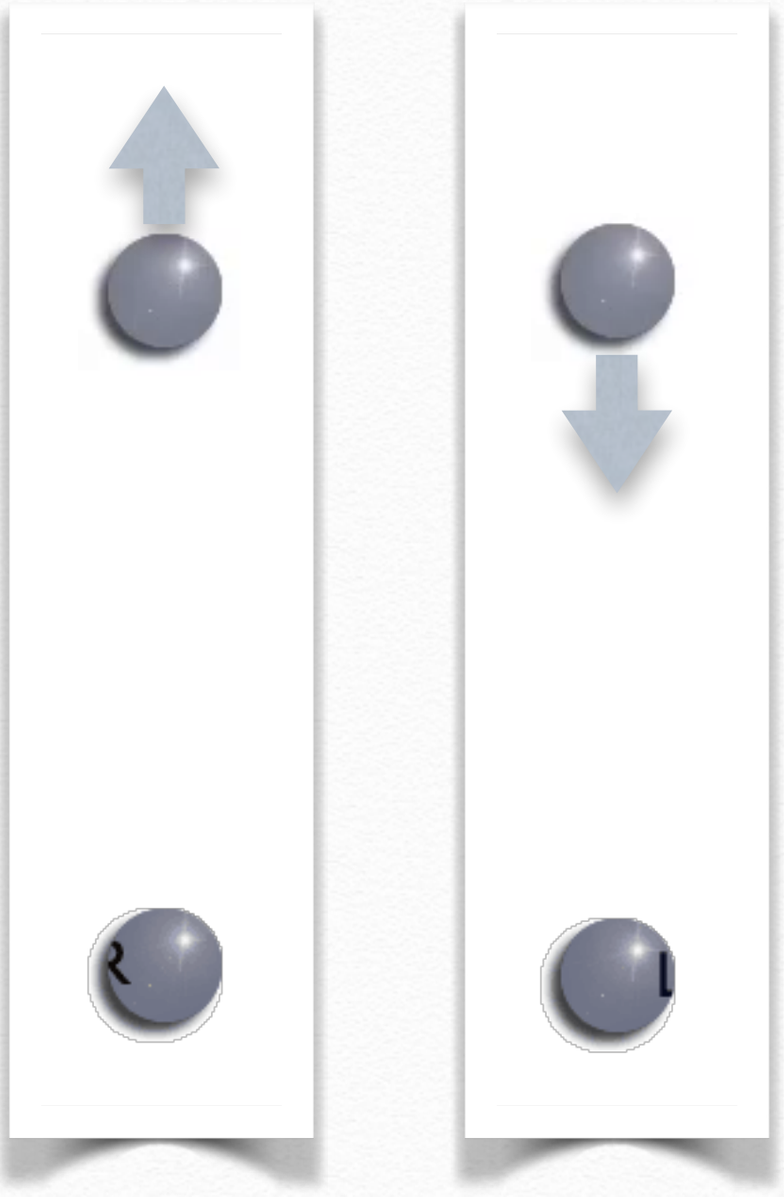
electron and positron: mirror images

Massless particles: chirality = helicity

high energies:
particles effectively massless

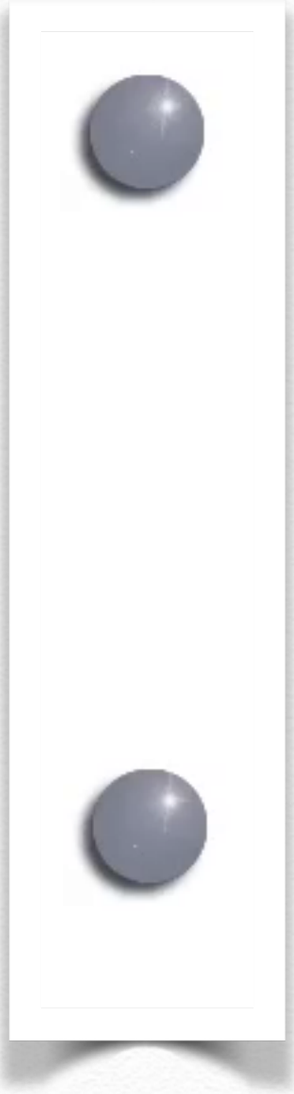
helicity:
projection of spin on the direction of motion

