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The History of the W and Z Bosons

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This talk, given in June of 2013 at the XXI International Workshop High Energy Physics and Quantum Field Theory, is - in historical perspective - about the discovery of the W and Z intermediate vector bosons, from the unexpected discovery of radioactivity, the first tentative thoughts of a mediator of the weak interaction expressed by Hideki Yukawa and later by Oskar Klein, to the triumphal confirmation 30 years ago of their real existence by the CERN experiments UA1 and UA2 - nearly a century in the history of physics.

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1. Introduction.

The weak interaction is one of the four known fundamental forces of nature. It is responsible for the burning of the stars, thus providing the basis for life. Today we know that three of the four kinds of interaction work by the exchange of vector bosons between the interacting particles: the massless photon and gluon, giving rise to electromagnetic and strong forces, and the heavy intermediate vector bosons $W^{\pm}$ and Z^0, responsible for the weak interaction. Conceived of on theoretical grounds by Hideki Yukawa in 1935, their existence was finally confirmed by two teams of physicists in 1983. The leader of one of these teams, Carlo Rubbia, was in 1984 awarded the Nobel Prize for physics for this achievement, together with Simon van der Meer, who invented the method of cooling of the antiproton beam that made the realization of the experiment possible.

2. The first 30 years of β decay: from Becquerel to Fermi and Yukawa.

The history of the W and Z begins with the unexpected discovery of radioactivity by Becquerel in 1896. Radioactivity fired the imagination of many physicists. In his 1903 Nobel lecture [1] Becquerel names 18 contributors to this exciting new field of physics; among these were of course Pierre Curie and Marie Skladowska-Curie, who shared the Nobel Prize with him, but notably also Ernest Rutherford, who had shown that there were three kinds of radiation which he named α-, β- and γ-rays.

For more than 30 years, the study of radioactivity was the business of experimentalists. They found that the emitted β particles were electrons, and that the spectrum of the emitted β particles was continuous which, of course, was incompatible with the observed two-body decay of nuclei that everybody was seeing. Two theorists suggested a way out of this β-decay crisis: Niels Bohr suggested that on the atomic level energy need not be conserved - which was courageous but wrong; the young Wolfgang Pauli postulated the existence of a neutral spin-1/2 particle - now called neutrino - of a mass similar to or less than the electron mass and emitted together with the β particle [2]; that was also courageous and correct.[1] Enrico Fermi was one of the few to embrace Pauli's idea enthusiastically and formulated the first theory of beta decay [3].

Fermi's 1934 theory of β decay was modeled after electromagnetism. Fermi did not speculate about a carrier of the force, proposing a point interaction. Amazingly, Fermi's theory stood the test of time for over 20 years, when it was proved not wrong but just incomplete: this was when in 1956 parity was shown to be violated.

Serious speculations about a carrier of the weak force appeared soon after Fermi's work, first in the work of Hideki Yukawa on the strong nuclear force [4]. Yukawa postulated that every force between particles must be associated with a force field, and that on general grounds of quantum field theory the quanta of that field are particles. It is the exchange of these quanta between the interacting particles that mediates the interaction. Today this may seem obvious, but at the time of Yukawa this was a mighty leap of imagination, generalizing the mechanism of electromagnetic interaction - the exchange of photons between charged particles - to an unknown entity. The mass of these quanta could be estimated from the nuclear size using Heisenberg's uncertainty principle,

[1] Pauli's postulate of the neutrino removed also another problem of β-decay, namely conservation of angular momentum, that appeared violated without a spin-1/2 particle being emitted together with the β particle.

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and it came to be intermediate between the masses of electrons and nucleons, and for that reason they were called mesons, and eventually π mesons or just pions. Mostly remembered is that the pion is connected with the strong nuclear force. Largely forgotten is that in Yukawa's theory the meson was also coupled to leptons - this was the mechanism giving rise to beta decay. Moreover, the meson was coupled to pairs of leptons, which foreshadows the weak neutral current. But 40 more years of work were needed, involving many theorists and even more experimentalists, before Yukawa's ideas matured into the Standard Model of particle physics.

A few years after Yukawa, Oskar Klein - the Klein of the Klein-Fock-Gordon equation and of the Kaluza-Klein theory - took up the idea of the carrier of a force responsible for β decay and reasoned that they should be charged bosons and have a mesonic mass. In the published version in 1948 [5] he said: "*The role of these particles, and their properties, being similar to those of the photons, we may perhaps call them 'electro-photons'*".

