Subnuclear Physics: Past, Present and Future
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THE ORIGIN OF LEP AND LHC

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1- Introduction

1.1 Innovations in theory

In Subnuclear Physics, the decade 1965-1975 has seen an impressive number of innovations in theory, which brought the modelling of fundamental forces and relationships between particles in term of a single theory framework, a unified quantum field theory.

Without being exhaustive, a few essential new concepts should be quoted:

- The introduction of the concept of quarks/antiquarks to build hadrons (Gell-Mann and Zweig in 1964); the quark distribution in the nucleus was observed in 1969 ("partons" distribution). The new concept brought order into the complex zoology of hadrons then available;
- The introduction of the concept of supersymmetry in 1971-1974, of QCD and "asymptotic freedom" in the strong interaction domain, etc…;
- The application of gauge theory to interactions (local symmetry);
- The mechanism of spontaneously broken symmetry, when the symmetries of the interaction Lagrangian are not symmetries of the vacuum.

1.2 The electro-weak interaction

A unified quantum field theory for electromagnetic and weak interactions was established in the lepton sector (Glashow, Salam, Weinberg in 1967-1968) and later in the hadron sector (Weinberg in 1972), after the charm quark was introduced.

The very short range of the weak force, described from Fermi until then through the "contact model" of four fermions, questioned the possibility of quantum fields to model properly the case. It was potentially answered by Higgs in 1963, when he noted that vector fields become massive from interaction with scalar fields, a property to justify later the fermions masses.

This unification of two forces into one unique electroweak interaction was a very brilliant achievement, from application of the SU(2) x U(1) gauge group and of the spontaneous symmetry breaking resulting from the introduction of a scalar (higgs) field.

The corresponding gauge bosons are the three W bosons of weak isospin from SU(2) ($W+$, $W-$, W^o) and the B^o boson of weak hypercharge from U(1).

The symmetry breaking provides mass to the bosons and causes the W^o and B^o to mix into two different bosons one massive neutral Z^o and one massless the photon γ; the mixing is parameterized by the angle θ_W.

The masses and interactions of the vector bosons are predicted in term of the single angle θ_W; the mass of the scalar Higgs boson was unknown and free, but its couplings with the fermions are also predicted to provide their masses.

1.3 Experimental discoveries

At the same time, an irresistible move occurred to show that the concepts introduced by theory were not only mathematical entities, but real particles or interactions: experiments were designed to verify the theoretical results. A few important examples are:

- The lepton τ was discovered at SLAC (SPEAR), making 3 lepton families;
- Identification of quarks: an experiment at SLAC, under Friedman, Kendall, and Taylor in 1968, found that electrons were sometimes scattered from nucleons at large angles, showing the existence of point-like “partons”;
- Different types of quarks were identified: up, down, strange, bottom;
- After the theoretical prediction of the necessary existence of the charm quark by Glashow, Illiopoulos and Maiani in 1970, the charmonium was discovered by Richter-Ting in 1974, followed by the naked charm quark at SLAC (1976); only the top quark was missing to build also 3 quark families; the essential question at that time was if more families were to come;
- In matter of e-weak interactions, the discovery of neutral currents at CERN in neutrino scattering in “Gargamelle” in 1973 was an essential step to confirm the theory and to justify the preparation of experiments to verify the other quantitative predictions: M_Z = 90 GeV and M_W= 80 GeV from the theoretical relations:

  $M_w = M_z . \cos\theta_w$ and $\sin^2\theta = 0.23\text{-}0.25$; and $G_F . 4\sqrt{2} . (M_{W.} \sin\theta)^2 = e^{2.}$

1.4 The Standard Model

The success in the electroweak interactions from the introduction of gauge theory pushed to apply it also to strong interactions, which will become the description of Quantum Chromo Dynamics. The SU(3) symmetry group in the three color space with no spontaneous breakdown led to massless mediators, 8 Gluons, as carriers of the strong force.