anti-particles =
opposite helicity



helicity: right left

Fermion (Dirac) mass

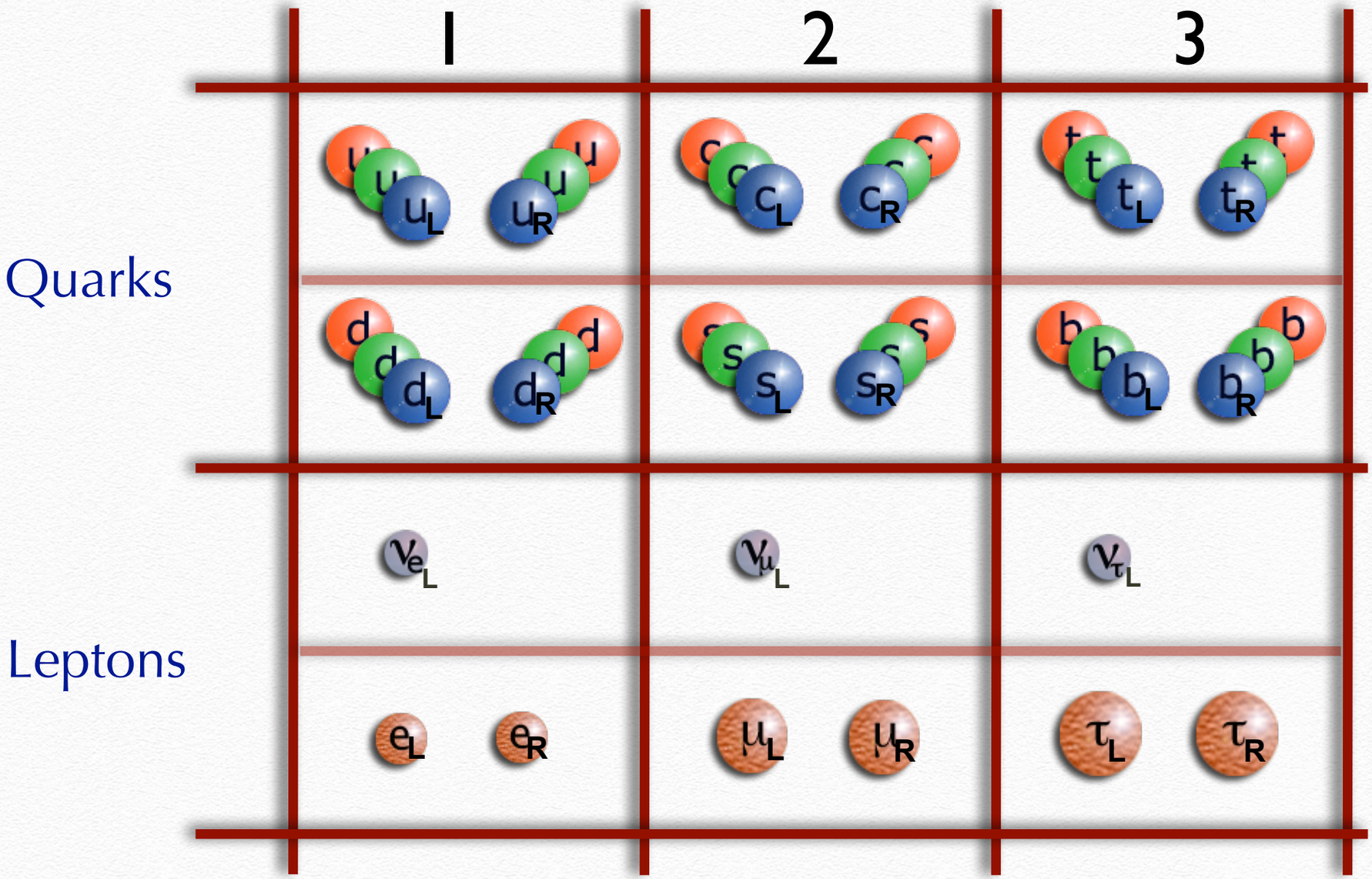


$u_R^\dagger u_L$

$$e = e_L + e_R$$

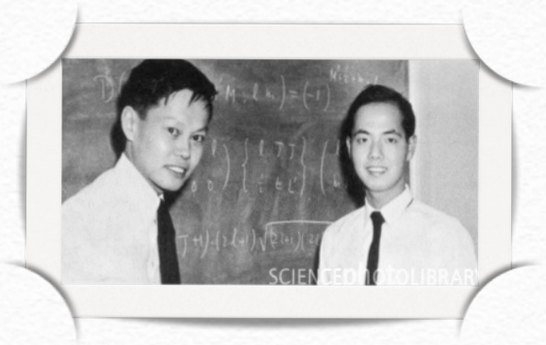
connects R with L

Fermion generations



Parity violation

Lee, Yang 1956



And if L-R symmetry was broken?

Chen Ning Yang & Tsung-Dao Lee

experiment ➡ L-R symmetry maximally broken

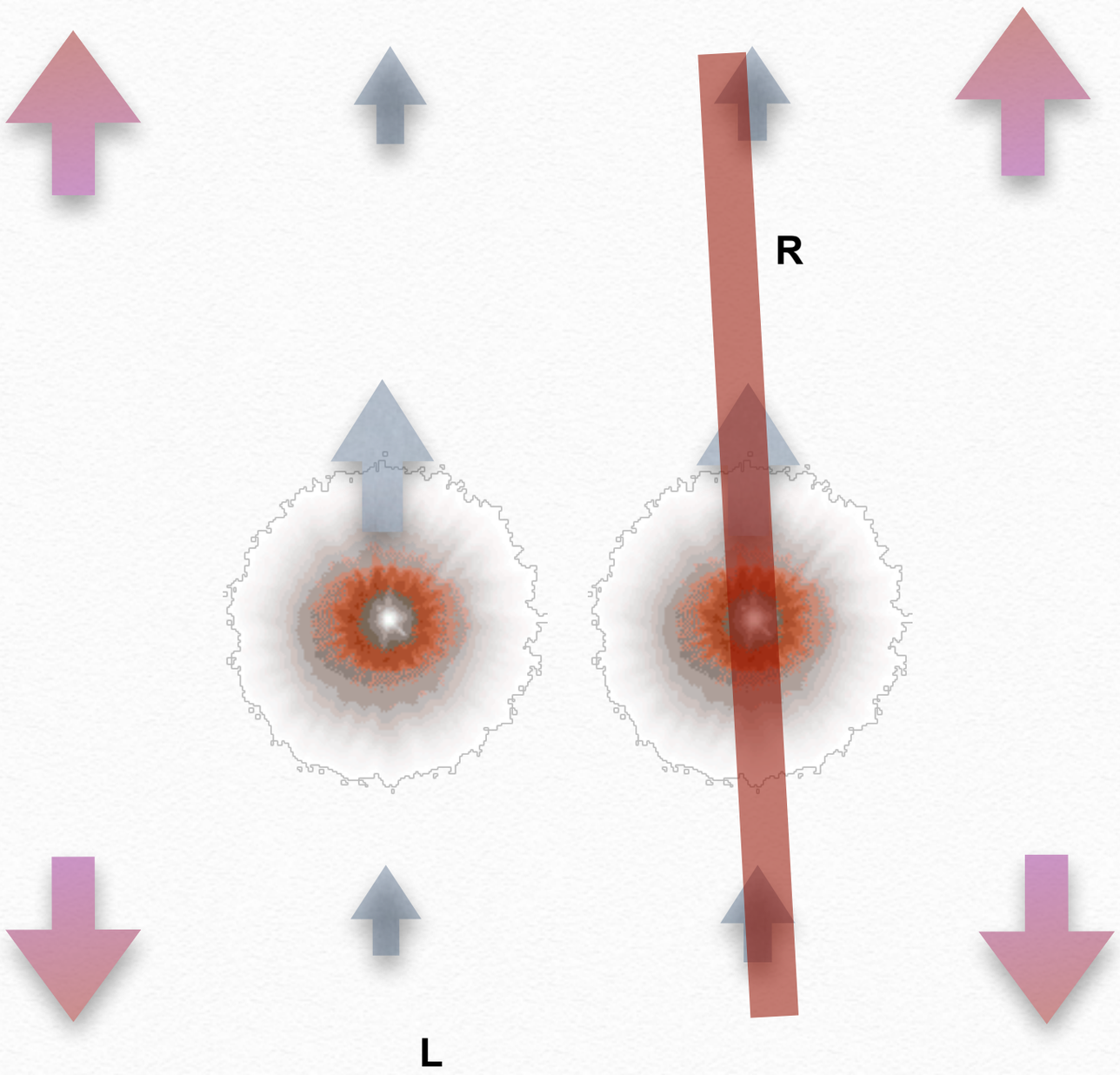
Chien-Shiung Wu

Wu et al 1956

P violation

$W^- \to e + \bar{\nu}$ at rest $\qquad S_z^W = 1$

$M_W \simeq 100\,000\, m_e$ ➡ electron mass = practically zero



electron and neutrino = LH
in weak interaction

The theory

Noether theorem

Emmy Noether

symmetry: looks the same

discrete symmetries

continuous symmetries

global continuous symmetry -> conserved charge

Noetherian symmetries

- Energy and momentum - symmetry under translations E1 = E2, p1 = p2

- Angular momentum - symmetry under rotations L1 = L2

- Electromagnetic charge - symmetry under change of phase $\psi \rightarrow e^{i\alpha}\psi$

U(1) gauge symmetry *Maxwell 1865*

Theories based on symmetries

Charges  Interactions

Symmetries

Gauge symmetry

Dirac equation $(i\,\gamma^\mu \partial_\mu - m)\psi = 0$

$\psi \to e^{i\alpha}\psi$ $\alpha = const$ phase symmetry

Noether 1918

conserved em charge

ask: $\psi \to e^{i\alpha(x)}\psi$  messenger - photon 

couples to electromagnetic current $\mathcal{H}_{em} = e\, J^\mu_{em}\, A_\mu$

Power of gauge symmetry

QED = electromagnetic (em) interactions  photon

Feynman Schwinger Tomonaga '48 -'50

computations with unimaginable precision '50s - today

Dyson, …Kinoshita, … anybody '48 -'50

messenger - m=o  gauge symmetry

Gauge theory of weak and em interactions

SU(2L) x U(1)

L-R symmetry
broken completely

Glashow 1961

$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$

$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$

quarks & electron
massless

LH particles - weak force

RH particles - no weak force

A

Glashow symmetry

SU(2)

Neutrinos neutral - electrons charged

SU(2)

photon ⟷ W boson

photon is massless - W has huge mass

no such symmetry

no such symmetry

Could this explain why this seminal work is ignored?

