THE HIGH ENERGY FRONTIER AND THE
COLLABORATION IN COLLIDER EXPERIMENTS

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In this note I shall review the Japan-Italy cooperative work in high energy collider
experiments, in particular OPAL at LEP, CDF at Fermilab, ZEUS at HERA and ATLAS
at the future LHC.

1 Introduction

The Standard Model (SM) of particle physics has been checked to an unprecedented
level of accuracy by the precision measurements at LEP, SLC, HERA and the Fermilab
colliders. For the Higgs boson there were some indications and limits at LEP: the search
for the Higgs boson is one of the main items to be studied at the Fermilab-2 \( p\bar{p} \) collider
and at the future LHC pp collider. The SM has theoretical inconsistencies and too
many free parameters, and it could be a low energy approximation of a more complete
theory. Thus many physicists are looking for physics beyond the SM, for instance
supersymmetry, compositeness, etc. New particle searches is thus an other important
subject of research. Connected with these problems there is also a strong interest in
finding the deep structure of the proton at ever smaller distances.

Experimentation at higher energies forced the concentration of the experiments in
larger national and international laboratories, where high energy accelerators were avail-
able. From the 1960’s the experiments started to grow in size and complexity and started
to be performed by collaborations of few groups from different Institutions: experiments
grew larger, with a tendency to go towards the use of all purpose detectors. The experi-
ments at LEP, SLC, Fermilab and HERA, required another step, with tens of groups and
hundreds of physicists and engineers, with interconnections at the national and regional
levels. The next experiments at the LHC require hundreds of groups and thousands of
physicists, with interconnections in a sort of world organization.

In this context many cooperative efforts were made by Japanese and Italian groups.
Here I shall first recall a personal experience in the United States at the end of the
1950’s, and then I shall discuss the cooperative efforts by Japanese and Italian groups
in the experiments OPAL at LEP, CDF at Fermilab, ZEUS at HERA and ATLAS at the future LHC collider.

It may be worth recalling that these collider experiments use $4\pi$ general purpose detectors, with many subdetectors, some of which immersed in a magnetic field. They have several hundred thousand electronic channels and very many microprocessors and computers. The detectors have a cylindrical symmetry, with a "barrel" and "endcap" structure; some subdetectors are further structured in different ways. Starting with the innermost detectors and proceeding outward one finds: a microvertex detector, a central tracking detector with $dE/dx$ and time-of-flight capabilities; the momentum is measured by track curvature in the magnetic field. Then follow the electromagnetic and hadron calorimeters, and, after the iron of the magnetic field return yoke, the muon detector.

The collider luminosity was measured using forward detectors and precision "luminometers".

2 The "old times"

In the 1950’s the standard high energy experiment was small and was performed by a small group of physicists and graduate students from a single university.

At the University of Rochester, Rochester, N.Y., USA, a special situation was created by the late Robert Marshak, who accepted many foreign students, mostly from Japan and Italy. They attended graduate classes together, participated in seminars and colloquia and performed experiments together, in small groups. I like to recall some of the Japanese and Italian colleagues: M. Koshiba, K. Miyake, S. Okubo, T. Yamanouchi and others from Japan; from Italy: R. Cester, G. Maltoni, T. Regge, C. Schaerf and others. This was probably one of the first interactions between Japanese and Italian physicists. In their diversity of culture they found many things in common, among which the fact that both lost world war two!

The high energy accelerator of that time at Rochester was a synchrocyclotron of 240 MeV, which produced pions, below threshold. Some of the main fields of experimental research concerned the measurement of the cross sections for pion-nucleon elastic and charge exchange processes at lab. energies smaller than 100 MeV [1] and analyses of nuclear emulsions mainly exposed to cosmic rays. There was also a very strong theory group.

3 OPAL at LEP

OPAL (Omni Purpose Apparatus for Lep) was one of the four LEP detectors [2]; it used a conventional magnetic field. The collaboration, which started in the early 1980’s, consisted of about 300 physicists and graduate students from 34 different Institutions from many different countries. About 20 Japanese physicists and graduate students, mainly from the University of Tokyo, the International Center for Elementary Particle
Physics (ICEPP), and from the University of Kobe, participated in OPAL. Approximately the same number of physicists and students were from Italy, mainly from the University of Bologna, the Bologna Section of INFN and CERN.