Therefore around 1975, a theoretical model was available for all particles and their interactions known at that time, using the symmetries of the non-Abelian group SU(3)xSU(2)xU(1) introducing 12 vectors gauge fields with self-interaction. This model, called now **the Standard Model of Particles and their Interactions, was confirmed by all discoveries to come later.**

2- The Origin of the Large Electron- Positron Collider: LEP

2.1 The preliminary studies

In early 1976, when the SPS construction was coming to its end, John Adams organized a Group at CERN (chaired by Darriulat) to study the possibility of a e+e- collider to be built at CERN in order to verify the electro-weak (e-w) model predictions.

The Group envisaged the concept of a storage ring where beams of 100 GeV collide with a luminosity of 10^{32} $cm^{-2}s^{-1}$; it was supported by ECFA in its meetings of 1976 and 1977, which created its own ECFA Working Group (chaired by Zichichi) to bring the majority of physicists behind the study of all aspects of the e+e- collider concept, as the most sensible to pursue for establishing the next experimental programme for Europe in High Energy Physics.

An international Review at “Les Houches” in1978, presented with the “Blue Book”(100 GeV per beam in a ring of 22 km length) showed the common confidence in the predictions of the e-w theory on which to base all experimental expectations.

The wish to reach the highest energy in order to increase the probability to discover new massive particles (other quarks and fermions??; supersymmetric particles ??) led ECFA in November 1979 to recommend another design (130 GeV in 30 km long ring) described in the “Pink Book” and to show the general consensus to see the project, called LEP (Large Electron Positron collider) to be built at CERN.

2.2 A short cut to the W, Z Discovery

In 1976, even among people working on LEP studies, impatience was high, having to wait for more than a decade to identify W, Z and H in LEP. A proton collider was probably the fastest complementary solution; the ISR (Intersecting Storage Rings : the very first collider) had not enough energy (30 GeV/beam); none was available in the world in the range 100-200 GeV.

A proposal was made by Carlo Rubbia in 1976: to use the SPS after its start of operation, but with only one single ring it should become a p-pbar collider.

The difficulties to build a source of anti-protons to provide a beam as intense as the proton beam led people to be skeptical. Only Carlo Rubbia’s vision, competences and determination have assured the final success.

The p-pbar collider in the SPS was accepted as an experiment in 1978 (not as a Project in order to avoid any political damage to the LEP project). In 3 years, Carlo achieved the ”tour de force” to realize the appropriate anti-proton source, after building an Accumulator/ Collector (AA/AC), testing the cooling methods (proposed by van der Meer) in ICE, and promoting the realization of two large detectors UA1 and UA2.

Collisions began in 1981 and Z and W were identified in 1983, for a Nobel Price in 1984, never before granted so rapidly after a discovery.

2.3 The decision to build LEP

In 1979, John Adams proposed a policy to get approval of LEP construction by CERN Council, even if no new specific resources would be granted. LEP could be built inside the current CERN budget under certain constraints:

- closing the programmes of SC (Synchro-Cyclotron)and ISR in early 80ies,
- starting LEP investment only when the ppbar experiment is ready for operation in 1982,
- assuming the LEP construction achieved in 7 years for 150 MCHF/year,
- sharing some tasks and exchanging staff with National Labs.

As the investment in LEP (mainly civil work and RF costs) varies as E^2, the square of the beam energy, its design should look for economic choices inside the above constraints and the inevitable limits of the electrical power drawn by CERN from the mains to a value around 200 MW. Finally the ECFA-LEP Working Group, chaired by A. Zichichi, recommended to construct a 27 km accelerator ring-tunnel adjacent to CERN between the French Jura and Geneva airport. Accordingly the main LEP design parameters were decided:

- Tunnel length: 26.6 km, with 8 arcs of 3.1 km radius and 8 straight sections, and 4 caverns excavated at P 2, 4, 6, 8, for experiments, (tunnel cross-section large enough to add a possible proton collider)
- Beam energy: 60 GeV each with Cu cavities, and a possible extension to 100 GeV when the R&D on superconducting cavities (SC), launched immediately, will have led to interesting results.

The positive decision to build LEP was taken in CERN Council in December 1979, assuming 3 years of preparation before a start of construction in 1982 and of operation in 1989. Four general purposes detectors will be installed in four caverns around the ring: L 3, ALEPH, OPAL, and DELPHI.