Spontaneously broken symmetry

global continuous symmetry

Nambu 1960

Goldstone 1961

Symmetry exists

Universe - symmetry hidden

scalar field (s=0 boson) knows it -
it is there even in vacuum

Gauge symmetry & Higgs mechanism

Brout, Englert 1964

24/6/1964

Higgs 1964

27/7/1964

- Gauge bosons get mass if they interact with the vacuum

Called Higgs mechanism =
Brout-Englert-Higgs mechanism

VOLUME 13, NUMBER 9 PHYSICAL REVIEW LETTERS 31 AUGUST 1964

*Work supported in part by the U. S. Atomic Energy Commission and in part by the Graduate School from funds supplied by the Wisconsin Alumni Research Foundation.

[1]R. Feynman and M. Gell-Mann, Phys. Rev. 109, 13 (1958).

[2]T. D. Lee and C. N. Yang, Phys. Rev. 119, 1410 (1960); S. B. Treiman, Nuovo Cimento 15, 916 (1960).

[3]S. Okubo and R. E. Marshak, Nuovo Cimento 28, 56 (1963); Y. Ne'eman, Nuovo Cimento 27, 922 (1963).

[4]Estimates of the rate for $K^+ \to \pi^+ + e^+ + e^-$ due to induced neutral currents have been calculated by several authors. For a list of previous references see Mirza A. Baqi Bég, Phys. Rev. 132, 426 (1963).

[5]M. Baker and S. Glashow, Nuovo Cimento 25, 857 (1962). They predict a branching ratio for decay mode (1) of $\sim 10^{-6}$.

[6]N. P. Samios, Phys. Rev. 121, 275 (1961).

[7]The best previously reported estimate comes from the limit on $K_2^0 \to \mu^+ + \mu^-$. The 90% confidence level is $|g_{\mu\bar{\mu}}|^2 < 10^{-3} |g_{\mu\bar{\mu}}|^2$: M. Barton, K. Lande, L. M. Lederman, and William Chinowsky, Ann. Phys. (N.Y.) 5, 156 (1958). The absence of the decay mode $\mu^- \to e^- + e^+ + e^-$ is not a good test for the existence of neutral currents since this decay mode may be absolutely forbidden by conservation of muon number: G. Feinberg and L. M. Lederman, Ann. Rev. Nucl. Sci. 13, 465 (1963).

[8]S. N. Biswas and S. K. Bose, Phys. Rev. Letters 12, 176 (1964).

BROKEN SYMMETRY AND THE MASS OF GAUGE VEC

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Brux
(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.

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.

We shall first treat the case where the original fields are a set of bosons φ_A which transform as a basis for a representation of a compact Lie group. This example should be considered as a rather general phenomenological model. As such, we shall not study the particular mechanism by which the symmetry is broken but simply assume that such a mechanism exists. A calculation performed in lowest order perturbation theory indicates that

those vector mes
rents that "rotate
ones which acqui
We shall then e
based on chirality
more fundamenta
with a chirality-
duce both vector
thereby guarante
phase and local
this model the ga
the γ_5 invariance
inal Fermi field,
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In the last para
argument which
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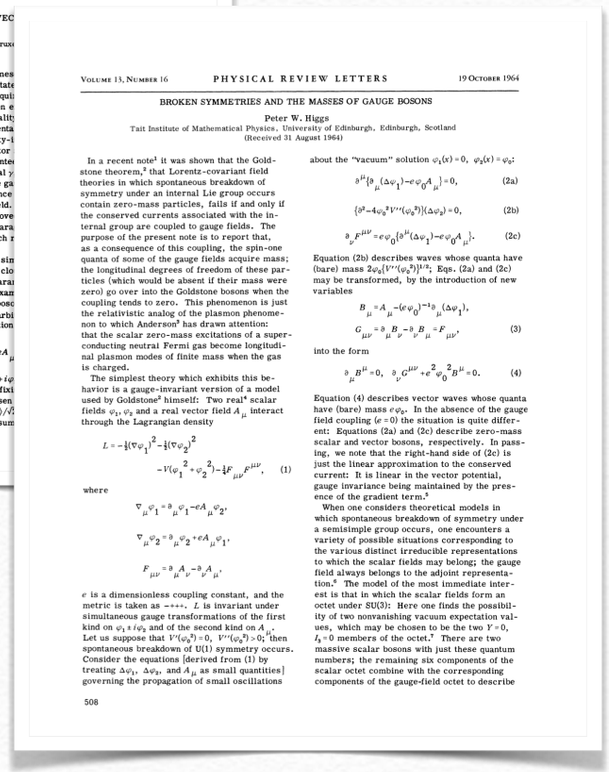
(1) Lest the sin
shrouded in a clo
sider a one-para
senting, for exam
of a charged bosc
ization to an arbi
The interaction
fields is

$$H_{\text{int}} = ieA_\mu$$

where $\varphi = (\varphi_1 + i\varphi$
symmetry by fixi
the phase chosen
$\langle\varphi\rangle = \langle\varphi^*\rangle = \langle\varphi_1\rangle/\sqrt{2}$
We shall assum



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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; 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 through the Lagrangian density

$$L = -\tfrac{1}{2}(\nabla\varphi_1)^2 - \tfrac{1}{2}(\nabla\varphi_2)^2 - V(\varphi_1^2 + \varphi_2^2) - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu}, \quad (1)$$

where

$$\nabla_\mu\varphi_1 = \partial_\mu\varphi_1 - eA_\mu\varphi_2,$$

$$\nabla_\mu\varphi_2 = \partial_\mu\varphi_2 + eA_\mu\varphi_1,$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu.$$

e is a dimensionless coupling constant, and the metric is taken as $-+++$. L is invariant under simultaneous gauge transformations of the first kind on $\varphi_1 + i\varphi_2$ and of the second kind on A_μ. Let us suppose that $V'(\varphi_0^2) = 0$, $V''(\varphi_0^2) > 0$;[5] then spontaneous breakdown of U(1) symmetry occurs. Consider the equations [derived from (1) by treating $\Delta\varphi_1$, $\Delta\varphi_2$, and A_μ as small quantities] governing the propagation of small oscillations about the "vacuum" solution $\varphi_1(x) = 0$, $\varphi_2(x) = \varphi_0$:

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

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

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

Equation (2b) describes waves whose quanta have (bare) mass $2\varphi_0\{V''(\varphi_0^2)\}^{1/2}$; Eqs. (2a) and (2c) may be transformed, by the introduction of new variables

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

$$G_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu = F_{\mu\nu}, \quad (3)$$

into the form

$$\partial_\mu B^\mu = 0, \quad \partial_\nu G^{\mu\nu} + e^2\varphi_0^2 B^\mu = 0. \quad (4)$$

Equation (4) describes vector waves whose quanta have (bare) mass $e\varphi_0$. In the absence of the gauge field coupling ($e = 0$) the situation is quite different: Equations (2a) and (2c) describe zero-mass scalar and vector bosons, respectively. In passing, we note that the right-hand side of (2c) is just the linear approximation to the conserved current: It is linear in the vector potential, gauge invariance being maintained by the presence of the gradient term.[5]

When one considers theoretical models in which spontaneous breakdown of symmetry under a semisimple group occurs, one encounters a variety of possible situations corresponding to the various distinct irreducible representations to which the scalar fields may belong; the gauge field always belongs to the adjoint representation.[6] The model of the most immediate interest is that in which the scalar fields form an octet under SU(3): Here one finds the possibility of two nonvanishing vacuum expectation values, which may be chosen to be the two $Y = 0$, $I_3 = 0$ members of the octet.[7] There are two massive scalar bosons with just these quantum numbers; the remaining six components of the scalar octet combine with the corresponding components of the gauge-field octet to describe

