Fundamental interactions set

Challenges to Nuclear Physic(ist)s

Standard Model established:

- Gauge interactions (chiral, i.e. Left-Left or Right-Right transitions) (respect CP, break maximally C and P)
- Very small scalar interactions (Brout-Englert-Higgs scalar boson) seen for now as the sole source of CP violation
- Neutrino mass established (oscillations), *but neutrino nature NOT established: (Majorana or Dirac)*

  (are ν_R present, accessible at nuclear or accelerator energies?)

Extensions needed:

- Needs extensions to account for Dark matter (for which ample evidence exists), dark energy
- Not understood in Standard Model : origin of the current excess of matter (possibly linked to the nature of neutrinos)
- *Questionable evidence* for extra neutrinos (reactor anomaly, MCurie)

Extensions expected:

- *More on aesthetical grounds* : grand unification (only 1 gauge coupling) , possible Left-Right symmetry restoration; fundamental understanding of CP violation understanding the number of families, the masses and mixing patterns.

For most topics in red, Nuclear physics needed or expected to hlep !

I will not discuss here :

- Dark matter : direct detection on Earth is based on very sensitive recoil detectors, neutrons are the main background, and nuclear physics plays a key rôle in those essential (and technically beautiful) experiments

- Direct measurement of neutrino masses (tritium decay en d point)

But we will consider :
Nature of neutrinos
CP and electric dipole moments (EDM)
Extra neutrinos, « Reactor anomaly »and very short neutrino oscillations

In 3+1 dimensions, the Lorentz group accepts in fact 2 independent
2-component rep., called Weyl spinors,
From a Standard Model viewpoint, they should be seen as independent particles

$$\begin{pmatrix} \xi_L \\ \eta_R \end{pmatrix}$$

Each of them can paticipate in gauge interactions:

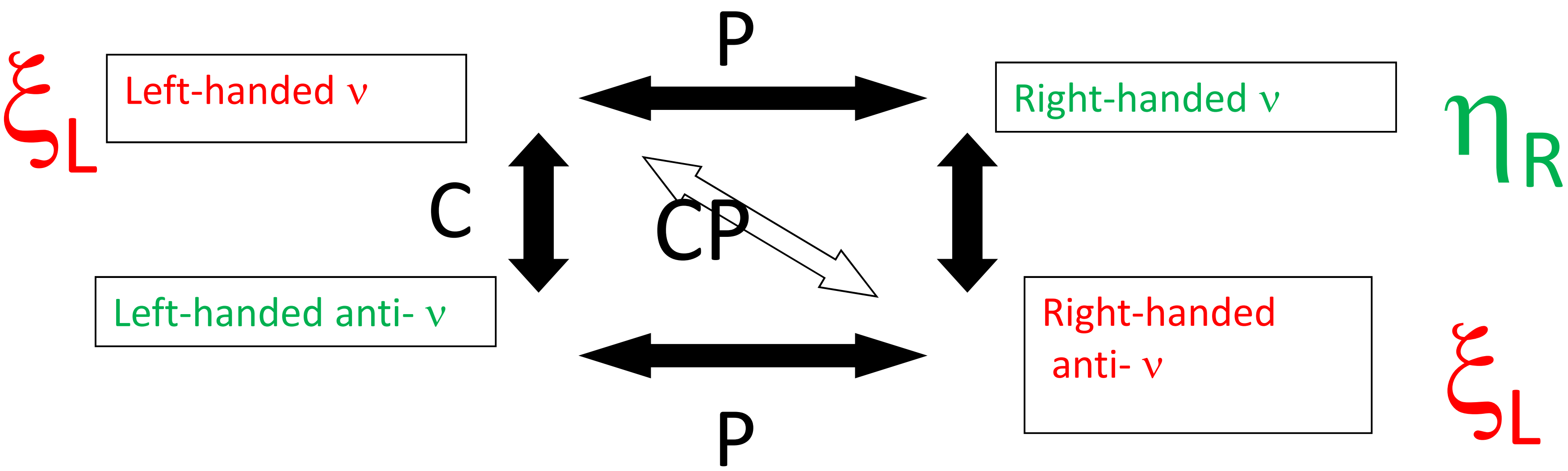
neutral ones (photon and Z) couple separately
to L and R

$$Z^\mu(g_L\ \overline{\xi_L}\gamma_\mu\xi_L + g_R\ \overline{\eta_R}\gamma_\mu\eta_R)$$

$g_L \neq g_R$ → P (and C) violation
(independently of neutrinos!)

ξ_L describes both a left-handed neutrino
and a right-handed anti-neutrino,

is both C and P violating, but CP conserving



CP is the natural symmetry of (massless) gauge theories, only
broken by mass and scalar interactions

In the Standard Model, charged currents only see the L part,
This is true **both for quarks and leptons**, so, here again, the nature of the neutrino (presence or absence of the R component is of no effect .

$$W^{\mu} \quad \xi_L^e \gamma_\mu \xi_L^\nu$$

Left-Right transitions occur
through scalar couplings, and the
resulting mass terms, after breaking.
(H is the Brout-Englert-Higgs doublet,
and h the remaining scalar, after symmetry breaking)