A few years after the start of LEP construction, a decision was reach in the US to also build a e+e- collider, the SLC, at SLAC reusing the available 50 GeV Linear Accelerator which thus allowed the SLC to start operation at the same time as LEP. The two colliders had similar research programmes during LEP Phase I; it was a period of “collaborative competition”. Because of its more limited beam energy the SLC could not compete with the following LEP Phases.

3- The LEP Design, Construction and Operation

3.1 The different Phases

The physics objectives of LEP pushed to consider two Phases in Operation with respectively a minimum beam energy of 60 GeV to create single Z, and 85 GeV to produce W^+W^- pairs using Cu cavities.

Phase I was authorized for investment in 1979 (Phase II for planning only) including besides the civil work:

- 128 Cu cavities to be installed in 272 m of active length (1.5 MV/m) fed by 16 MW of RF power from Klystrons at 350 MHz with a total dissipation of 75 MW,
- Beam Injection at 20 GeV through a chain including an e+e- accumulator at 600 MeV, the PS at 3.5 GeV and SPS at 20 GeV (compatible with interlacing proton acceleration to 450 GeV for other experiments),
- Operation at 45-60 GeV with a luminosity > 10^{31}cm^{-2} s^{-1} (at 55 GeV) with four bunches/beam.

Phase II was started with the goal to reach 85 GeV with 192 SC, added to the previous 128 Cu cavities, and built with a film of Nb sputtered on Cu after a successful development.

Phase III was approved in 1993 to replace 64 Cu cavities by 32 SC cavities and to operate with 8 bunches/beam. Phase IV was approved in 1995 adding 48 SC cavities. Thus the circumference Voltage has been increased through the Phases from an initial 400 MV to >3500 MV and the RF power from 16 MW to 48 MW; this has allowed to reach >96 GeV per beam and a peak luminosity of 1.4 10^{32} cm^{-2}s^{-1}. LEP operation was put to an end by December 2000 to give free access to the tunnel for removing components and start LHC construction.

3.2 Main Physics Results of LEP

3.2.1- During LEP Phase I, 18. 10^6 Z were observed.
The analysis of the Z-line shape (Fig.1) in the cross-section from e+e- collisions leading to hadrons, of the decay branching ratios and of the asymmetries led to values of high precision : M_Z = 91, 187.5 ± 2.1 MeV; Γ_Z = 2495.2 ± 2.3 MeV and $\sin^2\theta$ =0.23138 ± 0.00014 mass around 170 GeV (this mass was too large for the top to be directly produced).