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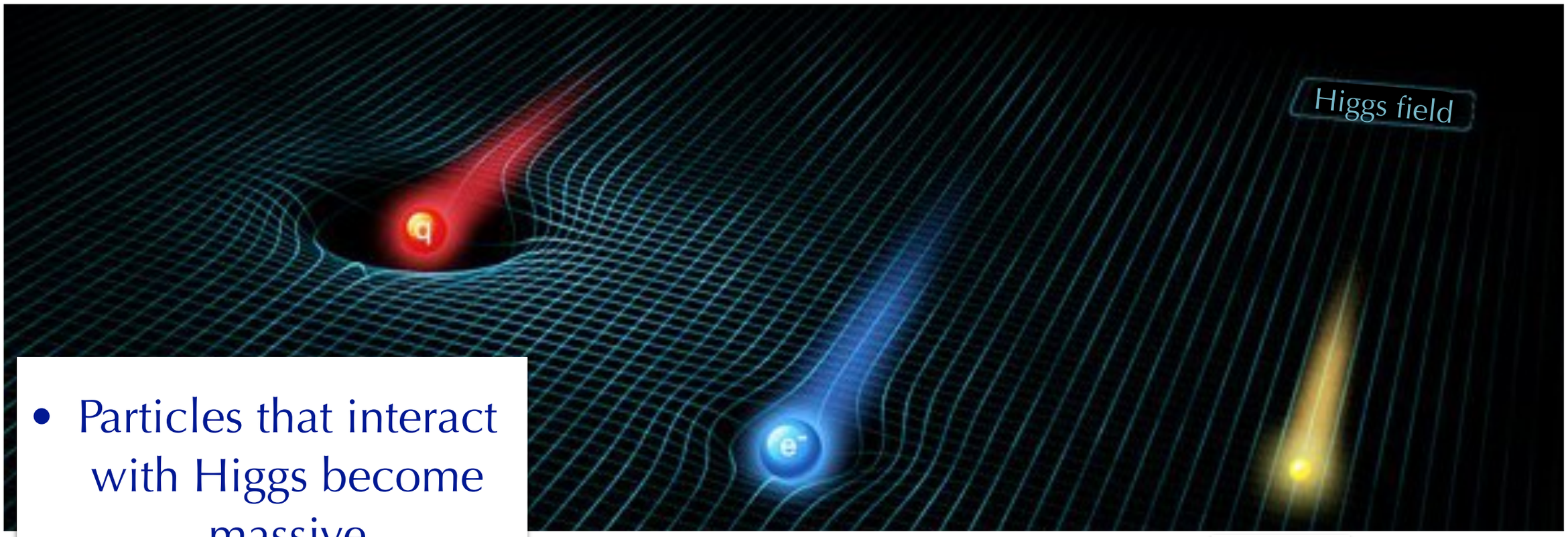
- Higgs rediscovers a scalar s=0 field of Goldstone

Called Higgs boson = Goldstone-Higgs boson?

Vacuum is not empty

Vacuum =
Goldstone-Higgs field



- Particles that interact with Higgs become massive
- Stronger interaction = heavier particle

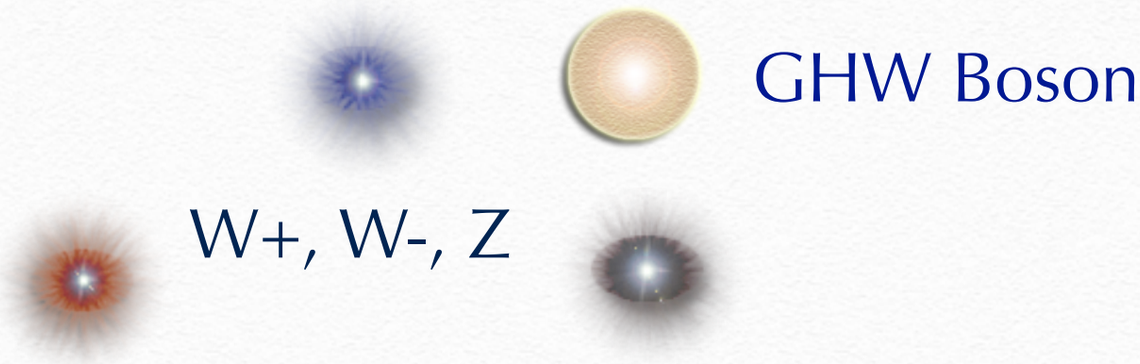
Standard Model = final theory

Weinberg 1967

Salam 1968

Higgs mechanism applied to Glashow gauge theory

W and Z gauge bosons (messengers of weak force) get masses

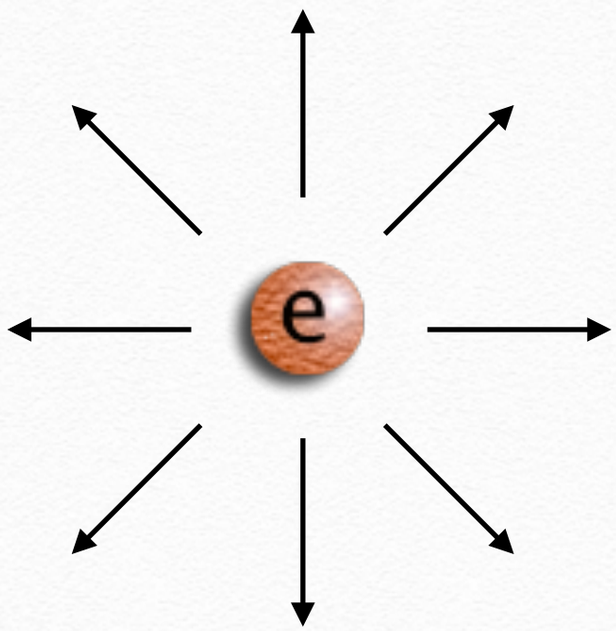


Again this seminal work completely ignored -
will take years and genius of ’t Hooft to bring it to life

Mystery explained

Nutshell: lines of weak force (field) are absorbed by the Higgs field

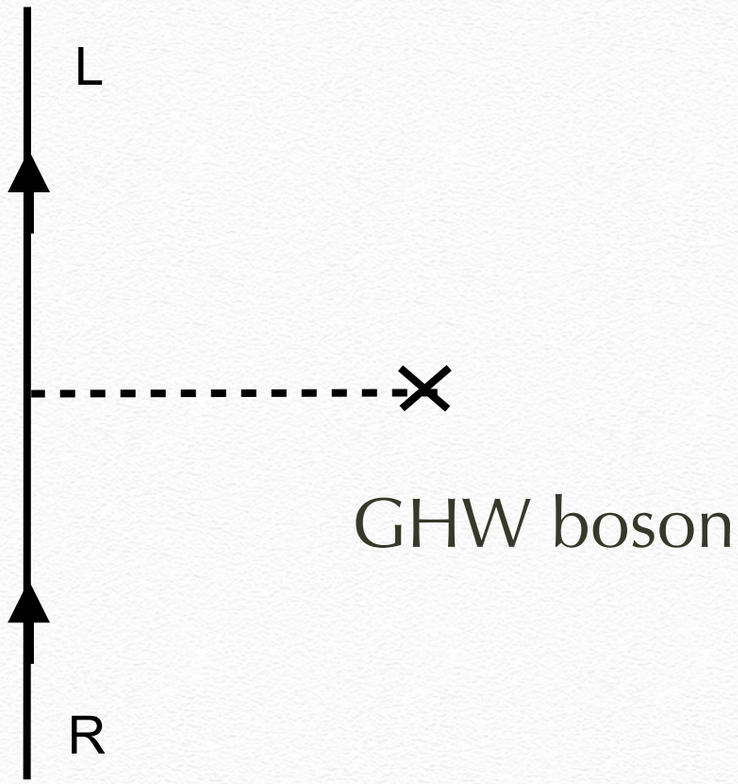
Weak force short ranged - em spread everywhere

