THE EXPERIMENTAL CHALLENGES OF LHC

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Abstract. I will review some of the challenges set by the LHC machine, the LHC detectors and the extraction of LHC physics. I will also consider briefly another question: which road should one follow after the first phase of LHC?

1. Where do we start from?

As a preliminary remark, let me state that, besides the many challenges it raises, the LHC represents a wonderful opportunity for the HEP community. A first problem is clearly the scarcity of what we know beyond the SM, as summarized in the first two figures (1). This ignorance implies that we must keep our eyes wide open. Remember the ISR story! (2). No a priori intellectual bias is permitted. We must consider all kinds of possible scenarii, as shown in the third figure. Exotic ones, true or not, are welcome, because they bring into the game new channels and topologies. However they are no more than guides, and we must prepare ourselves for a systematic “topological approach”, namely to study and measure all topologies which can be mastered well enough, theoretically and experimentally.

An important information from LEP is that we observe a quasi-perfect convergence of the three coupling strengths at $10^{16}$ GeV in low mass SUSY, as shown in figure 4 (3). This is however a hint rather than a proof of the existence of SUSY.

Many scenarii of SUSY are possible. As newcomers, let me mention for instance the Focus Point, Split, Supersplit, Split Split and Twin versions (4). Even in the basic MSUGRA model, as shown by figure 5, one can consider a large variety of different spectra. Furthermore there are still open questions in SUSY phenomenology, like the possible role of phases. The MSSM offers a single firm prediction: the existence of a very light Higgs boson $h^0$, lighter than 130 GeV (5) and likely to be SM-like.

The search for this light boson has been started at LEP2 (figure 6). A lower limit of 114 GeV has been put on its mass. 80 more SC cavities (360 instead of 280) would have been needed to get the final answer about its existence and offer its discovery or a falsification of the MSSM. The future, at LHC or, if much progress is made, at the Tevatron (figure 7), will tell, in particular whether a weak signal at 115 GeV was real or not.
Figure 1. Information, indirect (circles) and direct (triangles), on \( m_{\text{top}} \). Information on \( m_{\text{higgs}} \) in the SM frame. Simple Technicolor does not agree with data. The accurate measurements are nearly insensitive to SUSY.
Figure 2: The results of the muon g–2 still present some ambiguity. A possible violation of unitarity in the CKM matrix has disappeared, because of a change in $V_{us}$. Atomic Parity Violation agrees with the SM expectation. Indirect (the tip of the triangle) and direct (angle $\beta$) determinations of the Unitary Triangle agree. Neutron EDM, unseen up to now, is a promising measurement.

Figure 3: The various avenues beyond the SM.
Figure 4: convergence of the couplings in linear scale, the observed evolution of the strong coupling, a zoom on the high energy region.

Figure 5: two possible mass spectra of MSUGRA
Figure 6: a brief history of the SM-like Higgs search at LEP2

Figure 7: present and foreseen luminosity at Tevatron. Its potential for the SM-like Higgs search (from N. Varelas, hep-ex/0507062).
2. The promises of LHC
The Higgs boson, if it exists, is within LHC reach (figure 8, left). SUSY, if it exists, should appear first as a signal of missing energy, then as an excess of simple topologies (figure 8, right). Figure 9 shows some of the signals expected from extra-dimensions at LHC (6).

A first difficulty is that LHC will have only two large multipurpose experiments. This will require to define and follow a clear methodology to compare their findings, especially in case of divergent observations (figure 10).
Let me start with a short history (or at least a personal view) of the LHC project.

Building the LHC in the LEP tunnel was anticipated since long. We can thank warmly the foresight of our elders. A luminosity $L=10^{33}$ cm$^{-2}$s$^{-1}$ was foreseen, but, due to the competition of the SSC (40 TeV), it was suggested in La Thuile 87 to aim at $10^{34}$ cm$^{-2}$s$^{-1}$ and this goal was adopted soon after. So, when we will speak of $10^{35}$, let me recall that it is an “upgrade of an upgrade”.

The first thoughts about detectors came long ago: an “iron ball”, a high resolution electromagnetic detector. Then the choice was made of open, multipurpose detectors and a very strong and all-azimut R&D detector programme, the DRDC, was started and pursued thoroughly to demonstrate that the expected luminosity could be fully exploited. However, contrary to what happened for LEP, the anticipated timescale of the LHC was very optimistic! Let us hope that, as for LEP, the expected performances will be reached and even overtaken.

Figure 10: a false signal, according to Quino.

Figure 11: announced timetables for LEP (J.Adams, les Houches 1979) and LHC (in 1990). The date foreseen for LHC versus the year of announcement. LEP performances, foreseen and achieved.
3. Heavy ions collisions
At the SPS, strangeness enhancement and the \( J/\Psi \) suppression were observed. RHIC has demonstrated the increase in elliptic flow and high–\( P_t \) particle suppression. Its findings are presently summarized as evidence for a “perfect liquid”. Let us hope that more elaborate and less mediatic conclusions will emerge.