3.2.2. There are only three families of leptons and of quarks.

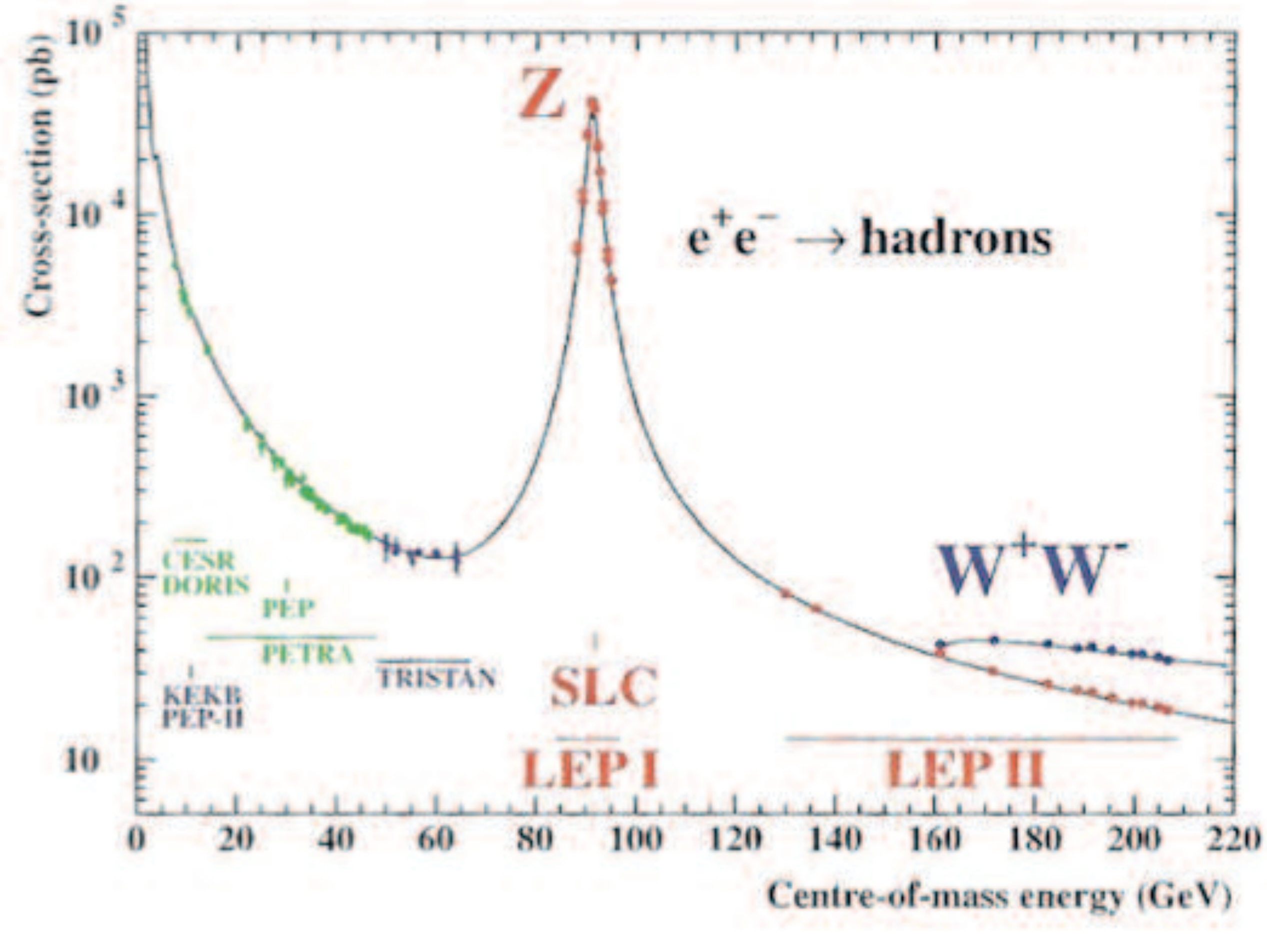

Fig. 1. *The e+e- annihilation cross –section to hadrons from low energies to the range of energies accessible in the Phases of LEP operation (from lepewwg)*

3.2.3. In Phase II, 80. 10^3 W were observed and the direct measure of W mass and decay width was: M_W = 80. 4 GeV and Γ_W = 2.15 GeV. The charged

W+W-pairs are produced in e+e- collisions by three different mechanisms (photon, neutrino, Z-boson exchanges; if any of them is isolated from the others, suppressing their interference, it leads to a cross-section indefinitely rising instead of decreasing with energy as shown in Fig.2.

