THE STANDARD MODEL, ABDUS SALAM AND CERN

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Abstract

CERN’s contributions in establishing the experimental foundations of the Glashow-Salam -Weinberg Electro-Weak model will be briefly reviewed: (1) the early neutrino experiments and the discovery of neutral currents, (2) the development of the p-pbar collider and the discovery of the IVB’s and (3) the systematic consolidation work of LEP will be discussed.

The catalysing role of Abdus Salam for the experimental HEP community will be underlined. His vision and his scientific message for much higher energies (LHC) and bold explorations beyond the SM (proton decay and neutrino oscillations) will be briefly recalled, mostly out of personal recollections.

*Paper presented on the occasion of the Special Colloquium in Memory of Abdus Salam at CERN on 23 September 1997*
The scientific works of Abdus Salam and in particular the one which goes under the name of the Standard Model of electroweak interactions which he has powerfully contributed to define, together with Steve Weinberg and Shelly Glashow, who have worked on the theory independently — has guided in a major way the scientific programmes of CERN throughout all its history and — through CERN — the whole of the European High Energy physics programmes.

Weak interactions, and their subsequent extension to the electro-weak sector, have always been a preferred subject at CERN, dating back to the early days of the synchrocyclotron with the discovery of the $\pi \rightarrow e$ and the $\pi^+ \rightarrow \pi^0$ decay modes and the extensive work on the muon related legs of the then called Puppi-Tiomno triangle, embodying muon capture, muon and beta decays. This early experimental work was made possible by a new breed of young, enthusiastic European experimental physicists or "fisicists" as Bernardini used to call them, of which I would like to recall George Charpak, Johahim Heinze, Hans Sens, Volker Soergel and Nino Zichichi amongst others. They were guided by a wiser and more senior group, of which I recall the late Sir Alec Merrison and Giuseppe Fidecaro, Francis Farley and Aarne Lundby, again just to mention a few amongst the many. It was at that time that — then a bright young CERN fellow — Nicola Cabibbo, perceived the real meaning of Universality of Weak interactions, introducing the concept of the mixing angle, precursory to the further progress of the GIM (Glashow-Iliopoulos-Maiani) mechanism, of which the main discoverers are with us in the room today.

Just about at the same time, Glashow, Salam and Weinberg were developing in a series of separate papers a theory extending the Fermi theory combining the weak and the electromagnetic interactions in a common formalism, destined to dominate the CERN experimental programmes for
many decades to come. Their work, extending some very early ideas of Oscar Klein, made powerful use of some earlier work of Yang and Mills, who had elaborated in the mid-fifties a generalisation of the Gauge Principle. One can safely say that the echo of these works did not strike immediately the imagination of the scientific community at CERN, busily engaged to construct the fundamental hardware components of the High Energy experimentation for Europe. An inevitable consequence of the theory was the existence of the neutral currents, apparently contradicted by the non observation of a direct $K \rightarrow \pi + \text{neutrino}$ and $K \rightarrow \mu\mu$ decays. It was later that the GIM mechanism enlightened the experimental community, removing the naive objection of non existence of strangeness violating neutral currents and incidentally also paving the way to the discovery of charm.

At CERN the real action started with the neutrinos and with the advent of the first strong focusing proton synchrotron in the world, the PS, brilliantly realised by John Adams and his team. After the difficult start-up of this entirely new experimental technology for CERN — so different from the SC experiments — and the disappointment of having missed the two neutrinos, the real CERN weak interaction physics started with the development of horn-focused neutrino beam due to Simon Van der Meer and the advent of the Gargamelle bubble chamber, extending earlier work at CERN with the heavy liquid chamber of Collins Rahm. The extraordinary scientific personality which was Andre Lagarrigue has been determinant in a novel approach to neutrino physics, based on visual techniques and precision measurements, free of experimental biases and pre-conceived assumptions. The relatively small mass of Gargamelle ($\pi$ tons as one used to say, more than one order of magnitude less than the “electronic” detectors [T1]) was more than compensated by the richness of information due to a powerful magnetic field ([T2], almost 2 Tesla) and the spatial resolution of the bubble chamber (1 mm$^3$ bubbles). It suffices here to show again the slim electron track [T3]
which signalled the occurrence of the neutral currents and changed the way of conceiving the weak interactions.