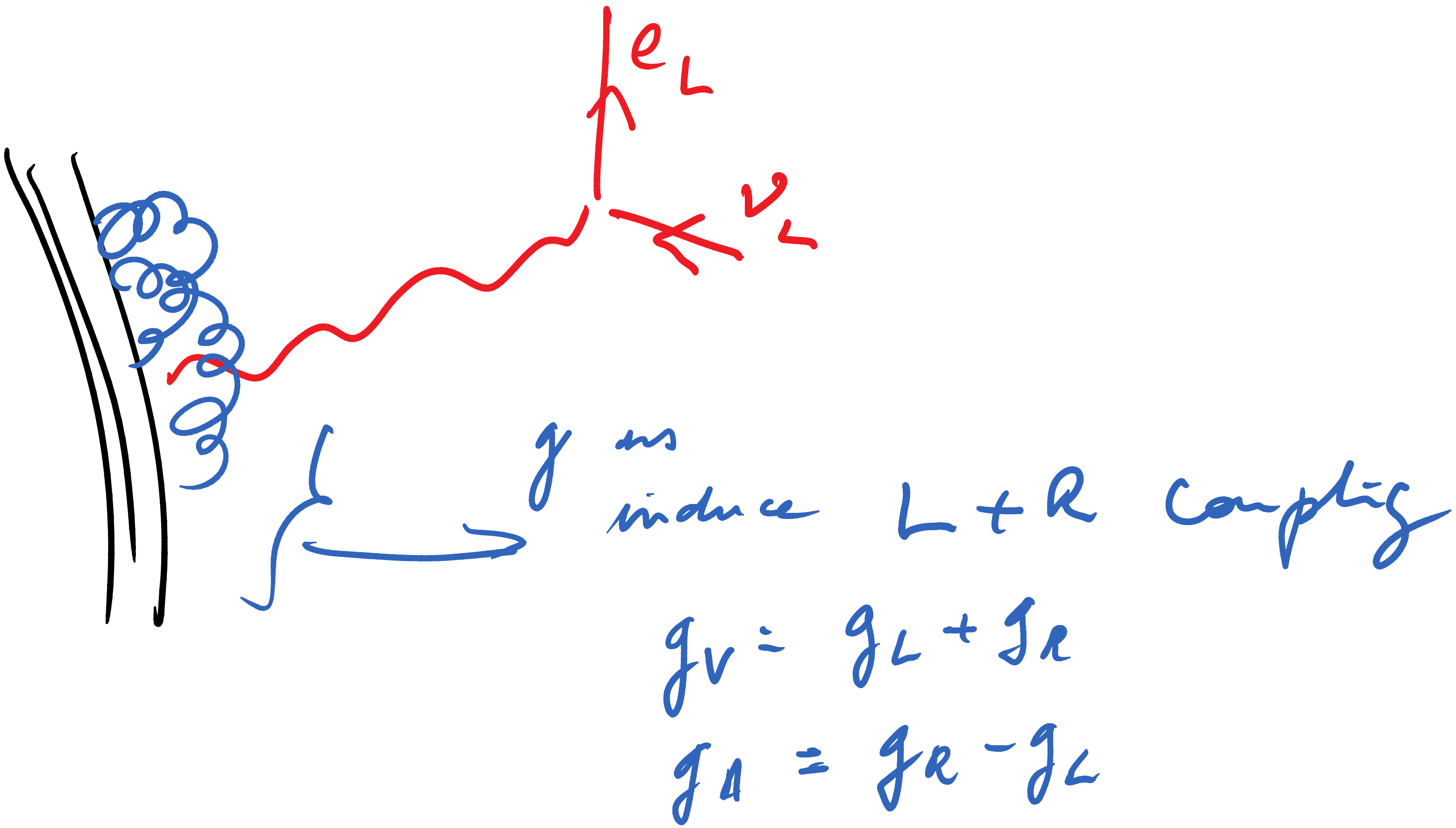
$$\lambda \, \overline{e_R} \, H \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$

$$m_e (\overline{e_R} e_L) \; \left(1 + \frac{g_W}{\sqrt{2} m_W} h^0\right) \quad + \text{h.c.}$$

Since λ can be complex, CP violation can occur (Kobayashi and Maskawa have shown that 3 families were needed to allow for the observation of these phases in the SM)

But the effects are small, since all the mass ratios $m_{fermion}/m_W$ must come into play

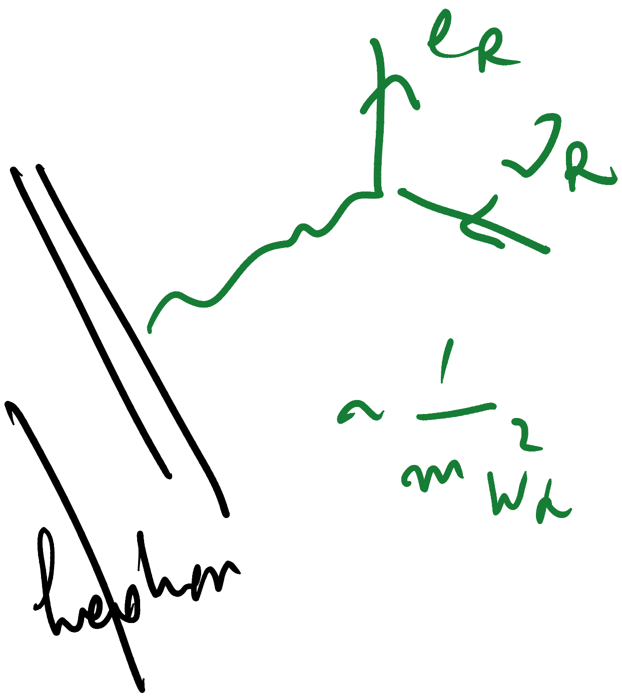
But (scalar) left-right transitions are also induced by strong interactions, through «confinement», which breaks chiral symmetry, resulting in constituent masses, pions, $g_A > g_V$ instead of $g_A = -g_V$ in V-A (left-handed) SM, This effectively induces a right-handed coupling in the hadronic part.