The Japanese colleagues constructed and maintained the Barrel electromagnetic calorimeter, made of 9440 lead glass counters, all working after 11 years of operation! They also provided a large computer (a mainframe), which was essential for off-line analyses at the beginning of LEP operations.

It may be worth recalling that computer technology increased very fast, about a factor of 1000 between LEP construction in the 1980’s and the end of LEP operations in November 2000. The tendency was towards clusters of PCs. Off-line analyses involved off-line reconstruction of events, Monte Carlo simulations and physics analyses. During this period of about 15 years the storage capacity went from megabytes to gigabytes, the computer interconnectivity improved dramatically, and CERN made its most important invention: WWW, the World Wide Web.

The Italians constructed and maintained the Iarocci limited streamer tubes for the Hadron Calorimeter. The tubes were fabricated at the ”tubificio” in Frascati, and use was made of the so called ”magic oil”, which was pressed in place with a sponge; this improved the quality of the inner conducting surfaces of the tubes, which then worked more reliably: the vast majority of the tubes was still working well at the end of the experiment. Italy contributed also to the Luminometer and to the microvertex detector.

During the first years of data taking, it became clear that several improvements could be made. In particular: the available forward detectors allowed luminosity measurements to few percent. In order to fully exploit the LEP accelerator and the detectors, precisions ”Luminometers” were designed and built: they allowed measurements with precisions of better than 0.1%. To reach these precisions it was also essential to compute the radiative corrections of forward $e^+e^-$ Bhabha elastic scattering to ever increasing precisions: there was a healthy competition between theorists and experimentalists to reach the desired goal. The final measurements were made with impressive precisions, much better than expected. The same ”silicon technology” was used for the new microvertex detectors.

Both Italians and Japanese physicists were very active in improving and analyzing the luminosity measurements, and in many types of physics analyses.

4 CDF at Fermilab

The CDF (Collider Detector Facility) is one of the two general purpose detectors operating at the Fermilab $pp$ collider. CDF started taking data in the 1990’s at a center of mass energy of 1.8 TeV. In the second part of the 1990’s there was a long shutdown of the collider: several improvements were made resulting in an energy increase from 1.8 to 2 TeV and to a considerable luminosity increase. Also the CDF detector had many improvements: it is now called CDF2 and it started the so called run2. The CDF collaboration consists of about 480 physicists and graduate students from $\sim 50$
Institutions from all over the world. The Japanese physicists are about 50 from 5 Institutions (Hiroshima, KEK, Osaka, Tsukuba, Waseda), while the Italians are about 80 from 6 Institutions (Bologna, Frascati, Padova, Pisa, Roma 1, Trieste).

Also in this experiment the Japanese and Italian contributions were and are very important: Japanese and Italians built different crucial subdetectors; in particular they contributed to the equipment made for the precision measurements and to the microvertex detectors; the Italian groups pioneered the silicon microstrip detectors and constantly improved them.

CDF contributed to the precision electroweak measurements, discovered the top quark, studied in detail quark-quark collisions yielding large $p_t$ events, studied minimum bias events, b-physics and performed many new particle searches.

The EW precision measurements from LEP, SLC and Fermilab yielded the following values [4]:

| Measurement | Fit | $|\Delta Q^\text{max}|$  |
|-------------|-----|-------------------------|
| $\alpha_{\text{em}}(m_Z)$ | $0.02758 \pm 0.00055$ | $0.02767$ |
| $m_Z$ (GeV) | $91.1873 \pm 0.0021$ | $91.1874$ |
| $f_Z$ (GeV) | $2.4952 \pm 0.0023$ | $2.4959$ |
| $\sigma_{\text{tot}}$ (pb) | $41.540 \pm 0.037$ | $41.478$ |
| $R_b$ | $20.767 \pm 0.025$ | $20.742$ |
| $\Lambda_b$ | $0.01714 \pm 0.00035$ | $0.01643$ |
| $\Lambda_b(P_{\text{T}})$ | $0.1465 \pm 0.0032$ | $0.1460$ |
| $R_b$ | $0.21629 \pm 0.00098$ | $0.21579$ |
| $R_f$ | $0.1721 \pm 0.0030$ | $0.1723$ |
| $\Lambda_3$ | $0.0692 \pm 0.0016$ | $0.1038$ |
| $\Lambda_{26}$ | $0.0707 \pm 0.0035$ | $0.0742$ |
| $A_2$ | $0.923 \pm 0.020$ | $0.935$ |
| $A_2$ | $0.670 \pm 0.027$ | $0.668$ |
| $A_{L(D)}$ | $0.1513 \pm 0.0021$ | $0.1480$ |
| $\sin^2\theta_W$ | $0.2324 \pm 0.0012$ | $0.2314$ |
| $m_W$ (GeV) | $80.410 \pm 0.022$ | $80.377$ |
| $T_W$ (GeV) | $2.123 \pm 0.067$ | $2.032$ |
| $m_t$ (GeV) | $172.7 \pm 2.9$ | $173.3$ |