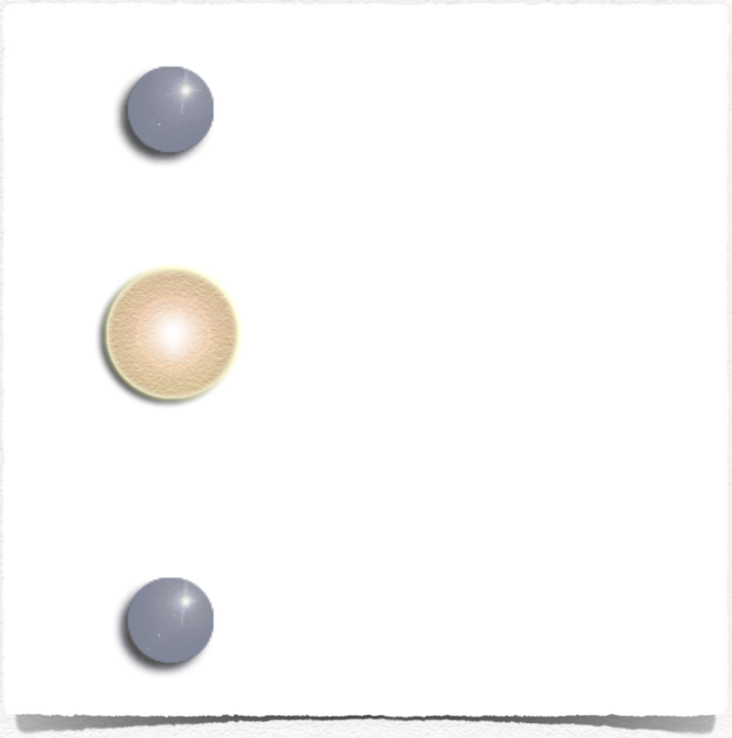


electromagnetic field

Fermion masses: (Brout-Englert) Higgs mechanism

Weinberg 1967





$h\langle\phi\rangle\,\bar{\psi}_L\psi_R$

Goldstone - Higgs - Weinberg boson crosses the wall

decays of GHW boson predicted $\Gamma(h \to p\bar{p}) \propto m_p^2$

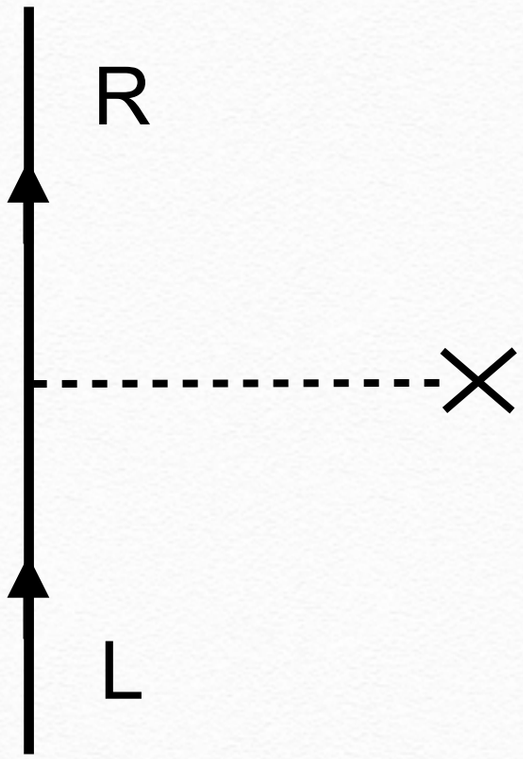
Goldstone - Higgs - Weinberg boson

Goldstone 1961

Higgs 1964

Weinberg 1967

- zero em charge
- spin = 0



- huge mass = 125 GeV

$$GeV = m_p$$

- negligible interactions with quarks and leptons

desperately hard to produce

Desperately searched for $GeV = m_p$

- Large Electron Positron = LEP@CERN E = 200 GeV

ring = 27 km

One channel: Higgs mass -> 115 GeV :(

Other channel: Higgs mass -> 200 GeV

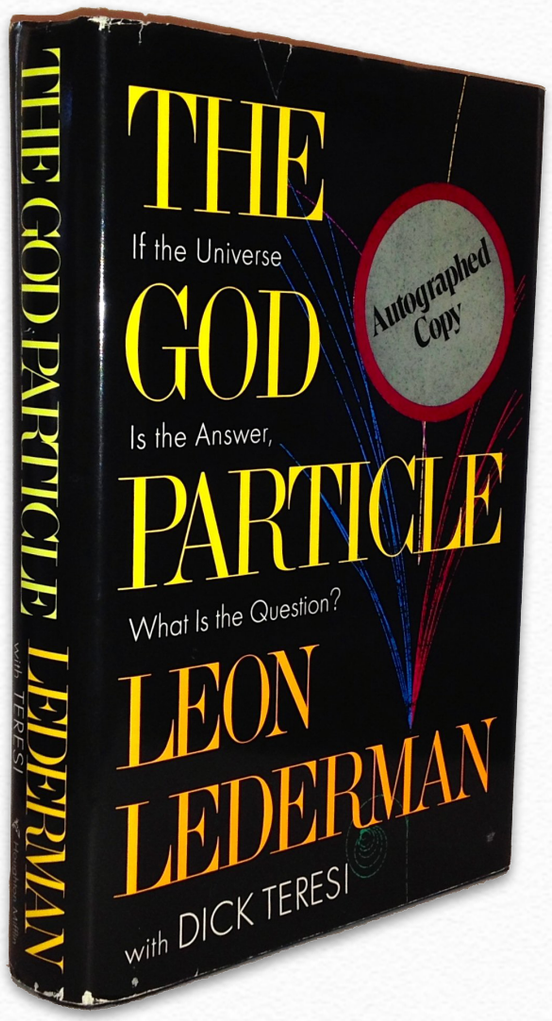
but too weak :(

- Tevatron@Fermilab E = 1000 GeV

ring = 7 km

Too weak processes :(

Goddamn particle *Lederman*



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The God Particle

Large Hadron Collider (LHC)

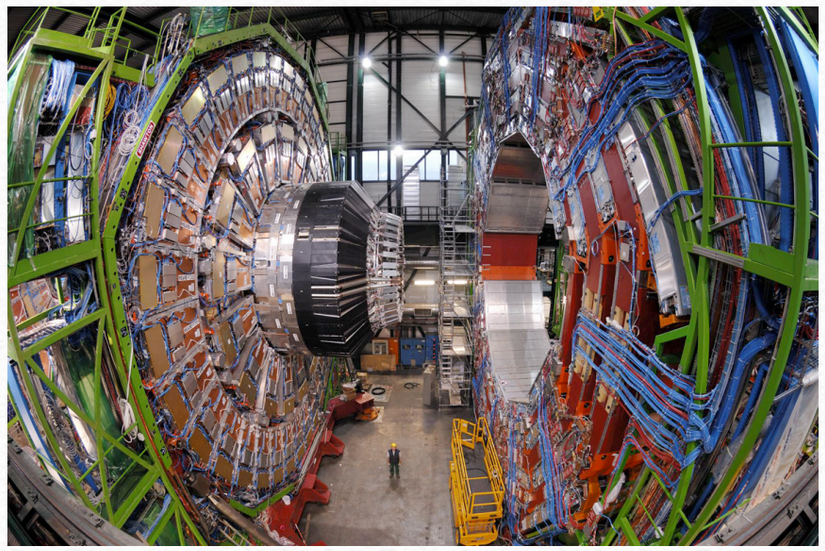
$GeV = m_p$

ring = 27 km

E = 14 000 GeV

LEP tunnel

$M_W = 80\, m_p$



CMS detector

~3500 people

ATLAS detector

~3500 people

July 4, 2012

discovered @LHC

W, Z, t, b, tau = Higgs origin

meanwhile Englert + Higgs = Nobel prize 2013 -

incredibly Goldstone omitted (I tried hard)