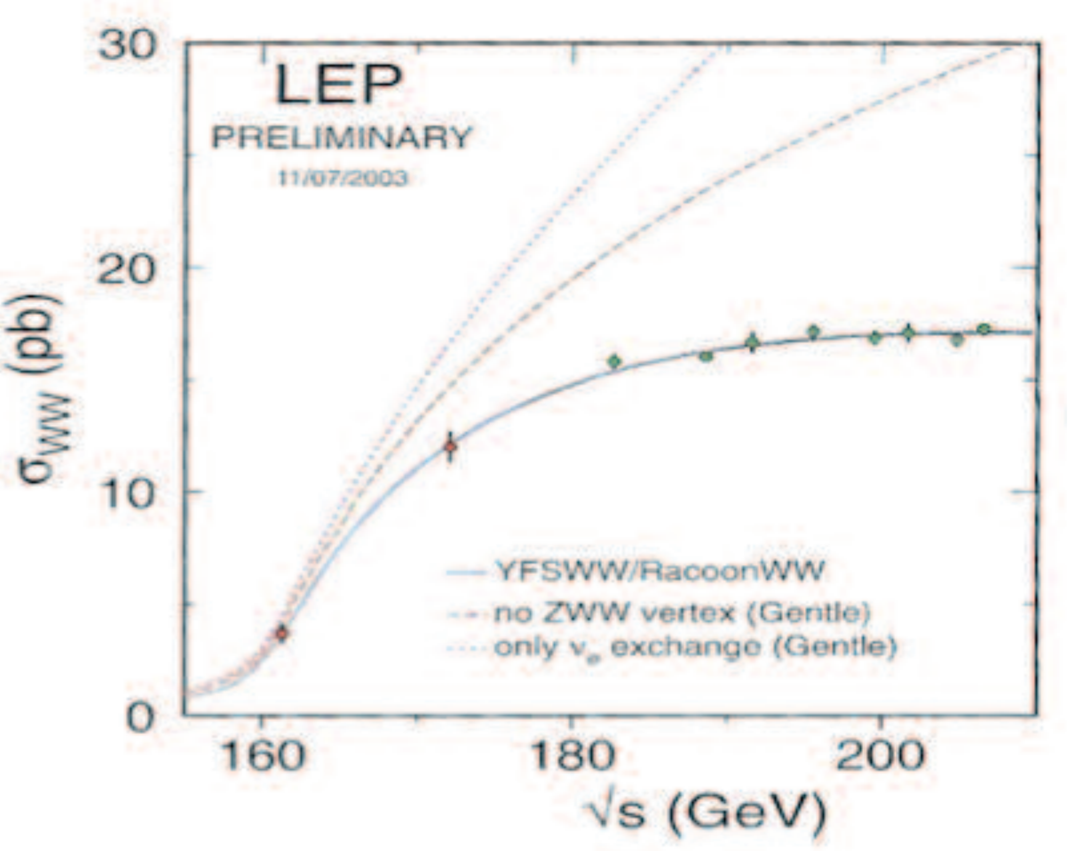

Fig. 2. *The total cross-section of W –pairs production in e+e- collisions at LEP (from lepewwg)*

3.2.4. The QCD coupling dependence with energy was confirmed leading to the “asymptotic freedom”, a feature of the non-Abelian gauge theories.

3.2.5. No evidence of Higgs or supersymmetric particles below 114 GeV.

In conclusion, LEP did not reveal anything new, but provided precise verification of every thing expected, confirming the Standard Model of Matter and Forces but missing the experimental proof of the process giving fermions their masses.

4- The Origin of the Large Hadron Collider: LHC

4.1. Preliminary studies

In 1984, in the middle of LEP construction and following the discovery of W-Z in UA 1 and UA 2, an ECFA Workshop was held just before an ICFA meeting, where US Physicists will describe the SSC proposal. The prepared answer from EU Physicists was that they were considering a proton-proton collider of 10-20 TeV in the center of mass, to be installed in the LEP tunnel, giving also access to e-p and heavy-ions collisions.

Another ECFA meeting at La Thuile in 1987 considered the relative discovery merits of p-p, e-p, e+e- colliders 10 T magnets, 7.7 TeV/beam, luminosity of 1.6 10^{34}cm^{-2}s^{-1}, 4725 bunches of 10^{11} p, spaced by 15 ns, reaching the extremely large value of energy in the beams 583 MJ /beam.

This preliminary design was quite ambitious, but already showing some attractive design features of the final LHC: “two in one” and HeII cryogeny; a strong R&D effort was proposed on superconducting magnets and on performing detectors (the most difficult task in the case of hadron collider) .

4.2. Key questions of Particle Pysics

The LHC programme objectives was considered the natural long-term extension of the LEP programme , with remaining key questions:

- How is the electro-weak symmetry broken and what is the origin of mass?
- Is the Higgs mechanism responsible? only one Higgs particle or more?
- The 17 orders of magnitude gap from W, Z to Planck masses cannot be understood without new physics entering around one TeV.
- Is Supersymmetry a contender for this new physics, a key to the unification of the forces? Is it justifying the dark matter in the Universe?
- What could explain the replication of quark and lepton families?
- Are these particles not elementary, but composite?
- Is the left-right asymmetry of weak interaction only a low-energy effect?
- What is the origin of flavors and of CP violation?
- Might extra-dimensions scenarios change the above issues?