3. Emergence of the concept of weak interaction - from Pontecorvo to Gell-Mann.

After the discovery of the muon in 1937 [6], it took some time before it was understood that it was not Yukawa's meson. The evidence was that, although this meson had the right mass, it was not strongly interacting with nuclear matter, and its decay resembled beta decay. So the question was: what is this meson? The answers to that question led to the emergence of the notion of a weak interaction, at first in a proposal by Bruno Pontecorvo [7], and finally in matured form only in 1955, *i.e.* just before the discovery of parity violation in weak interactions.

In his recollections in 1989 [8], Pontecorvo lists the questions he asked when it had become clear that what at the time was called the 2.2-*microsecond meson* was not Yukawa's meson:
(i) Why should the spin of the muon be integer?
(ii) Does the muon decay into an electron and a neutrino, or into an electron and two neutrinos, or into an electron and a photon?
(iii) Is the charged particle emitted in muon decay really an electron?
(iv) Are particles other than electron and neutrino emitted in muon decay?
(v) In what form is energy mainly released in nuclear muon capture?

The answers to these questions are well known, so there is no need to spell them out here. Let me just say that after Pontecorvo, these questions were also discussed by Oskar Klein, Puppi, T.D. Lee, M. Rosenbluth and C.N. Yang, and by J. Tiomno and J.A. Wheeler [5, 9, 10, 11]. Pontecorvo ends his recollections saying: "*... at the Pisa conference of 1955, mainly as a result of the wonderful talk of M. Gell-Mann, the notion of weak interactions, which was introduced in 1947 [7] became finally established*".

I will conclude this brief survey of the early period by listing in Table 1 the important milestones in the development of weak interaction physics from 1941 to 1955.

4. Parity violation, two-component theory of the neutrino, and $V-A$ theory.

The discovery in 1956 of parity violation heralded a new chapter in the development of weak interaction physics. In the decade preceding this discovery, many more elementary particles had been discovered in cosmic rays and then also copiously produced in accelerators. Some of these

Year	Milestone	Author	Ref.
1941	muon β decay and lifetime	Rasetti; Rossi, Nereson	[12]
1947	muon is not a hadron	Conversi, Panchini, Piccioni	[13]
1947	discovery of pion; $\pi \rightarrow \mu\nu$ decay	Lattes, Occhialini, Powell	[14]
1947-48	concept of $\mu - e$ universality	Pontecorvo; Klein; Puppi	[15]
1947	discovery of hyperons and K mesons	Rochester, Butler	[16]
1948	absence of $\mu \rightarrow e\gamma$ decay	Hincks, Pontecorvo; Piccioni	[17]
1948	π and μ in accelerators;		
	accurate determination of their masses	Gardner, Lattes	[18]
1953	isospin multiplets of hadrons	Gell-Mann; Nishijima	[19]
1955	$K^0 - \bar{K}^0$ oscillations	Gell-Mann and Pais; Piccioni	[20]

Table 1: Milestones in weak interaction physics 1941-1955

particles, mesons and baryons, were created in strong interactions but decayed weakly. Puzzling was the behavior of two mesons called at the time τ^+ and θ^+ but now designated K^+: within experimental errors they had the same mass, but decayed differently. One of them decayed into two pions - a positive parity system, and the other into three - which has negative parity. This "$\tau - \theta$ paradox" prompted Lee and Yang to ask the question: are the τ and θ different particles with parity conserving decays, or could they be one and the same particle with parity violated in its decay? They examined all available experimental evidence and found that none of the experiments had been testing parity conservation [21]. They also proposed an experimental test of parity conservation, and within a short time C.S. Wu with her collaborators demonstrated that parity was indeed violated in the β decay of cobalt-60 [22], two experiments found parity violation in muon and pion decay [23, 24], and another experiment demonstrated parity violation in nuclear γ decay [25].

The discovery of parity violation triggered an industry of work that in 1958 led to the $V - A$ theory. Landau was the first to realize that parity violation could result from the neutrino having only one direction of its helicity [26]. This could be naturally described by a two-component wave function of the (*massless!*) neutrino.[2] Abdus Salam [28] and T.D. Lee and C.N. Yang [29] also published versions of the two-component theory of the neutrino.