THE TRUE STORY
Poslušajte zanimljivo predavanje čovjeka koji je otkrio Higgsov bozon

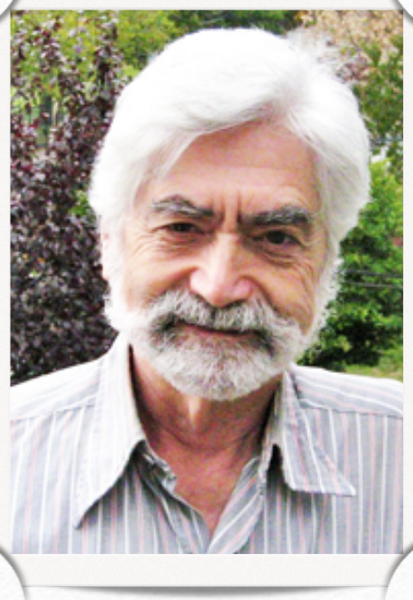
Prof. dr. sc. Goran Senjanović, jednan od najuglednijih svjetskih teorijskih fizičara, na splitskom FESB-u, u dvorani A100, održat će znanstveno-popularno predavanje za opću publiku naziva 'Higgs boson, the true story'.

Dalmatinski portal

Nisam otkrio (nazalost) Higgsov bozon -
ali sam otkrio da nije ni sam Higgs :)

Talking of omissions: quarks

Zweig 1964

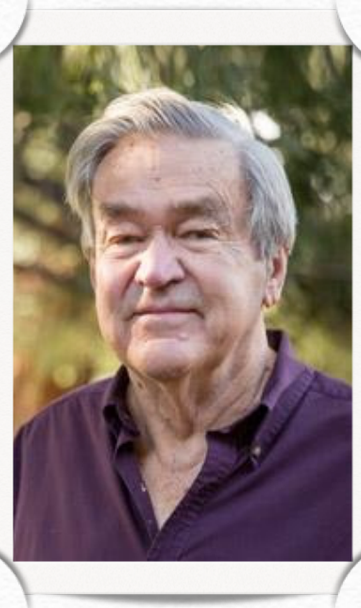


George Zweig

Developed a theory

Still no Nobel prize

Bjorken 1968



James Bjorken

Showed how to see them

Kobayashi & Maskawa got it for quarks 5 & 6

LR asymmetry = essential

Imagine instead symmetric world

Try to construct
Standard Model

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \qquad \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

$$\begin{pmatrix} \nu_L \\ e \end{pmatrix}_L \qquad \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$$

You will fail

Great theories of nature

- General theory of relativity = gravity in stronger fields; fast particles

Einstein 1915

Black holes & gravitational waves

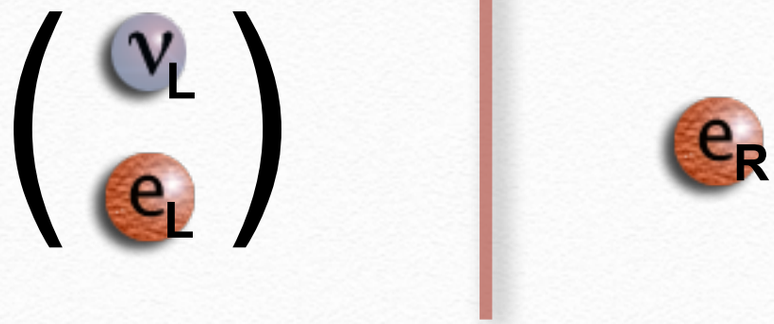
- Standard Model = gauge theory of weak force

Glashow 1961

Theory of origin of mass

Today a high precision theory -
no clouds on horizon?

Standard Model -> neutrino massless



no ν_R

no neutrino mass

Today neutrino mass confirmed

And if parity was restored at
the fundamental level?

Left-Right Symmetric Model

SU(2L) x SU(2R) x U(1)

Pati, Mohapatra, Salam 1974

Mohapatra, GS 1975

W_L^- $\begin{pmatrix} u_L \\ d_L \end{pmatrix}$ $\begin{pmatrix} u_R \\ d_R \end{pmatrix}$ W_R^-

Z_L neutrino is massive Z_R

W_L^+ $\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$ $\begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$ W_R^+

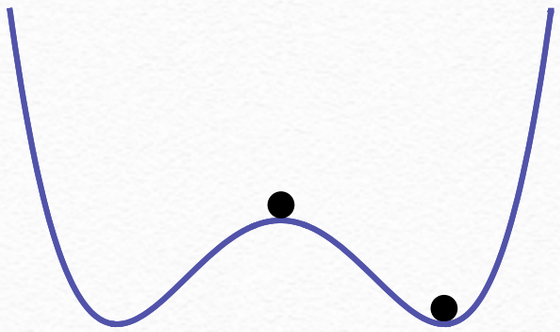
A

Neutrino mass predicted long before experiment

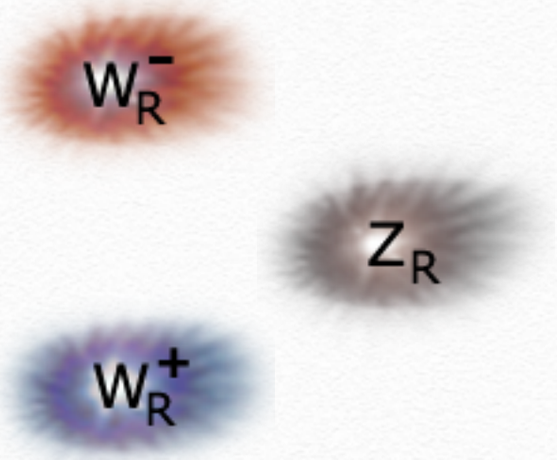
Spontaneous breaking of LR symmetry

Mohapatra, GS '75

GS '79



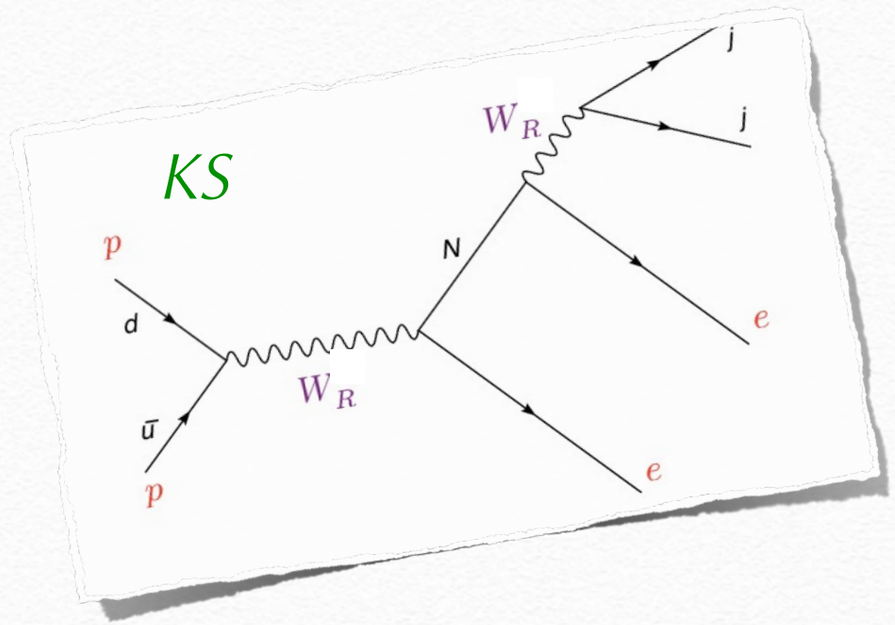
New mediators very heavy



- SM = theory of e mass ⟷ LR = theory of neutrino mass
- LHC: rich physics of RH gauge bosons and neutrino