The best hope for detecting charged R couplings is to hope for both

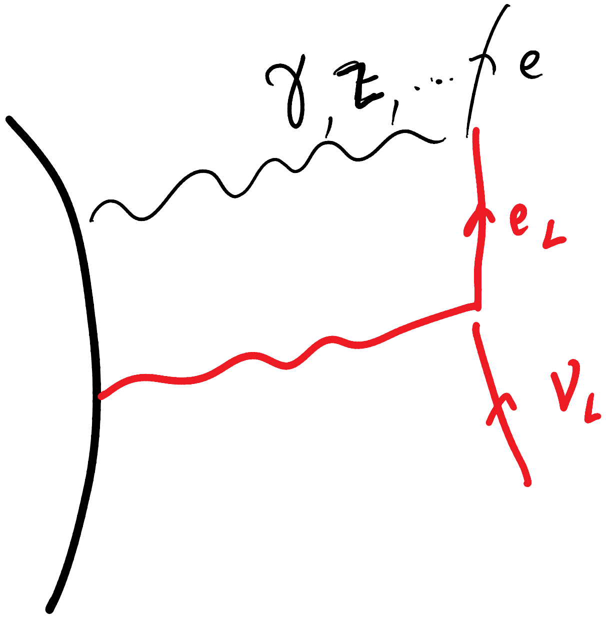
- R gauge bosons , like in SU(2)L X SU(2)R X U(1), possibly inspired by SO(10)
- Kinematically accessible right-handed neutrinos (more about this later)

Such WR would be accompanied by similar mass Z' , detectable at LHC

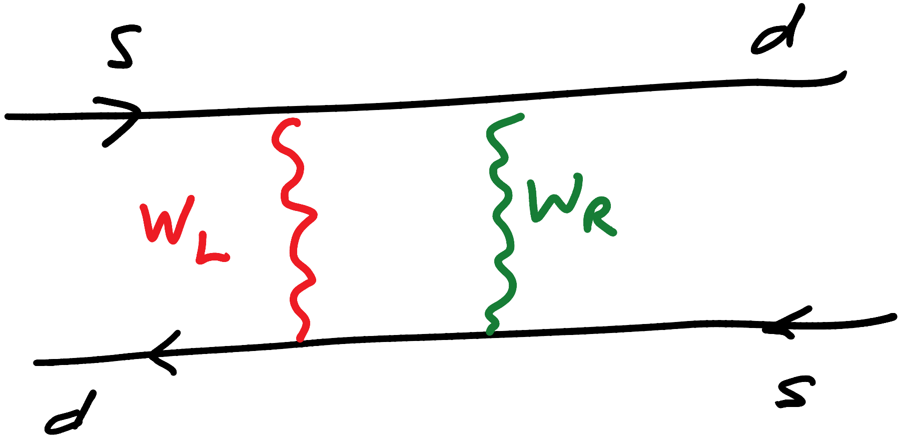


Typical « collider » limits 1 TeV M_R → 10^{-4} effect at best if no interference!

Higher order (weak + e-magnetic) corrections can induce additional couplings at α level in amplitudes



In other approaches, radiative corrections can be put to use for getting indirect limits on W_R



This graph contributes to the neutral K mixing (mass difference of KL and KS) has long been known to be greatly amplified wrt the SM calculation (400x) for chirality and other reasons. It gave a very early lower limit on WR

$\rightarrow M_{W_R} > 1.7\ \text{TeV}$

Is the R neutrino accessible to Nuclear Physics ?

$$\begin{pmatrix} \xi_L \\ \eta_R \end{pmatrix}$$

Posssible Lorentz invariants (in 2-component notation)

$$\bar{\eta}_R \cdot \xi_L \quad + h.c.$$

$$\epsilon_{ij}\xi_{Li}\xi_{Lj} + h.c.$$

$$\epsilon_{ij}\eta_{Ri}\eta_{Rj} + h.c.$$

MASS MATRIX

	ξ_{Li}	$\epsilon_{ik}\eta^{+}_{Rk}$
$\epsilon_{il}\xi_{Ll}$	0	m
η^{+}_{Ri}	m'	M_2

« Dirac »

« Majorana » arbitrary in SM, linked to W_R mass in LR models

0 is forced by gauge invariance

Majorana and Dirac are somewhat improper terms here,
The general case is in fact Majorana.

Traditionnally, « Majorana mass » term refers to a fermion-number violating term, while Dirac means fermion-number conserving.

$$\xi \to e^{i\alpha}\xi$$

$$\eta \to e^{i\alpha}\eta$$

$$m\ \bar{\eta}_R \cdot \xi_L\ + h.c.$$ invariant

$$M_1\ \epsilon_{ij}\ \xi_{Li}\xi_{Lj} + h.c.$$

$$M_2\ \epsilon_{ij}\ \eta_{Ri}\eta_{Rj} + h.c.$$

Violate fermion number by 2 units,

Obviously, when both kinds of terms are present, fermion number is violated, and one cannot speak of « Dirac » anymore

> Neutrinoless double beta
>leptogenesis

To come back to our general neutrino mass matrix,

	ξ_{Li}	$\epsilon_{ik}\eta^{+}_{Rk}$
$\epsilon_{il}\xi_{Ll}$	M_1	m
η^{+}_{Ri}	m	M_2

M typically >> 1 TeV
« explains » the small mass of light neutrino (if some rationale provided for the value of M)

The diagonalisation leads to 2 Majorana or Weyl spinors;
For $M_1 = 0$, and $m \ll M_2$
one gets the familiar See-Saw eigenstates and values

$$\lambda_1 \approx \xi_L - m/M \ \epsilon \cdot \eta_R^{+} \qquad |m_1| \approx m^2/M$$

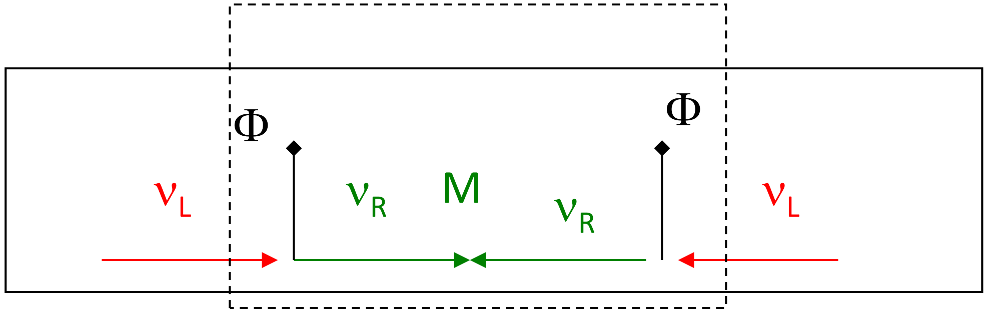
$$\lambda_2 \approx \eta_R + m/M \ \epsilon \cdot \xi_L^{+} \qquad |m_2| \approx M$$

$$\lambda_1 \approx \xi_L - m/M \ \epsilon \cdot \eta_R^+ \qquad |m_1| \approx m^2/M^2$$

$$\lambda_2 \approx \eta_R + m/M \ \epsilon \cdot \xi_L^+ \qquad |m_2| \approx M$$