In 1958 the vector-axial vector – or simply $V - A$ – theory of weak interactions was formulated independently by Marshak and Sudarshan [30], Feynman and Gell-Mann [31] and Sakurai [32]. It is interesting that the three papers take three different starting points: Marshak and Sudarshan started from a conjectured chirality invariance, Feynman and Gell-Mann based their approach on the two-component theory of the neutrino, and Sakurai started from mass-reversal invariance. These three approaches proved to be equivalent and led to the same result - the formulation of the $V - A$ theory of weak interactions. Like Fermi's theory, $V - A$ has a 4-fermion point interaction. In fact, the V part of $V - A$ is just Fermi's theory, and parity violation is the result of interference of the vector with the axial vector.

[2]Of historical interest is that a two-component theory of massless spin-1/2 fermions was proposed by Hermann Weyl in 1929 [27], *i.e.* even *before* the neutrino was proposed by Pauli; and it was Pauli who rejected Weyl's theory on the grounds that it was parity violating - which in Pauli's view, shared at the time by everybody, was inconceivable.

5. Gauge theories, broken symmetry and the Nambu-Goldstone boson.

Parallel to work on weak interactions, and unrelated to it, the concept of gauge invariance emerged and developed into a fundamental principle of field theory.

The first non-Abelian gauge theory was the 1954 work of Yang and Mills [33]. Significant for our story is the application to weak interactions, to which many theorists contributed: Schwinger in 1957 [34], Glashow in 1961 [35], Salam and Ward in 1964 [36] and others.

Yet another concept was the work of Nambu, Goldstone and others that developed the concept of the broken symmetry and hence led to the Higgs mechanism [37, 38], which ultimately was of decisive importance for the unification of electromagnetism with weak interactions.

6. Neutrino physics of the 1960s.

Today's neutrino physics is all about neutrino oscillations and related topics. This was not so in the 1960s, when high-energy and high-intensity neutrino beams became available first at the Brookhaven Laboratory [39, 40], and soon after that at CERN [41]. Then what mattered was the measurement of neutrino-nuclear cross sections, the study of neutrino deep inelastic scattering, and, more generally, the study of weak interactions, to which the neutrino is arguably the most appropriate tool. One of the objectives of the early neutrino experiments was to test the hypothesis that there was a muon neutrino distinct from the electron neutrino [42, 43]. For their successful experiment that established that $\nu_\mu \neq \nu_e$, Lederman, Schwartz and Steinberger were awarded the Nobel prize for physics in 1988 [44].

Another high priority was the search for the intermediate vector boson W, postulated to be the carrier of the weak force [40]. In his lecture at the 1966 Enrico Fermi School T.D. Lee remarked: "*From a theoretical point of view, it seems to me that the existence of W has an intrinsic appeal. While it still leaves a number of problems unsolved, its existence simplifies and unifies our present picture of weak interactions. The experimental proof of this particle will undoubtedly be a crucial landmark in the understanding of weak interactions*" [45].

7. Unification of the electromagnetic and weak interactions.

The unification of the electromagnetic and weak interactions was finally achieved in 1967-68 in the work of Weinberg and Salam [46, 47].

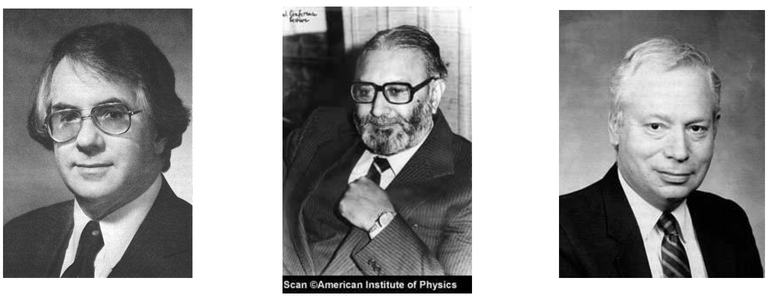

Figure 1: Left to right: S. Glashow, A. Salam, S. Weinberg

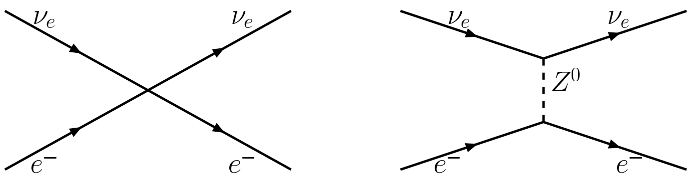

Figure 2: Feynman diagrams of $\nu - e$ elastic scattering in $V - A$ (left) and GSW (right) theories.