Keung, GS '83

LR@LHC



ATLAS 2019

neutrinos (N_R). A search for W_R boson and N_R neutrino production in a final state containing two charged leptons and two jets ($\ell\ell jj$) with $\ell = e, \mu$ is presented here. The exact process of interest is the Keung–Senjanović (KS) process [10], shown in Figure 1. When the W_R boson is heavier than

$$M_{W_R} \gtrsim 5\,TeV$$

Stay tuned

Thank you

Review of history

Glashow 2020

https://inference-review.com/article/the-yang-mills-model

Senjanovic 2020

https://inference-review.com/letter/further-questions-for-glashow

Bottom line: Glashow forgot his masterpiece :)

In 1964 paper on charm he does not cite his 1961 paper that started it all

Gravity: negligible

38 orders of magnitude weaker than electromagnetic

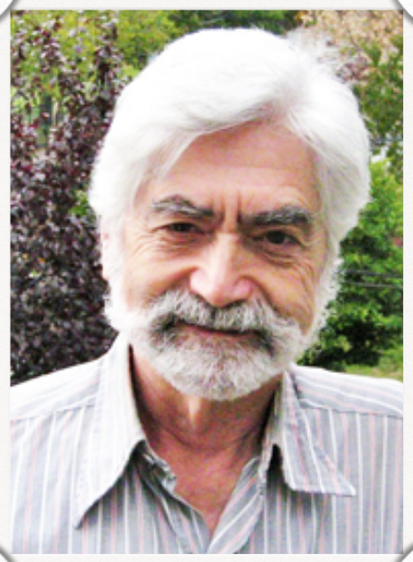
- why does gravity matter?
- why does matter gravitate?

$\odot$ sun - 10^{50} particles

zero charge

Talking of omissions: quarks

Zweig 1964



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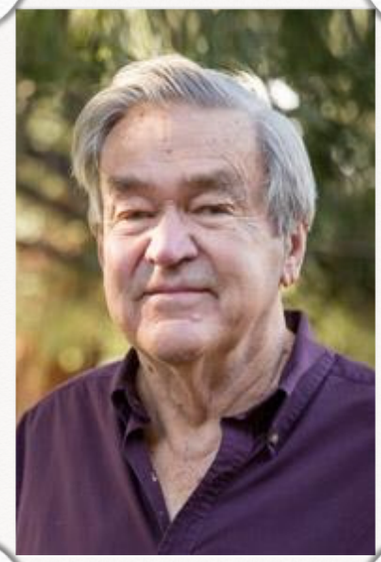

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You will fail

Vacuum full of Higgs field - how to test directly?

Analogy with water

Test? Heat it up - phase transition

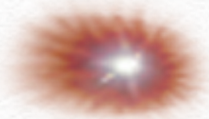
Problem - temperature hundred thousand
times the temperature of Sun

Relevant only for cosmology of early universe

Discovering W

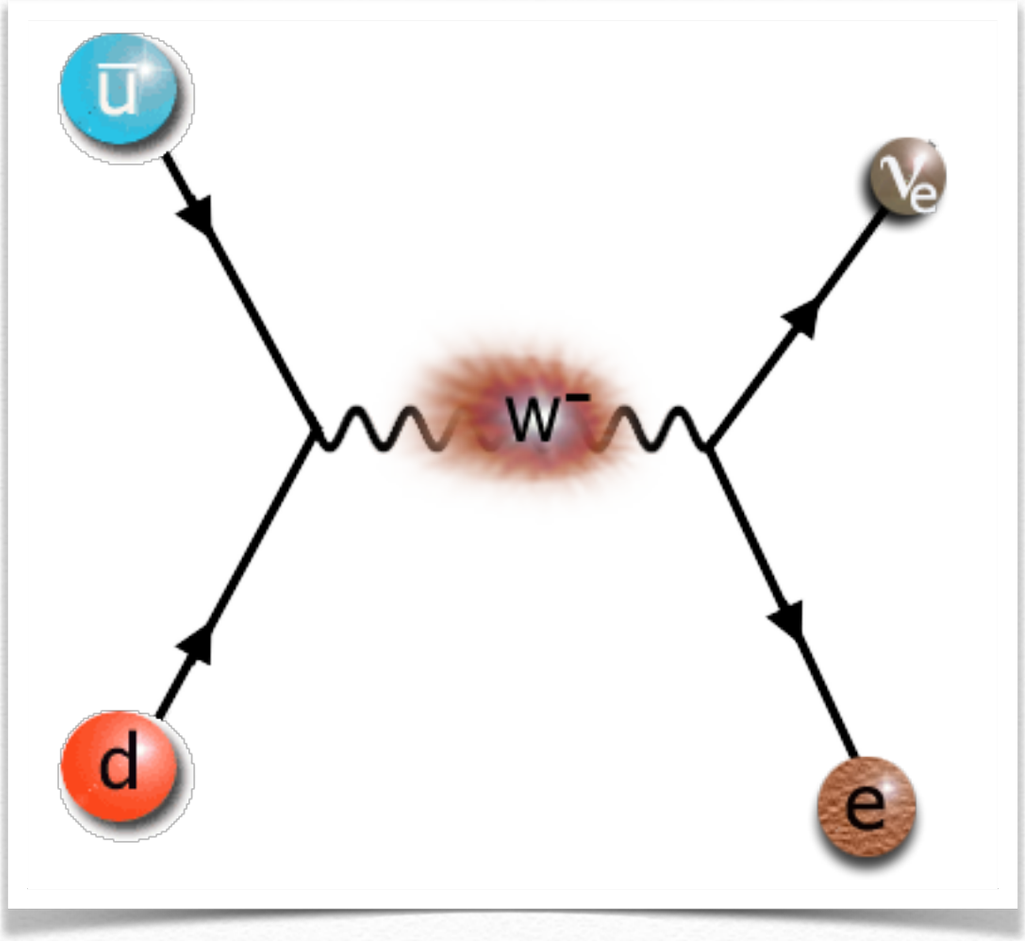
$$\mathcal{H}_{fund} = \frac{g}{\sqrt{2}} J^{\mu}_{W} W^{+}_{\mu}$$