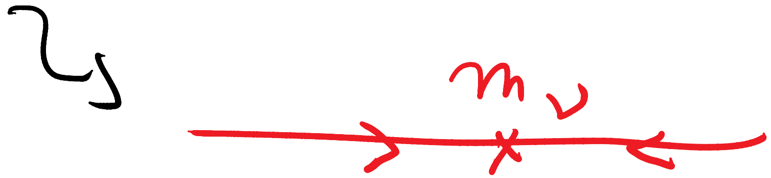
In practice, « mostly R » neutrino beyond reach of nuclear and most particle physics, … m/M mixing too small to observe …

But .. m^2/M mass of light neutrino of «Majorana » type (does not conserve lepton number) → neutrinoless double beta decay

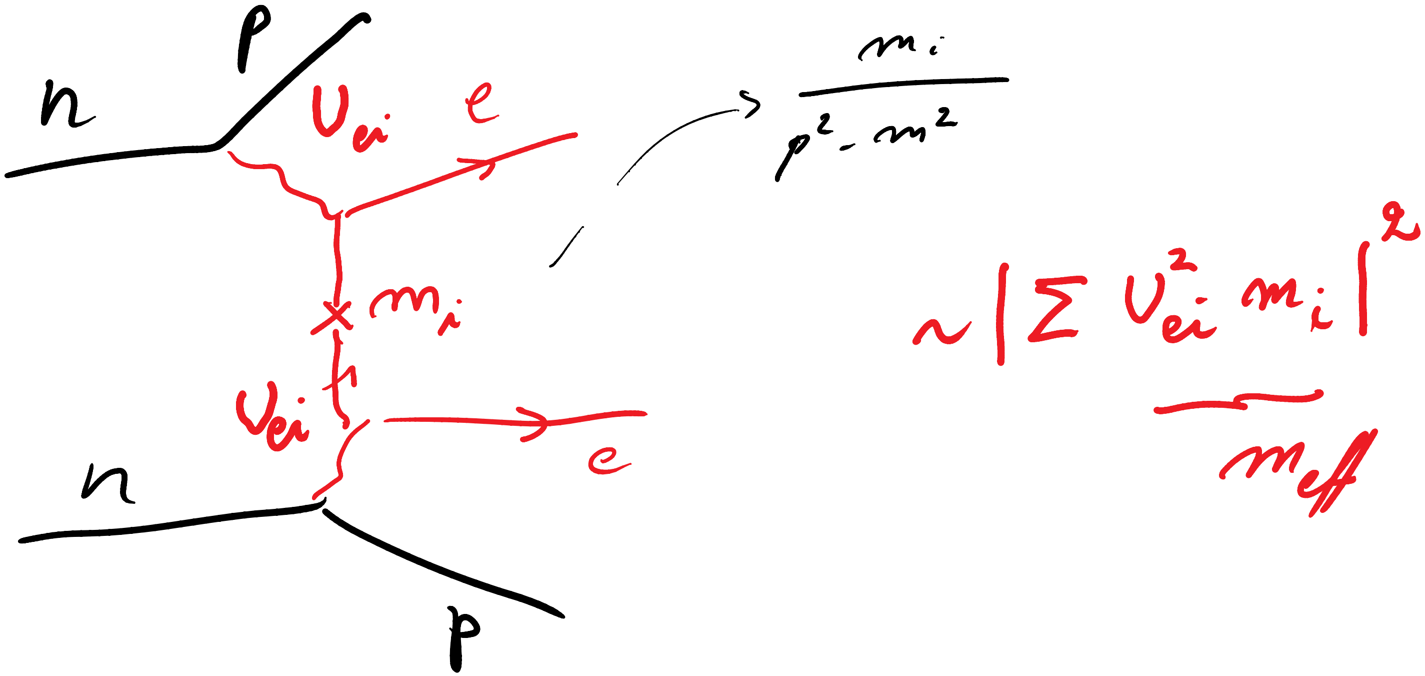


Thus, mixes high and low energy scales

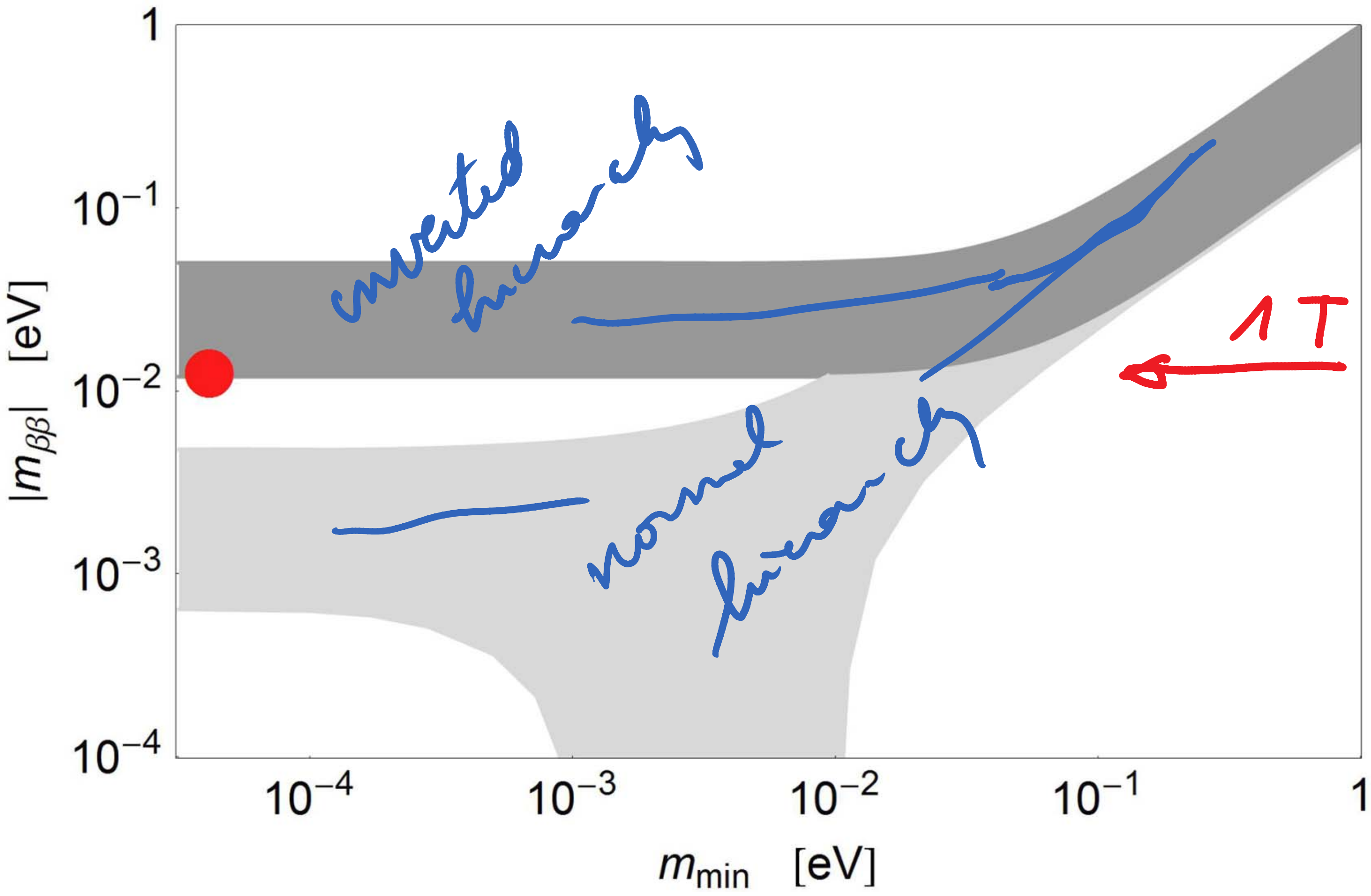
Mass generation (graphical interpretation)



Neutrinoless double beta decay $0\nu2\beta$



Perspectives for 0ν2β

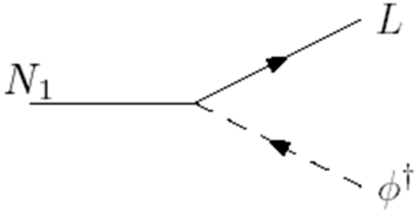


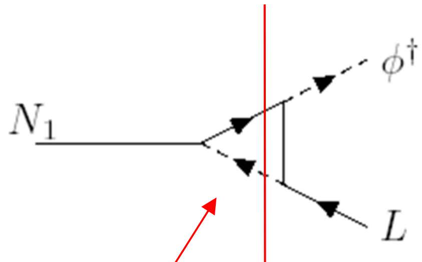
How leptogenesis works….N decay unequally in Land anti-L

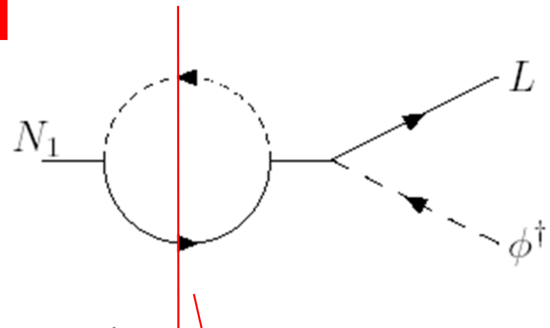
Assume that we have some population of heavy N particles…