The most striking prediction of the electroweak interaction theory was the existence of a weak neutral current or, in other words, of a heavy neutral partner Z of the charged boson $W^{\pm}$. This comes about by the mixing of the third component of the weak isospin triplet of vector bosons with the weak hypercharge singlet B_μ, which is of the form of a rotation in weak isospin space giving the massless photon A_μ and the Z boson:

$$A_\mu = B_\mu \cos\theta_W + W_\mu^3 \sin\theta_W, \qquad Z_\mu = -B_\mu \sin\theta_W + W_\mu^3 \cos\theta_W \tag{7.1}$$

Now, these things have acquired a space in undergraduate textbooks even as long ago as the 1980s (see *e.g.* [48]), so it is only to fix the notation that I am displaying this and the next formulæ. There is an immediate consequence of this mixing: the coupling g of the weak isospin currents to the W, and the coupling g' of the weak hypercharge current to B are not independent but are related to each other and indeed to the electric coupling e as

$$g \sin\theta_W = g' \cos\theta_w = e \tag{7.2}$$

and the masses of the W and Z are related to each other, to e and to the Fermi constant G_F by

$$M_W^2 = \frac{\sqrt{2}e^2}{8G_F}\frac{1}{\sin^2\theta_W}, \qquad M_Z = \frac{M_W}{\cos\theta_W}$$

and since e and G_F are known, we have in numbers

$$M_W = \frac{37.3\,\mathrm{GeV}}{\sin\theta_W}, \qquad M_Z = \frac{74.6\,\mathrm{GeV}}{\sin 2\theta_W}$$

which immediately sets lower limits for the masses: $M_W \geq 37.3\,\mathrm{GeV}, \quad M_Z \geq 74.6\,\mathrm{GeV}$. Now, this is a powerful prediction, good enough to start planning experiments to see the W and Z, or else to get a better idea of their masses by measuring the mixing angle θ_W.

One reaction that, according to the GSW theory, has a simple dependence on $\sin^2\theta_W$, is elastic neutrino-electron scattering; the corresponding Feynman diagrams are shown in Fig. 2. The differential neutrino- and antineutrino-electron elastic cross section is

$$\frac{d\sigma_{el}(\nu e)}{dE} = \frac{G^2 m_e}{\pi}\left\{(g_V+g_A)^2 + (g_V-g_A)^2\left(1-\frac{e}{E_\nu}\right)^2 + \frac{m_e E}{E_\nu^2}\left(g_A^2 - g_V^2\right)\right\},$$

where E_ν is the neutrino Lab energy and the couplings g_V and g_A are shown in Table 2; the last term in curly brackets is negligible, and omitting it we get after integration

$$\sigma_{el}(\nu e) = \sigma_0\left\{(g_V+g_A)^2 + \frac{1}{3}(g_V-g_A)^2\right\}, \qquad \sigma_0 = E_\nu G^2 m_e/\pi$$

The ratio $\sigma_{el}(\nu e)/\sigma_0$ is a function of $\sin^2\theta_W$ in the GSW theory, and is constant in the $V-A$ theory. The most striking difference between the prediction of these theories is the absence of the process with muon-neutrinos in the $V-A$ theory. Plots of the cross sections are shown in Fig. 3. Note that with the value of $\sin^2\theta_W \approx 1/4$ that we know now, the elastic cross sections in the $V-A$ and GSW theories are very similar, and considering the low statistics of early neutrino experiments it is not surprising that no convincing results on the mixing angle were produced even by 1972.