Messenger = W boson



spin=1

anti-proton



proton

heavy $M_W = 80\, m_p$

$M_Z = 90\, m_p$

W discovery@CERN 1983

Super Proton Synchrotron (SPS)
- 7 km circumference

Forgotten history

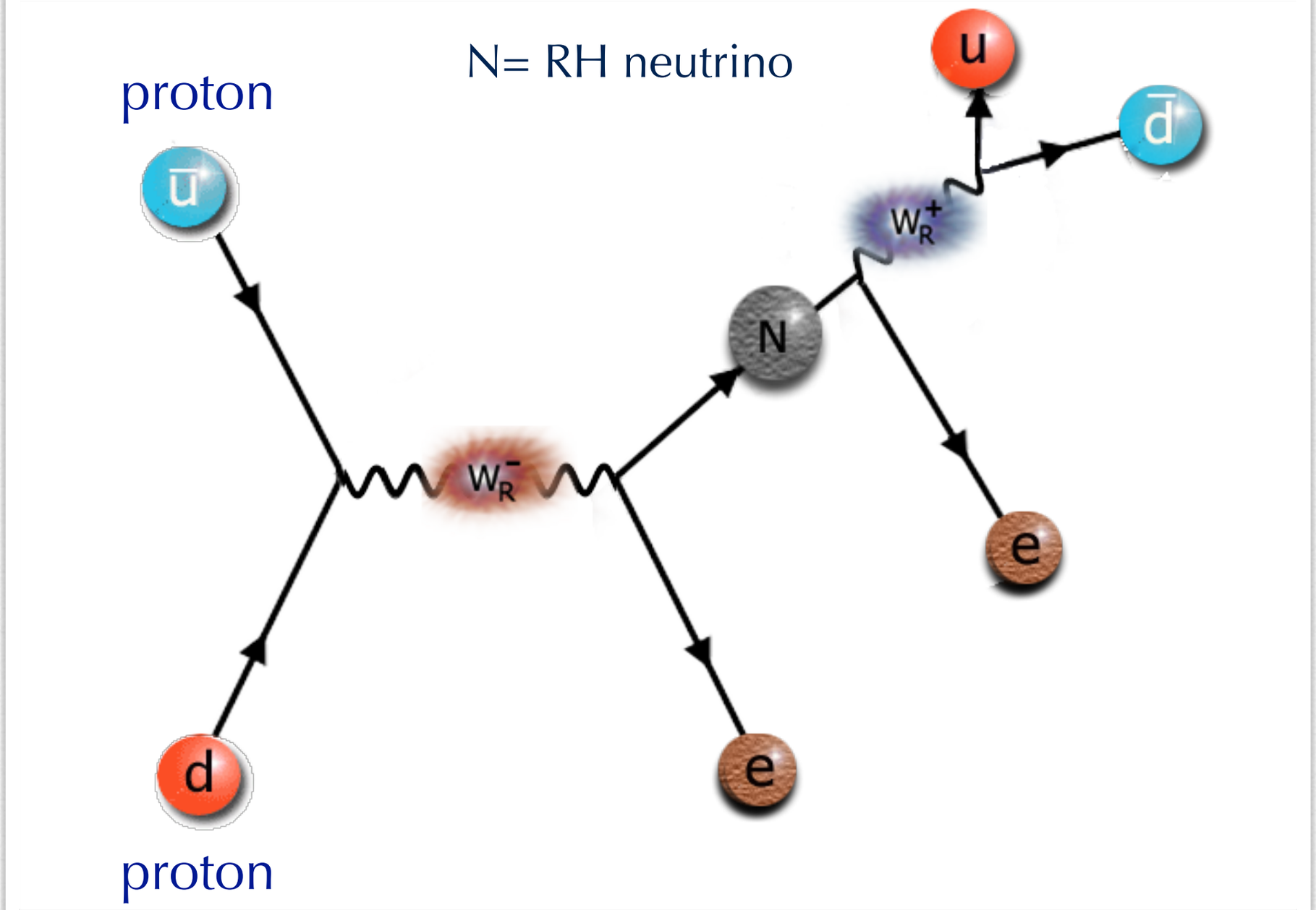
Lee, Yang 1956

conjecture on the last page:
LR is a hidden symmetry

parity broken maximally - they forgot it

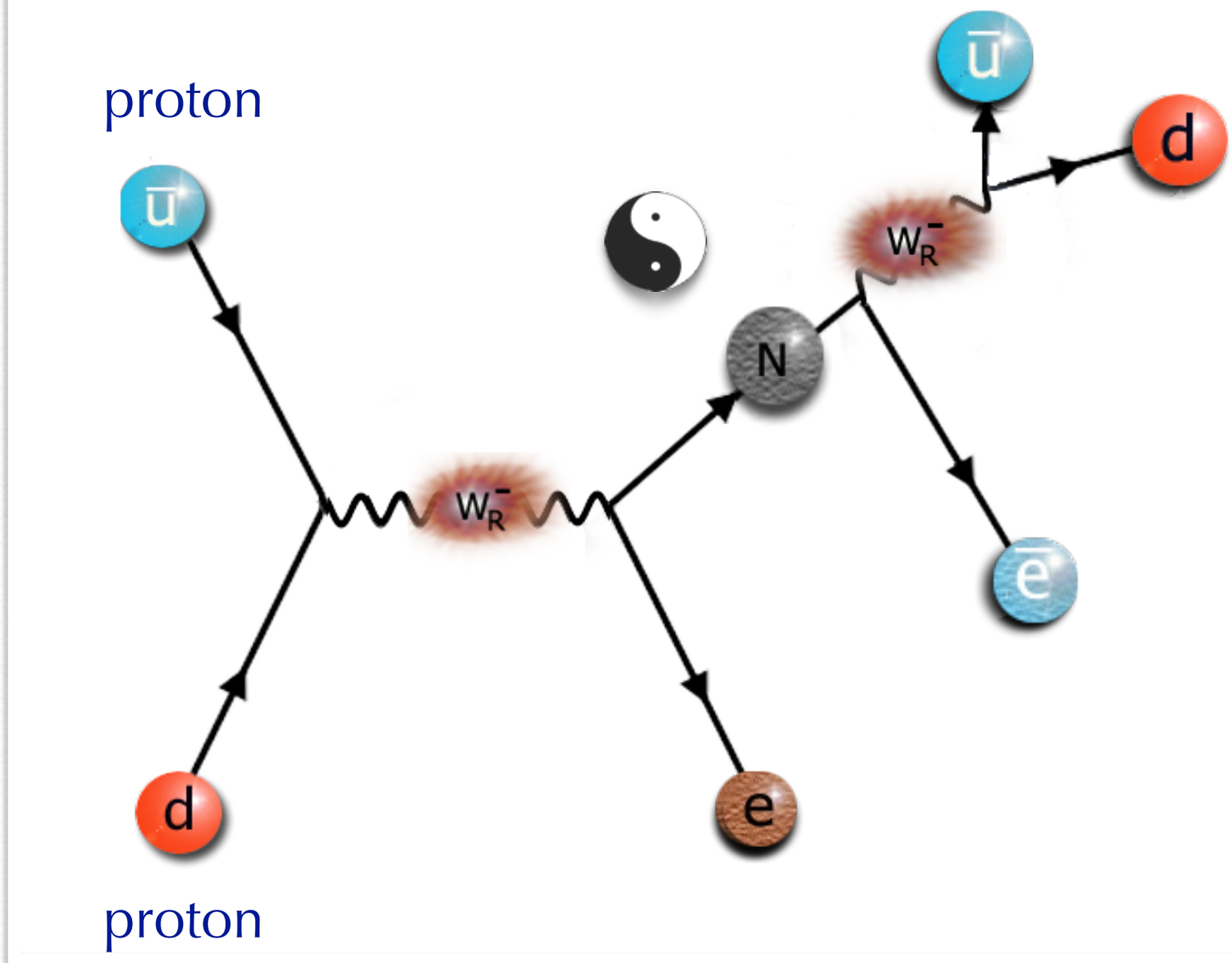
From Majorana to LHC

Keung, GS 1983



… and back

Keung, GS 1983



N = Majorana particle ➡ decays equally into positron

Neutrino mass: Higgs mechanism

$$\Gamma(N \to We) \propto m_\nu m_N^2$$

Nemevsek, GS, Tello 2012

GS, Tello 2015 - 2020

and a number of similar decays

testable at LHC?

SM for charged fermions

$$\Gamma(h \to f\bar{f}) \propto m_h m_f^2$$

Weinberg '67