(either initial thermal population, or re-created after inflation) ; due to their heavy mass and relatively small coupling, N become easily relic particles.

Generation of lepton number

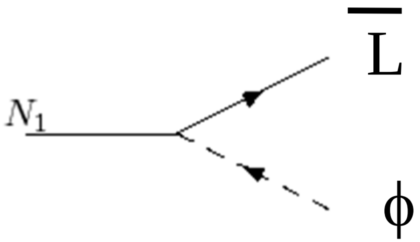
L =+1







N can decay to Lepton L + $\phi^\dagger$ as above, or to the opposite channel $\bar{L}\phi$



Interference term

L =-1

Possible unitarity cuts

N is « heavy » neutrino

Main importance: very Heavy (10 -10^15 GeV) Majorana neutrinos can lead to Leptognesis, currently the best candidate for expalin the « Defeat of Antimatter »

How leptogenesis works….N decay unequally in Land anti-L
Excess anti-Leptons genrated, converted by anomalies into Baryon number

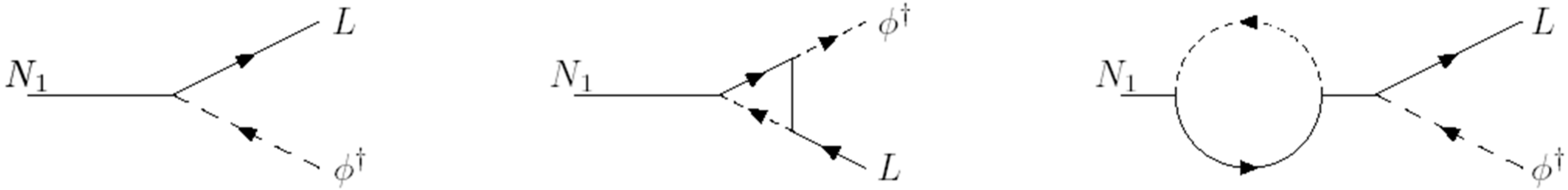
Observed: (with support from nucleosynthesis, CMB ..)