One may argue today why it took that long to discover a $\approx 30\%$ muon-less effect in the anti-neutrino hadronic events of which by then thousands of events had been collected by the electronic detectors. But one has to understand that at that time the psychological impact of the two neutrino discovery had been so great, that in the mind of most of the experimental physicists of the time, neutrino interactions were associated with the inevitable presence of the muon! The early spark chamber experiments at CERN for instance already had detected some anomaly (see for instance the thesis of Martin Holder and the earlier work with the Collin Rahm bubble chamber) but they were always eventually washed away as a neutron background.

It took the careful and systematic approach of Lagarrigue and of its team and the rather unexpected, faint electron track to start a "revision" process which lead to the confirmation of the existence of the neutral currents both at CERN and Fermilab.

I still recall vividly the passionate and friendly personal insistence of both Abdus Salam and of Steve Weinberg on the necessity of exploring experimentally all aspects, from atomic physics to neutrino experiments, of what was then called the "Weinberg-Salam" Model. One can certainly say that their wish was fully fulfilled by a prompt, monumental response of the experimental community, which in only a few years of tremendous work laid the confirming evidence of the electro-weak model.

It is worth mentioning here besides the neutrino experiments, the remarkably accurate SLAC experiment with polarised electrons (to which Willy Jentche, after being CERN-DG, also participated), the evidence of parity
violation in nuclei and the beautiful experiments on atomic spectra showing the presence of a tiny polarisation in ordinary light. Finally at PETRA, in DESY, the presence of the electro-weak interference term was shown, hinting at the presence of a finite mass $Z^0$ propagator. A bit earlier, Gerald 't Hooft (then Tini Veltman's student) had put the theory on firmer ground showing that it was renormalizable.

By then it had become abundantly clear that all that new and absolutely fundamental physics ahead needed were new, major tools and a major change in the experimental strategy and technology. CERN has been exceptionally fortunate in finding two exceptional leaders in Leon Van Hove and John Adams [T4] who promptly understood the immense importance of the theoretical message and the necessity of launching a new breed of scientific experimentation with the simultaneous p-pbar and LEP programmes, as to say two faces of the same coin, the former intended as early experimentation, the second as a systematic consolidation of the electro-weak unification.

The p-pbar project though an extraordinary synergy between the accelerator and the physics communities of CERN has provided the fast demonstration of the existence of the W and Z particles and the assessment of its major properties. Amongst those which made it possible, let me recall the extraordinary ingenuity of Simon Van der Meer, but also Eiffionyd Jones and Roy Billinge which have both left us prematurely. Mastering of the antiproton cooled beams and storage have been a major research tool over the last twenty years of and the source of fundamental discoveries, from the highest energies of the Tevatron and the consequent detection of the top quark, down to the low energy LEAR and the production of atoms of antimatter.

Wire chambers, drift chambers [T5] and calorimeters [T6], also developed (one may say invented) in the meantime at CERN by several
extremely ingenious people, amongst whom George Charpak and Frank Krienen — let me mention also Herwig Schopper with his first calorimeter — had become the main components of a new type of large 4π, "hermetic" instruments [T7, T8, T9, T10], replacing the solid angle micro-management, typical of the early ISR days.

Such a new dimension in the detector quality and size and the corresponding much bigger effort became possible only with the help of larger experimental teams and a greater technical support which had become a necessity. This was made possible by the coordinated and extremely close participation of both CERN and of the major scientific institutions in the Member States. Such a collaboration had already worked very well when Bernard Gregory was DG and in particular in the case of Gargamelle, constructed in France and of the other large hydrogen bubble chambers.

But by then it had become clear that the electro-weak nature of the phenomenon needed electrons rather than protons [T11]. CERN had to face again a major change in the accelerator technology. The LEP programme in its subsequent phases, the last being the one of LEP200, on going today, was necessary in order to firmly secure the ultimate consolidation of the Standard Electroweak Model. This second, monumental realisation has engaged the whole of CERN for almost a decade, under the subtle and effective leadership of Herwig Schopper and the enthusiastic dedication of Emilio Picasso. Herwig, with us today, has been able to foster a masterpiece of integration of the whole European community in CERN, with the consequent creation of the formidable teams which have constructed the four large detectors and subsequently carried out relentlessly a decade of magnificent and flawless experimentation [T12]. With Herwig as DG had begun the transformation of CERN from an European to a planetary Laboratory, further pursued by his
successors. In retrospect we can say that even Abdus could not have done it any better!