Reaction	V-A theory		GSW theory	
	g_V	g_A	g_V	g_A
$\nu_e e \to \nu_e e$	1	1	$1/2+2\sin^2\theta_W$	$+1/2$
$\overline{\nu}_e e \to \overline{\nu}_e e$	1	1	$1/2+2\sin^2\theta_W$	$-1/2$
$\nu_\mu e \to \nu_\mu e$	0	0	$-1/2+2\sin^2\theta_W$	$-1/2$
$\overline{\nu}_\mu e \to \overline{\nu}_\mu e$	0	0	$-1/2+2\sin^2\theta_W$	$+1/2$

Table 2: Leptonic couplings in the $V-A$ and GSW theories

In 1972, at the High-Energy Physics Conference at NAL, D.H. Perkins presented results of measurements of the weak mixing angle from three laboratories [49] - see Table 3 - and he concludes: "*... even if in future improved experiments, a clear signal is detected, it is necessary, in order to finally demolish the Weinberg theory, to prove that the observed signal rate is consistent with the $V-A$ prediction within close limits* ".

Reaction	Laboratory	Technique	Limit 90% CL
$\overline{\nu}_e e \to \overline{\nu}_e e$	Savannah R.	Nucl. Reactor	< 0.35
$\overline{\nu}_\mu e \to \overline{\nu}_\mu e$	CERN	Gargamelle	< 0.6
$\overline{\nu}_\mu e \to \overline{\nu}_\mu ee$	CERN	Propane PC	< 0.85

Table 3: Experimental limits on $\sin^2\theta_W$: status of 1972

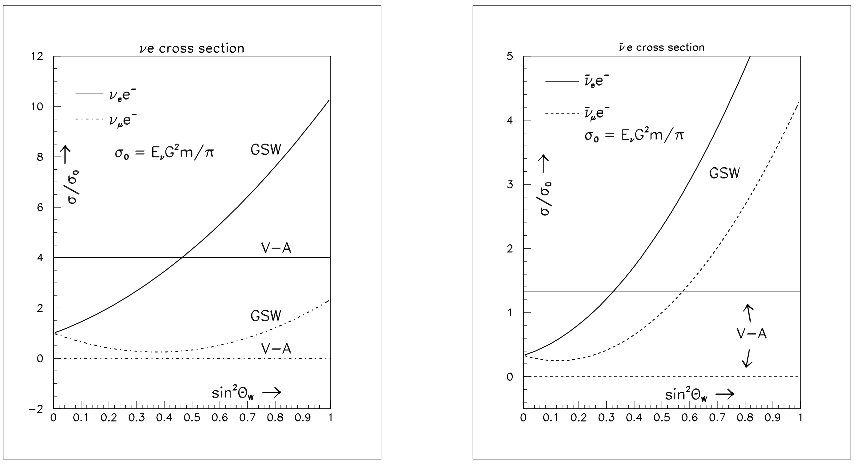

Figure 3: νe cross section (left) and $\overline{\nu}e$ cross section (right) as function of $\sin^2\theta_W$

8. Discovery of Neutral Currents: Gargamelle.

The discovery of neutral currents was finally achieved by the CERN experiment Gargamelle. Gargamelle was a large heavy liquid bubble chamber. It consisted of a cylindrical chamber, 4 m long, 1.88 m diameter, filled with 12000 liters of a heavy liquid (propane, freon, or a mix of the two), and contained in a 2 Tesla magnetic field. Operation of Gargamelle started in January 1971 with muon-neutrinos and antineutrinos from the CERN PS. In two years of running, nearly a million photos were taken. In 1972 the first observation of $\bar{\nu} + p \to \mu^+ + \Lambda^0$ was reported, and neutrino and antineutrino total cross sections were measured. Then, in 1973, the Gargamelle Collaboration reported the "*Observation of an event which may be interpreted as the reaction* $\bar{\nu}_\mu + e^- \to \bar{\nu}_\mu + e^-$", in other words, a neutral current elastic neutrino-electron collision [50]. This was followed by the observation of hadronic neutral current candidates. These results were, however, not immediately accepted as the discovery of neutral current, but rather seriously challenged for a few more years. There were also some contradictory experiments, but these were corrected. In 2003, at the celebration of the 30th anniversary of the discovery of neutral currents, Weinberg remembered [51]: "*Many other models were tried during this period. Finally, parity violation in the neutral currents was discovered at the expected level in electron-nucleon scattering at SLAC in 1978, and after that most physicists took it for granted that the electroweak theory is essentially correct.*"

9. First glimpse of the Z boson in e^+e^- collisions.

In e^+e^- collisions below the Z resonance, the Z boson shows up in the forward-backward asymmetry of the reaction $e^+e^- \to \mu^+\mu^-$. This is defined by

$$A_{FB} = (\sigma_F - \sigma_B)/(\sigma_F + \sigma_B)$$

where σ_F (σ_B) is the forward (backward) cross section. The theoretical expression for A_{FB} is well known (see, *e.g.*, Ref. [52]): it depends on the mass and width of the Z bsoson, on the fine structure constant α, the Fermi constant G_F and on the weak coupling constants g_V and g_A, which, in turn, are expressed in terms of the weak angle θ_W. Thus, the measured asymmetry can be used to determine the mass of the Z boson. This has been done in 1981-82 by the experiments JADE, CELLO, TASSO and Mark J at DESY [53, 54, 55, 56].