$$4\ 10^{-10} < n_B/n_\gamma < 7\ 10^{-10}$$

Requires (due to dilution and annihilation of other particles into photons) an initial asymmetry

$$\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim 10^{-8}$$

$$\lambda_\nu = v M^{1/2} R \,\mathrm{diag}\,(m_1, m_2, m_3)\, U^\dagger, \quad M = \mathrm{diag}\,(M_1, M_2, M_3)\,,$$



If the heavy Majorana particles N are very different in mass,
it is sufficient to consider the lightest (any asymmetry created by the others would be washed out by the remaining ones.
– by convention it is called N_1

Define the asymmetry:

$$\varepsilon_i^\phi = \frac{\Gamma(N_i \to l\,\phi) - \Gamma(N_i \to \bar{l}\,\phi^\dagger)}{\Gamma(N_i \to l\,\phi) + \Gamma(N_i \to \bar{l}\,\phi^\dagger)},$$

Non-de… se: get approx.

$$\varepsilon_i^\phi = -\frac{3}{16\pi}\frac{1}{\left[\lambda_\nu \lambda_\nu^\dagger\right]_{ii}} \sum_{j \neq i} \mathrm{Im}\left(\left[\lambda_\nu \lambda_\nu^\dagger\right]_{ij}^2\right)\frac{M_i}{M_j}.$$

Similar parameters
to light neutrino masses
but different combinations
-> no one-to-one link,
So full confirmation difficult
Finding Majorana masses
would be a big step

Remark : oscillation experiments tell us nothing about nature of neutrinos ..
Neutrino-antineutrino oscillation forbidden (protected by angular momentum)

Search plan for Nature of Neutrinos (this far)

ν_L

NO ν_R

Need scalar triplet χ probably accessible at colliders

Need absolute measure of neutrino mass (^{3}H, supernova propagation time)

ν_R

« light, Dirac type »

absolute measure of neutrino mass
If lucky, W_R light (TeV) -> pol. effect (??)

« heavy, Majorana type »

Need measure of light neutrino mass
Proof of Majorana character by $0\nu2\beta$ measurement
NO hope for WR observation in leptonic current.

Nuclear Anomaly? Very short distance oscillations?

Re-calculation of nuclear reactor neutrino flux by Müller et al suggests flux > observed (5% effect)
Circumstantial evidence (re-examination of Bugey expt, MegaCurie calibration of large Solar neutrino detectors, may hint in the same direction.

Calculations now disputed (error bars extended).

LA-UR-13-24535

Nuclear Physics Uncertainties in the Reactor Antineutrino Spectrum

A. Hayes, J. Friar, G. Garvey, G. Jungman (LANL)
G. Jonkmans (Chalk River)

Neutrino 2014
June 3, 2014
Boston,MA.

Gerald Garvey
Los Alamos National Laboratory

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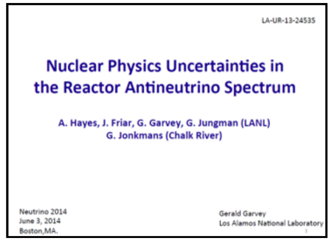
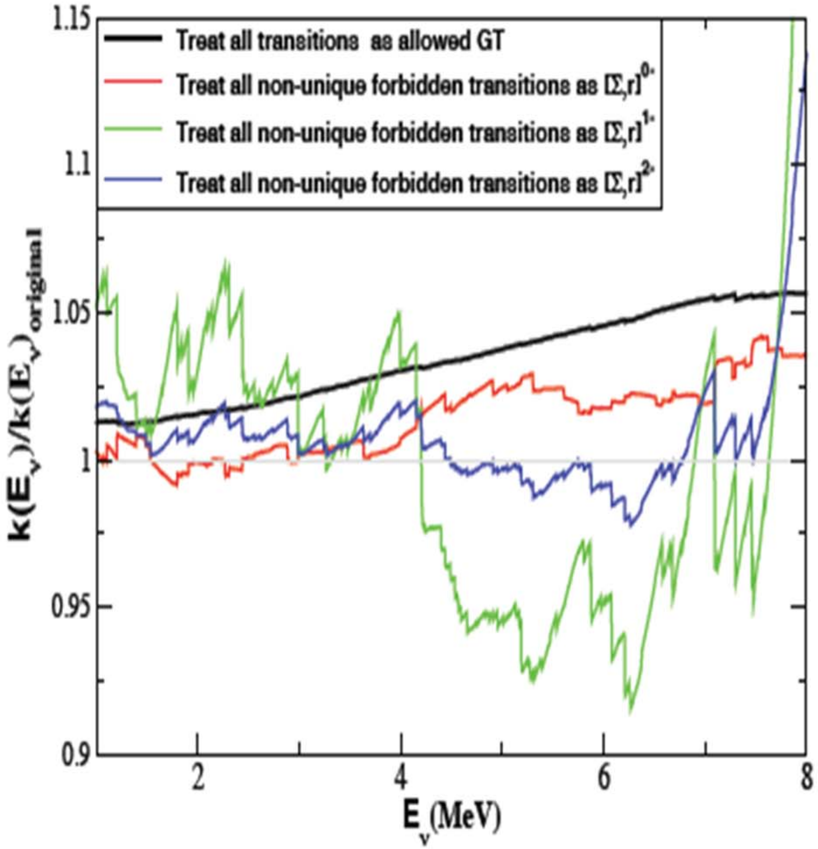




Found no path in the (E_n, E_e) plane that left the function $k(E_n, E_e)$ unchanged by 5%

=> Uncertainty in $N_\nu(E_\nu)$ is ~5%

$$k(E_e, E_\nu) = N_\nu(E_\nu) / N_\beta(E_e)$$

This prompted a number of suggestions (and more importantly experiments) to test for very short baseline oscillations …

If an oscillation into a sterile mode, only the active mode is observed,

$$P(\overline{\nu_e} \rightarrow \overline{\nu_e}) = 1 - sin^2(2\theta)\ sin^2(1.27\Delta(m^2)(eV^2)E(MeV)/L(m))$$

10% ??

If unresolved, averages to ½

Purpose: try to resolve the oscillation .. How far (or rather how close) do you need to go (mm oscillation would be impossible to resolve !