Today we can say that of the picture of nature introduced by Glashow Weinberg and Salam, only the Higgs particle has so far escaped detection. The need of "stabilising" the Higgs mass has naturally introduced the possibility — someone may say the need — of another breed of elementary particles, i.e. SUSY. The tremendous accuracy of the LEP results (the $Z^0$ mass is known within 1 MeV, i.e. 2 electron masses, [T13]) conjugated with the reliability of the electro-weak GWS model permits tight predictions based on radiative corrections to the masses to come [T14, T15, T16, T17]. It is in this way that the top mass was hinted at before being found and that there is a growing hope or belief that the Higgs is not too far away, even perhaps within reach for LEP200 [T18]. The development of large scale Superconducting Accelerating cavities at CERN has been essential in order to extend the operation of LEP beyond the W-pair production threshold [T19]. There are still a few bits of energy to go, fighting against the hard, $\propto E^4$ law of synchrotron radiation, but they are essential, since they may be holding major surprises. We must retain the lesson of ADONE, a 3.0 GeV $e^+e^-$ collider, where the fundamental discovery of the psi/J (3.098 GeV) was missed for a mere 3% in energy!

Abdus had an important role in advising on the CERN programmes in particular as member of the SPC. In 1987, when LEP was not yet operational, CERN Council and the then DG, Herwig Schopper, created the so-called "Long Range Planning Committee" to define the further steps for CERN. Abdus, together with Giorgio Brianti, Pierre Darriulat, Kjell Johnsen, Sam Ting and Simon Van der Meer, helped us in laying the foundations of what is today the present and future of CERN. It was in this small circle of seven people that the names LHC and CLIC were coined and the relative merits and
potentialities of the hadron and linear colliders were elaborated and evaluated in depth. I still recall his vivid enthusiasm and the clarity of Abdus’ vision on the future of CERN: he used to insist on the relevance of concentrating primarily on key, strategic choices related to fundamental questions. I believe that he has contributed in a major way in defining the next twenty years of CERN strategy in its essentials.

His vision of sub-nuclear physics goes far beyond the accelerator and collider physics and embodies in a very original form, through the so-called “Pati-Salam” model, the unification of all forces. In his vision of Grand Unification, relevant phenomena occur at a lower mass scale ($10^{10}$-$10^{12}$ GeV) than the standard GUT($10^{15}$ GeV). I must however confess that the intricacies of this theory have somehow escaped me, purely because of my ignorance of the subject. Though superficially and intuitively, since the nitty gritty of the details fully escape me, I feel however aesthetically attracted by the intrinsic elegance and originality of his Unification Model. He has always been a strong advocate of proton decay, as the analogue of beta decay in the exploration of the unified phenomenology, at a scale of energies which exceeds any reasonable extrapolation of the accelerators [T20].

I have no doubt that Abdus’s influence have significantly motivated also the emergence of the modern field of non accelerator, underground experiments. Personally I owe him my intense interest in searching for proton decay. I am sure that there is no process which he would have liked to see discovered more than proton decay. I recall his affectionate, repeated insistence, dating back initially as far as the seventies and since then constantly repeated, on the importance of bold, experimental searches for bias free proton decays. I believe that also in this field, what I would call “the Lagarrigue approach”, namely visual techniques and few but fully reconstructed events, in which high resolution is traded for share mass, may
be in the long run a worthwhile contribution. This is especially so if one takes into account that the dominant decays might involve neutrinos and strange particles, either because of the forbidden nature of the decay according to some of Pati-Salam like model or because of the pseudo-scalar nature of the effective decay interaction due to a predominance of the Higgs sector.

Abdus has been a man of immense faith, both religious and scientific. His main preoccupations have been three: the third World, Islam and Physics. In his mind Science and Religion are two separate and complementary aspects which relate to a common, divine design. For him there was no contradiction between Religion, which referred everything to one immutable text and the spirit of Science which must allow hypothesis, testing and the admission of error and change. Science and Religion are complementary. He said: "Science and Religion refer to different worlds. Religion refers to things like soul and Allah, not to matter."

He used to underline that one eighth of the verses of the Koran prise and remark on Nature and encourage investigation and the intelligent search for Knowledge: and that "no verse is in contradiction with Science". He wrote: "the holy Prophet of Islam emphasised that the quest for Knowledge and Science is obligatory on every Muslim". He could even perceive in the Koran a description of the Big Bang: "the Heavens and Earth were a mass all sewn up—and then we unstitched them". The Third World Academy of Sciences, his creation, has produced books which teach modern science through Koranic verses, so that both can be thought together in religious seminaries.

For Abdus, the word "unification" largely transcends the simple meaning of the one of the forces in Nature. It extends to the relationship of Science and Religion and to the necessity of a planetary Science which should include all people on earth, including the Third World. And such a bold, planetary unification must be performed with the help and the benefits of
Science: "Physics is the science of wealth creation par excellence. If a nation wants to be wealthy, it simply must acquire a high degree of expertise in both pure and applied physics".