Accordingly, the LHC should be designed to provide p-p high collision rates at the highest energy technically feasible to answer some of these questions and to discover new physics, in addition to relativistic heavy-ion collisions to study quark-gluon plasmas.

4.3. Progress toward the decision to build the LHC

In May 1991, a review of the available design and the physics programme pushed the LHC project ahead in the conclusions of a CERN " Long Range Planning Committee", chaired by Carlo Rubbia:

- Ten prototypes of superconducting dipoles were ordered in Industry,
- Discussions among physicists went on to build international Teams around concepts of detectors, in particular ATLAS and CMS,
- An assumed positive decision of construction, optimistically expected in 1992, was thought, even more optimistically, to lead to a start of operation in 1998 after only 5.5 years of construction.

In 1992-93, an External Review Committee recommended the CERN Council to go ahead with the project, but to launch immediately a larger effort in R&D.

After a new design version in 1993 (the White Book), the Council approved the LHC project in December 1994, on the basis of a machine built in two stages, the first one using a missing magnet scheme.
The decision to go back to one stage project was taken in December 1996 after the non-European Countries agreed to join the project and to contribute .

4.4. Progress in the LHC Design

In October 1995, the machine design was frozen after many modifications, but keeping the main technical choices: "two in one", meaning two beams in a single cryostat, and Helium II cryogeny, meaning that the magnet windings at high field will benefit from cooling by a static bath of helium at 1.9 K and atmospheric pressure. The main changes from the initial design are the following:

- Removing LEP from the tunnel,
- Keeping 4 crossing points instead of 8 in LEP,
- Excavating two large caverns in addition to the LEP caverns,
- Center of mass energy: 2x7 TeV, luminosity: $10^{34}cm^{-2}s^{-1}$ in protons collisions, and 1,148, $2x10^{27}$ respectively in heavy ions collisions,
- Bunch spacing increased to 25 ns – 7.5m and smaller number of bunches per beam 2835, leading to 335 MJ of stored energy per beam in protons collisions, and 125 ns, 608 bunches, only 4.8 MJ in ions collisions,
- Magnetic field: 8.4 T in longer dipoles of 15 m,
- Cryogenic piping in a separate line, not in the main cryostat,
- A long (150m) magnet Test String was built with the prototype magnets in order to gain operational experience for all components to use.

4.5. The Detectors Challenges

Two very large, general purpose detectors, ATLAS and CMS, were built according to different designs and new technologies, and installed in the two new dedicated caverns; they are facing the same challenges:

- Rapidity: 30 events/bunch crossingevery 25 ns, identified by 10^{11} tracks/s,
- Hermiticity and fine granulometry to provide the required accuracy in a huge volume,
- Radiation hardness of sensors and electronics (required level of hardness obtained thanks to the new 0.25 μm Silicon wafer technology),
- Huge number of cables (10^{8}) and, after reduction on-line from 40 GHz to 100 Hz, 0.1-1 Gbytes/s of measures to be transferred to a large memory (10 Peta-Bytes) and processed by 100.000 high-end processors distributed across the entire world in a “Computing Grid”,
- Extraction (with the help of many Monte-Carlo analysis) from the large background of the signature, for example of a specific Higgs particle-decay which depends of the unknown H-mass; therefore a large range of possible Higgs mass must be explored.

Two other detectors were built for specific purposes and installed in LEP caverns; they require less luminosity to operate:

- ALICE observes collisions between Pb ions beams with an energy of 2.75 TeV/nucleon, producing a plasma of quarks and gluons when they are no more confined in the nucleus ,
- LHCb exploits the LHC as a b-factory to study rare b-decays and CP violation, to link with the ratio matter-antimatter.

5- Conclusion

The LHC will be the first accelerator to explore directly the TeV scale and reveal new physics. Providing answers to some essential questions about the universe is justified, in spite of its costs; these questions , without the LHC will remain unanswered for long.

Paraphrasing Glashow at Les Houches in1978 about the LEP, it can be concluded that: **“The LHC is exciting, essential and expensive”.**

Efforts which were required for the LHC realization and next for its exploitation will be more than rewarded by **THE FUTURE DISCOVERIES.**

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