5 ZEUS at HERA

The HERA electron-proton collider is an asymmetric collider, with 30 GeV positrons (or electrons) in one ring and 820 GeV protons in the other ring; the c.m. energy is about 300 GeV. There was a recent upgrade which resulted in an increase of the HERA luminosity.

The ZEUS detector is one of the two general purpose detectors at HERA [5]. The ZEUS collaboration is formed by about 460 physicists, engineers and students from 52 Institutions from many countries.
The Japanese participation in HERA concerns about 20 physicists and students from 5 Institutions; there are about 55 Italian physicists and students from 7 Institutions. The Japanese concentrated in the electromagnetic calorimeter and in the problem of hadron-electron separation. The Italian contribution concerned the muon detection system, the leading forward (proton) spectrometer and the silicon microvertex detectors. Italy also contributed considerably to the construction of HERA.

There was a recent upgrade of the ZEUS detector (in particular of the silicon microvertex).

ZEUS results concern the study of the proton structure function, $F_2$, from data on deep inelastic scattering at very low values of the variable $x$ and at very large values of $Q^2$, the study of the photon structure, of heavy flavour production, of leading proton physics, of hadronic final states, of many searches for new particles and new phenomena, etc.

6 ATLAS at LHC

The future LHC collider at CERN will accelerate protons to 7 TeV, thus the c.m. energy will be 14 TeV. It will have a very high luminosity, about $10^{34}$ cm$^{-2}$s$^{-1}$. This will correspond to about 20 collisions per bunch crossing, which will have to be unscrambled by fast timing and fast triggers.

The ATLAS (A Toroidal LHC Apparatus) detector is one of the general purpose detectors at LHC; more than 1500 physicists and graduate students are building equipment and perform Monte Carlo simulations of complicated events [each of which requires a very large computing power]. The physicists are from 150 Institutions from 34 Nations [plus CERN + Dubna] from the 5 continents. It is thus a world collaboration, and it requires a complex organization.

There are about 50 physicists and students from 12 Japanese Institutions in ATLAS; from Italy there are about 100 physicists and students from 12 Institutions. The Japanese colleagues are involved in the superconducting solenoid, in the end-cap chambers, in electronics, triggers and other items. The Italians are involved in the B0 and toroid magnetic systems, in the RPC detectors for the barrel, in tracking detectors, and in calorimeters.

A major common effort of the LHC collaborations concerns the GRID computing project for off line analyses and Monte Carlo production; it also aims to improve the efficiency, speed and connectivity of all computers systems.

The expected physics programs at LHC will first concentrate on the search for the Standard Model Higgs boson; other studies will concern the physics items already discussed in Sections 3-5, in particular on new particle searches of larger masses, especially supersymmetric particles, using the anticipated very high luminosities. Other studies will concern heavy quark physics, large and small $p_T$ physics, also heavy ion collisions, etc.
7 Conclusions

It seems that most physicists who have been involved in one of the large collider experiments consider their experience to have been exciting. This was more so when the experiments were obtaining their most interesting physics results, like the 3 neutrino families, the precision determination of the electroweak parameters and of the strong interaction (QCD) parameters [3], the running of the strong and of the electromagnetic coupling constants, precise measurements of the lifetimes of short lived particles, the existence of the triple boson vertex, the discovery of the top quark, possible indications and new limits on new particles [8] and new phenomena.

The contributions of Japanese and Italian colleagues were always very important in the planning, construction and physics analyses.

One should not neglect the very large number of Diploma, Laurea and PhD theses with data from high energy collider experiments, and the strong impact on the public understanding of science.

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