Cosmology to the rescue : >1 -2 eV neutrinos with sizeable mixing excluded
→ Oscillation length of O(meter)

Many expts planned (compact nuclear expts, MegaCurie sources) , in particular in Belgium : SOLID

Neutrino oscillations – continued

- Reactor anomaly very short oscillations involve sterile neutrinos
- Not directly related to other claimed signals (LANL, Mini-Boone)

- But better understanding of low energy neutrino cross sections on matter needed (including possible coherent neutrino scattering)

T-odd vs T violation and CP -violation

$$(\vec{p}_1 \times \vec{p}_2) \cdot \vec{p}_3$$

T - odd

$(\vec{p} \to -\vec{p})$

$t \to -t$

Final state interactions can induce T-odd without T violation

But T reversal is not only changing the kinematical variables t → -t , it involves also
| initial > ⟷ < final |

And for testing CP, would need to test particle/antiparticle decay

this is done for instance in comparing the kinematics of K^+ and K^-,
a good place to look for LR –induced CP violation
Castoldi, Kane, JMF -- investigated by NA48 but not published

$K^+ \to \ell^+ \nu \pi \pi$

$K^- \to \ell^- \bar{\nu} \pi \pi$

But T reversal is not only changing the kinematical variables t → -t , it involves also | initial > ⟷ < final|

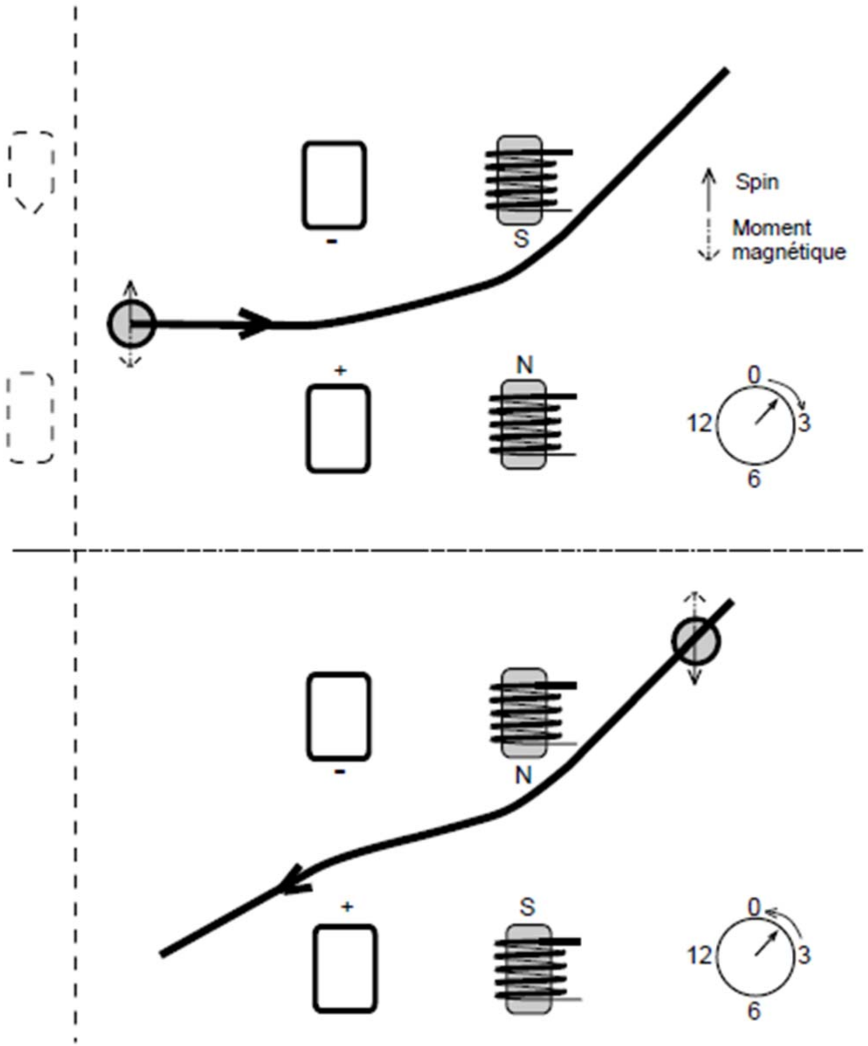
For this ,we need in practice to look for 1-particle evolution rather than decay
For instance , (K° → anti K°) vs (anti K° → K°) at CP Lear,
Or, more simply, Electric dipole moments of (nearly) elementary particles.

For instance, the neutron is seen as an s-state of 3 quarks, and behaves as an elementary particle: only directions available are momentum p and spin s

EDM d is a true vector, therefore

$\vec{d} \cdot \vec{s}$ T-odd
P-odd

And, since we are dealing with a static property, initial state = final state



Gedanken experiment illustrating T violation if neutron edm is observed ..

Where can EDM come from:

- Quantum anomalies → uncontrolled T-odd t term in effective Lagrangian

((affects equally proton and neutron) ---- only present if fermion mass present! essentially constrained by experiment

$\theta F_{\mu\nu} \tilde{F}^{\mu\nu}$

d(n) $< 2.9\ 10^{-26}$ e cm (current PDG value)

- Standard Model CP violation : p and n will differ, but below measurable level (of order 10^{-32} e cm

- **Beyond SM : in general large EDM predicted for p and n, already constrained : LR models, Susy extensions of SM**

Conclusions

Nuclear physics can bring critical information to our understanding of fundamental interactions,

But the most sensitive/important channels are the most difficult ones..

A very biased ordering:

*** Are the neutrinos Majorana (neutrinoless double beta decay, both at TH and an EXP challenge to nuclear physicists) *(this is both likely and a completely new type of particle)*

** Is there a neutron (or a proton, or an electron) Electric Dipole Moment ? (would prove physics beyond SM)

*** Can we observe local DM direct interactions (nuclear backgrounds a key issue, Beautiful new detector techniques (likely and a direct evidence of new physics)

- Short disctance neutrino oscillations, reactor anomaly, is a question to clear up, but also low energy neutrino cross sections should be better studied.