From the results shown in Fig. 4 TASSO found $\sin^2\theta_W = 0.29^{+0.09}_{-0.11}$, from which $M_Z \approx 82\,\mathrm{GeV}$ - out of reach of the DESY collider PETRA.

10. 1964-1976: from 300 GeV programme to CERN SPS.

In 1964/65, a programme was put forward at CERN for the construction of an accelerator of 300 GeV, ten times the energy of the proton synchrotron (PS). But those were difficult times economically, with reduction of science budgets in several European countries. There was also a politically difficult siting problem: 5 sites were proposed. So, all European Governments stalled. It was largely due to the diplomatic skill and leadership of the project leader John Adams that the

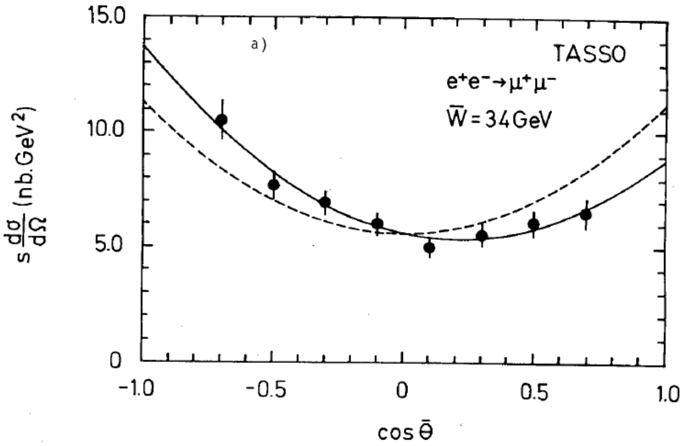

Figure 4: Asymmetry of $e^+e^- \to \mu^+\mu^-$ differential cross section; TASSO, 1982

difficulties were resolved and the SPS was built at CERN [57]. On the 17th of June 1976 the first 400 GeV pulse went round the SPS ring.

The original physics programme at the SPS was a programme of fixed-target physics. But it was not long before Carlo Rubbia proposed the conversion of the SPS into an proton-antiproton collider with the aim to search for the intermediate vector bosons (IVB) $W^\pm$ and Z [58]. The idea was to make an experiment in which the IVB was *produced* rather than exchanged between the interacting particles, thus providing *direct* rather than indirect evidence of its existence.

To produce a W or a Z in hadronic collisions, one must collide a quark from one hadron with an antiquark from the other. The cross sections for the processes $u\overline{d} \to W^+ \to \mu^+\nu_\mu$ and $u\overline{u} \to Z^0 \to e^+e^-$ are shown in Fig. 5 as functions of the centre-of-mass energy $\sqrt{s}$. [3]

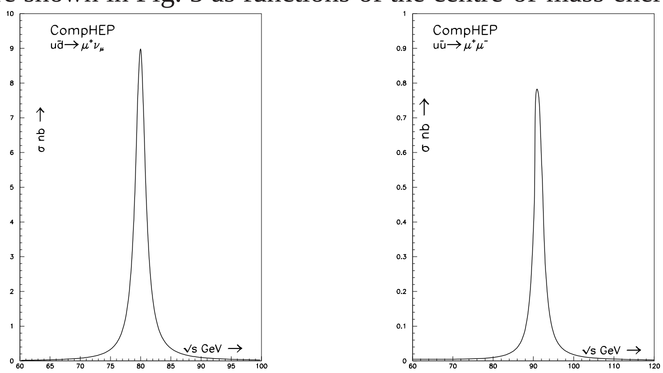

Figure 5: W boson resonance (left) and Z boson resonance (right) as function of $\sqrt{s}\,$GeV