But most important, (and this is the reason why we are here today) Abdus has been a dear friend to many of us. Though he never stayed here at CERN for long, he was a convinced supporter of what CERN stands for, both in Science and in its international, Cooperative Mission. He has been and he will always remain one amongst the exceptional breed of people — many of them unfortunately no longer with us today — which have powerfully contributed in making CERN successful and what it is today.

I would like to conclude and make us feel — if at all possible — as if he is still with us, by showing a couple of pictures [T21] taken in the very same Hall in which we are today and which has resonated so many times with his voice and in which we have been charmed by his warm, unique personality [T22].
T1. CERN Bubble Chamber Gargamelle

T2. Gargamelle being assembled
T3. First neutral current event found in Gargamelle

T4. A. Salam with J. Adams and L. van Hove
T5. Upper half of UA1 central detector

T6. UA1 hadron calorimeter
T7. View of the UA1 detector being assembled in the so called "garage" position

T8. The UA2 detector in the beam position
T9. Early UA1 event candidate for $W \rightarrow \mu \nu$
T10. UA1 missing energy plot for the first 43 $W \rightarrow eV$ energy

T11. Cross-section for $e^+ e^- \rightarrow$ hadrons with data from CESR, DORIS, PEP PETRA and LEP
T12. Example of a 3 jet event recorded by the ALEPH detector at LEP, at the $Z^0$ mass
T13. Determination of the $Z^0$ mass at LEP

**Z-Boson Mass [MeV]**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALEPH</td>
<td>91188.3 ± 3.1</td>
</tr>
<tr>
<td>DELPHI</td>
<td>91186.6 ± 2.9</td>
</tr>
<tr>
<td>L3</td>
<td>91188.6 ± 2.9</td>
</tr>
<tr>
<td>OPAL</td>
<td>91184.1 ± 2.9</td>
</tr>
<tr>
<td>LEP</td>
<td>91186.7 ± 2.0</td>
</tr>
</tbody>
</table>

$\chi^2$/DoF: 2.0/3

LEP calibr.: ± 1.5

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T14. Determination of the $Z^0$ width at LEP

**Z-Boson Width [MeV]**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>ALEPH</td>
<td>2495.1 ± 4.3</td>
</tr>
<tr>
<td>DELPHI</td>
<td>2489.3 ± 4.0</td>
</tr>
<tr>
<td>L3</td>
<td>2499.9 ± 4.3</td>
</tr>
<tr>
<td>OPAL</td>
<td>2495.8 ± 4.3</td>
</tr>
<tr>
<td>LEP</td>
<td>2494.8 ± 2.5</td>
</tr>
</tbody>
</table>

$\chi^2$/DoF: 3.9/3

LEP calibr.: ± 1.5

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1/σ = 128.898 ± 0.090

$\Gamma = 0.118 ± 0.003$

$m_H = 175.6 ± 5.5$ GeV

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$\Gamma_Z$ [MeV] vs. $m_H$ [GeV]
W-Boson Mass [GeV]

pp-colliders 80.41 ± 0.09

LEP2 80.48 ± 0.14

Average(world) 80.43 ± 0.08

χ²/DoF: 0.2 / 1

LEP1/SLD 80.329 ± 0.041

T15. Determination of the W mass at LEP

Effective Electroweak Mixing Angle

\[ \sin^2 \theta_{\text{eff}} = 1/4 \left( 1 - \frac{g_y^2}{g_\mu^2} \right) \]

A_{\theta^d} 0.23102 ± 0.00056
A_\phi 0.23228 ± 0.00081
A_\phi 0.23243 ± 0.00093
A_\phi^0 0.23237 ± 0.00043
A_\phi^0 0.2315 ± 0.0011
<Q_{\phi}> 0.2322 ± 0.0010
Average(LEP) 0.23199 ± 0.00028

χ²/DoF: 4.4 / 5

Average(LEP+SLD) 0.23152 ± 0.00023

χ²/DoF: 12.6 / 6

T16. Determination of the effective electroweak mixing angle at LEP
T17. Constraints on the standard model Higgs mass from W mass measurements

T18. Constraints on the Higgs mass within the standard model
**T19.** Cross section for $e^+e^- \rightarrow W^+W^-$ near threshold at LEP

**T20.** Feynman graphs for proton decays with $\Delta(B-L) = 2$ in the Pati Salam model.
T21. A. Salam in the CERN main auditorium

T22. A. Salam in the CERN main auditorium