Back up slides

Some like to claim that Brout-Englert → mechanism , while Higgs → Boson
Some even claim that the Scalar boson is hard to find in Brout-Englert paper ..

?

Let us look closer …
… we need to go all the way to
Equation 1

ization to an arbitrary compact Lie group.
The interaction between the φ and the A_μ fields is

$$H_{\text{int}} = ieA_\mu \varphi^* \overleftrightarrow{\partial}_\mu \varphi - e^2 \varphi^* \varphi A_\mu A_\mu , \qquad (1)$$

where $\varphi = (\varphi_1 + i\varphi_2)/\sqrt{2}$. We shall break the symmetry by fixing $\langle\varphi\rangle \neq 0$ in the vacuum, with the phase chosen for convenience such that

This is the Abelian case, and φ1 is « The » Scalar, φ2 being absorbed…

Looks familiar ?
From you SM course?

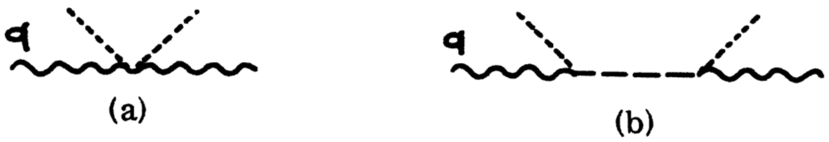


FIG. 1. Broken-symmetry diagram leading to a mass for the gauge field. Short-dashed line, $\langle\varphi_1\rangle$; long-dashed line, φ_2 propagator; wavy line, A_μ propagator. (a) $\rightarrow (2\pi)^4 ie^2 g_{\mu\nu} \langle\varphi_1\rangle^2$, (b) $\rightarrow -(2\pi)^4 ie^2 (q_\mu q_\nu / q^2) \times \langle\varphi_1\rangle^2$.

Now that we have found the Scalar particle in Eq. 1, *it is still possible to argue it should be named otherwise ….*

- **Higgs pointed out a massive scalar boson**

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

Equation (2b) describes waves whose quanta have (bare) mass $2\varphi_0\{V''(\varphi_0{}^2)\}^{1/2}$

- ” “… an essential feature of [this] type of theory … is the prediction of incomplete multiplets of vector and scalar bosons
- Englert, Brout, Guralnik, Hagen & Kibble did not comment on its existence

(from John Ellis’s talk in *Higgs Hunting 2011*)

(interesting comparison : the P-Q axion …)

In fact, this potential / mass issue was well-known
….. For example , Goldstone

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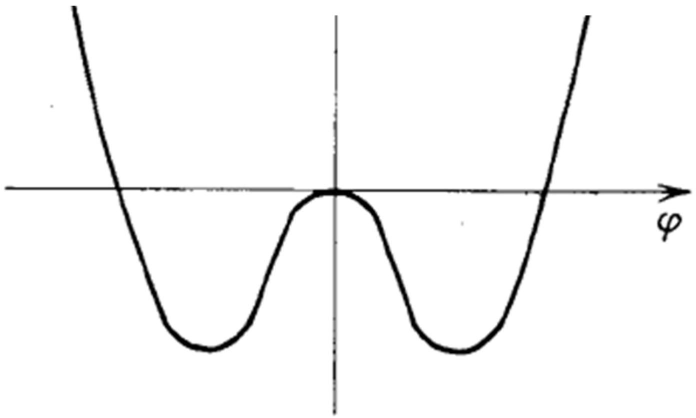

Fig. 7.

$$\frac{\mu_0^2}{2}\varphi^2 + \frac{\lambda_0}{24}\varphi^4 ,$$

is as shown in Fig. 7.

The classical equations

$$(\Box^2 + \mu_0^2)\varphi + \frac{\lambda_0}{6}\varphi^3 = 0 ,$$

now have solutions $\varphi = \pm\sqrt{-6\mu_0^2/\lambda_0}$ corresponding to the minima of this curve. Infinitesimal oscillations round one of these minima obey the equation

$$(\Box^2 - 2\mu_0^2)\,\delta\varphi = 0 .$$

These can now be quantized to represent particles of mass $\sqrt{-2\mu_0^2}$. This is simply done by making the transformation $\varphi = \varphi' + \chi$

	Article	Reception date	Publication date
1	F. Englert and R. Brout Phys. Rev. Letters 13 (1964) 321	26/06/1964	31/08/1964
2	P.W. Higgs Phys. Letters 12 (1964) 132	27/07/1964	15/09/1964
3	P.W. Higgs Phys. Rev. Letters 13 (1964) 508	31/08/1964	19/10/1964
4	G.S. Guralnik, C.R. Hagen and T.W.B. Kibble Phys. Rev. Letters 13 (1964) 585	12/10/1964	16/11/1964

Physics Lett B 12:
failure of NambuGoldstone
in presence of gauge fields


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A quote from GHK, About their remaining scalar (masslesss in their case ….)

part. The two degrees of freedom of A_k^- combine with φ_1 to form the three components of a massive vector field. While one sees by inspection that there is a massless particle in the theory, it is easily seen that it is completely decoupled from the other (massive) excitations,

VOLUME 13, NUMBER 20 PHYSICAL REVI

and has nothing to do with the Goldstone theorem.

VIEW LETTERS 16 NOVEMBER 1964

was partially solved by Englert and Brout,[5] and bears some resemblance to the classical theory of Higgs.[6] Our starting point is the ordinary electrodynamics of massless spin-zero particles, characterized by the Lagrangian

$$\mathcal{L} = -\tfrac{1}{2}F^{\mu\nu}(\partial_\mu A_\nu - \partial_\nu A_\mu) + \tfrac{1}{4}F^{\mu\nu}F_{\mu\nu} + \varphi^\mu \partial_\mu \varphi + \tfrac{1}{2}\varphi^\mu \varphi_\mu + ie_0 \varphi^\mu q \varphi A_\mu,$$