Observed are not such narrow resonances, but rather their convolution with the hadronic structure functions. The corresponding diagrams are shown in Fig. 6. If we denote the 4-momenta of the proton and antiproton p_1 and p_2, respectively, and the fractional momenta of the colliding quarks x_1 and x_2, then the square of the total quark-antiquark momentum is $s = (x_1\mathrm{p}_1 + x_2\mathrm{p}_2)^2 = x_1x_2S$, where $S = (\mathrm{p}_1 + \mathrm{p}_2)^2$. To produce an IVB in such a process, we must have $\sqrt{s} \approx m_V$, where m_V is the mass of the IVB, and hence $S \approx m_V/\sqrt{x_1x_2}$. One must choose $x_{1,2}$ such that the valence

[3]these plots were made using the CompHEP package [59]

Figure 6: Diagrams of charged current (left) and neutral current (right) processes in $p\bar{p}$ collisions

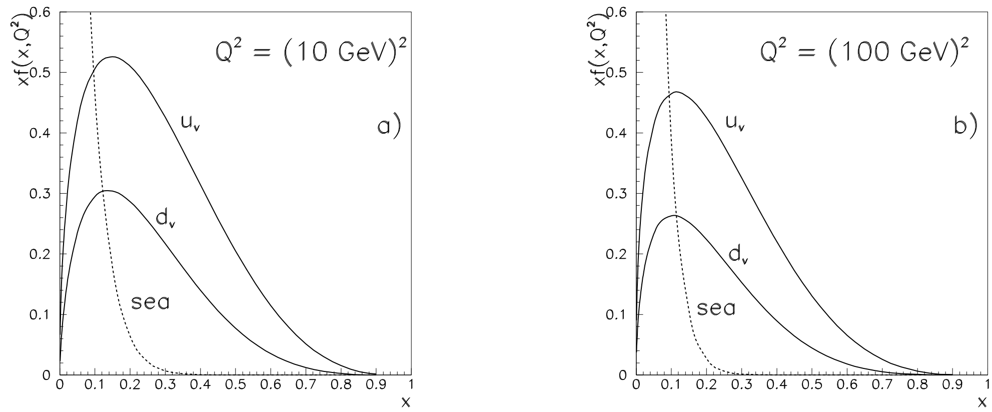

Figure 7: Parton densities of Buras and Gaemers 1978 [60]; u_v and d_v are the valence quark densities, and *sea* is the SU(3) symmetric quark sea.

quark structure functions dominate and the sea quark ones are small to avoid imparting the IVB an appreciable transverse momentum. The parton densities, as they were known at the time of planning the CERN experiments UA1 and UA2, are shown in Fig. 7 at two values of Q^2, a) 10^2 GeV^2 and b) 100^2 GeV^2. This is a QCD-improved parton model with SU(3) symmetric quark sea. From these figures one can see that the valence quarks dominate above Bjorken-x of about 0.2. Taking therefore $x_{1,2} \approx 0.2$, and the mass of the W boson at the predicted value of $\approx 80\,\mathrm{GeV}$ we get $\sqrt{S} \approx 400\,\mathrm{GeV}$, or beam energies of the proton and antiproton beams of $\approx 200\,\mathrm{GeV}$. Thus, the proton beam of the SPS was adequate, but it took five more years to convert the SPS to an proton-antiproton collider. This was achieved thanks to Simon van der Meer, who had invented the method of stochastic cooling of the antiprotons in an antiproton accumulator [61].

11. First observation of the W and Z bosons by UA1 and UA2.

Two multipurpose detectors, UA1 and UA2, were constructed with the aim of searching for the W and Z bosons, to study QCD jets, and to look for new physics beyond the standard model.

The UA1 detector [62] consisted of a transverse dipole magnet producing a uniform field of 0.7 T over a volume of $7 \times 3.5 \times 3.5\,\mathrm{m}^3$, a cylindrical drift chamber (CD) at the centre of the detector, an electromagnetic calorimeter surrounding the CD, followed by finely segmented hadronic calorimeters and muon chambers. The CD had a length of 5.8 m and a diameter of 2.3 m, and yielded bubble-chamber quality pictures of each $\bar{p}p$ interaction in addition to measuring the momenta and specific ionizations of all charged tracks.

The central section of the electromagnetic and hadronic calorimeters was used to identify electrons over a pseudorapidity interval $|\eta| < 3$ with full azimuthal coverage. Forward and very forward calorimetry gave coverage up to $|\eta| = 6.35$, thus allowing measurement of the total transverse energy - an essential requirement for identification of neutrinos from $W \to e\nu$ and $W \to \mu\nu$ decays by the method of missing transverse energy. This was a pioneering design that has since become a standard for collider physics experiments.[4]

Data taking took place over a 30 day period during November-December 1982. About 10^9 $\bar{p}p$ collisions at a center-of-mass energy of $\sqrt{s} = 540\,\mathrm{GeV}$ were recorded. From the cross section of the process $p\bar{p} \to W + X,\ W \to e\nu$ that was calculated assuming the GSW theory, one could estimate the expected tiny number of W production events. The signal of such events was a high momentum isolated track in the CD, matched by localized energy deposition in the electromagnetic calorimeter and no energy deposition in the matching cells of the hadronic calorimeter - these conditions together are interpreted as the signal of a high-energy electron. The associated neutrino was identified by the missing transverse energy, summed over all calorimeter cells, that had to be back-to-back with the transverse energy of the electron and of similar magnitude.

That final sample consisted of only six events. Applying full QCD smearing (Ref. [64]), correcting event-by-event for transverse W motion, and using the Drell-Yan predictions with no smearing, yielded

$$m_W = 81 \pm 5\,\mathrm{GeV/c^2},$$

an impressive result considering the 2012 World Average of $80.385 \pm 0.015\,\mathrm{GeV/c^2}$, obtained after three more decades of effort by UA1 and UA2 and the LEP and Tevatron experiments [52]. The UA1 Collaboration reported their results on the search for the W boson in Ref. [65] and the UA2 Collaboration in [66].

The Z^0 production cross section is about an order of magnitude less than the W production cross section, and therefore the discovery of the Z^0 boson had to wait for another run of data taking that was to follow in spring of 1983. Given sufficient statistics, one is looking for events with an extremely clear signal: two high energy tracks in the CD, almost back-to-back in the transverse plane, and matched by energy depositions characteristic of electrons in the calorimeters. The discovery of Z^0 was announced by UA1 in Ref. [67] and by UA2 in Ref. [68]. The Z boson mass presented in these papers was

$$\text{UA1:}\quad 95 \pm 2.5\,\mathrm{GeV/c^2}, \qquad \text{UA2:}\quad m_Z = 91.9 \pm 1.3_{stat.} \pm 1.4_{syst.}\,\mathrm{GeV/c^2},$$

which should compared with today's world average of $91.1876 \pm 0.0026\,\mathrm{GeV/c^2}$.

12. After the Discovery.

The discovery of the W and Z, like any discovery, opened up a wide field of exploration. With increased statistics, their masses could be measured with increasing accuracy. Probably even more

[4]The dramatic events in the run-up to data taking and even more so during data taking are told in the fine book [63] by Peter Watkins, one of the British members of the UA1 Collaboration.

important was the study of other properties, in the first place their spins. These were measured directly by the angular distributions of their decay products, and the result was as expected in the GSW theory, that they are indeed vector bosons. Moreover, this result was also testing - and confirming - the assumption of parity violation of the interaction of the IVB.

Nuclear beta decay and weak decays of muons, τ leptons and of unstable hadrons can be understood as reactions mediated by the IVB's. Precision measurements of their masses give an independent determination of the Fermi constant G_F, and confirm the universality of couplings to quarks and leptons of different flavours.

In his Nobel Lecture in 1984, Carlo Rubbia concluded [69]: "*. . . , the observed experimental values are completely compatible with the SU(2)* $\times$ *U(1) model, thus supporting the hypothesis of a unified electroweak interaction. However, a definitive confirmation of this theory must await further tests. <. . . >. A proton-antiproton collider of, say, 10 TeV centre-of-mass energy is ideally suited for these investigations, and it is being pursued at CERN and elsewhere.*"

A decade of work of the CERN electron-positron collider LEP and of the Fermilab $\bar{p}p$ collider Tevatron has produced precision measurements of the properties of the W and Z. Now we live in the era of the Large Hadron Collider, where intermediate vector bosons are copiously produced at vastly increased cross sections and, more important, the existence of the Higgs boson has been confirmed. It is tantalising that there are no clear indications of physics beyond the Standard Model. But this goes beyond the scope of the present historical review.

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