LHC will offer a much higher energy. The matter in quark-gluon plasma phase will be hotter, bigger, longer-lived. Much smaller \( x \) will be involved: the RHIC forward region, showing structure function saturation, will move to mid-rapidity at LHC. Much harder processes will be accessible.

Experimentally, compared to pp running, 3 orders of magnitude lower rates, and up to 3 orders of magnitude higher particle densities are expected.

Jet quenching, seen at RHIC, corresponds to energy loss of hard partons due to gluon bremsstrahlung. But actually it leads to a medium-induced redistribution of the jet energy inside the jet cone. A pure calorimetric measurement is thus insufficient, and one needs to study the modification of the jet characteristics. This requires in particular to reconstruct tracks and identify them down to low momenta.

In the field of heavy flavour production, the key objective is to measure the suppression pattern of quarkonia \( \psi \) and \( \Upsilon \). However one must also measure open heavy flavour production as a normalization. This implies to cover the low \( P_t \) region, to keep a low level of decay background, to have an excellent spatial resolution at the interaction point and a powerful particle identification.

These considerations have guided the conception of the ALICE experiment presented in figure 12 (7).

![ALICE experiment](image)

Figure 12: the ALICE experiment, views of its TPC, the range of its measurements.

4. General features of proton-proton collisions
Let us come back to proton-proton collisions and compare their scenery to lepton-antilepton in figures 13 and 14. One can contrast the broad band beams of partons in p–p to the spikes in energy offered by lepton colliders, which are definitely threshold machines. However, with respect to boson fusion, the two types of machines are more similar. Figure 15 gives some typical cross-sections, in particular those of basic SM processes, which should be the first goal of early analyses.
Figure 13: electron and proton collisions. The LEP scenery (courtesy U.Amaldi).

Figure 14: comparison of the scenery at an electron collider and at LHC
5. Tools and strategies

It is clear that at LHC, before claiming any discovery, it will be first necessary to “rediscover the SM”! But what will the SM look like? The cartoons of figures 16 and 17 show the many steps leading from the basic parton hard scatter to the final event (8).

Figure 18 recalls the importance of the knowledge of the parton structure functions in a Bjorken-x range requiring an extrapolation from the existing and foreseen measurements at HERA and Tevatron. The input of these machines is most important, but LHC will have to complement it by performing its own measurements of simple SM processes (9).

The best possible control on QCD production and decay mechanisms will be the key of LHC physics. The factorization theorem allows to separate partonic cross sections from initial state and final state histories. Three different realizations of this theorem are used:

1/ Cross-section evaluators: ex. the Drell-Yan process. One measures the inclusive spectrum of a leptonic final state, for which NNLO cross-sections have been calculated.

2/ Parton level event generators from Matrix Elements (ME): they are typically used to describe final states with several hard jets. Ex. W + jets, etc. Usually, calculations are available only for LO cross-sections, but NLO ones exist for several low jet multiplicity final states. These tools allow for more refined detector analyses. They are good to quickly study systematics and the best to describe multijet final states.

3/ Parton Shower (PS) Monte Carlo event generators: these yield physical measurable hadrons. Let us quote PYTHIA, HERWIG, ISAJET, SHERPA, etc. They are needed for realistic detector simulations. But they underestimate the rate of multijet states (figure 19 right).
Figure 16: from the basic parton collision to the complete jet configuration

Figure 17: the final dressing into hadrons (from B.Sjostrand, ref.8).
Figure 18: The relevant domain of parameters of the partons involved, some critical regions and distributions, some key SM processes and which constraints they bring (see ref.9).

Process: PDF constraint on:
di-jets quarks & gluons
die + photons quarks & gluons
die + W boson quarks & gluons
W & Z bosons quarks
Drell-Yan quarks Low-mass DY → small-x gluons

Figure 19 left: The impact of the Tevatron concerning jet production (from T. Greenshaw, talk at LIP, Portugal). Right: discrepancy between Pythia and a ME generator for hard jet production (from T. Lari, ref.10).

To improve the log accuracy, one needs to perform resummations and use Parton Showers. NLO corrections in Matrix Elements generators exist for 2/3J, heavy quarks and vector boson production. When including NLO ME in Parton Shower Monte Carlo one must mind to avoid double counting. This is implemented in MC@NLO codes, a superstructure built onto HERWIG MC. See (11).
Figure 20: $p_T$ distribution of top quark pairs with three different approaches, from S. Frixione et al, ref. 12).

Figure 21: the analysis chain. The les Houches Accord (from ref. 8).

What can be the strategies at LHC? (13).

Let us take as example the classic SUSY signatures (14):

- $n$ jets + $m$ leptons + missing $E_T$ (mSUGRA-like)
- 0 lepton + $\geq 2$ jets + missing $E_T$
- 1 lepton + $\geq 2$ jets + missing $E_T$
- 2 leptons + missing $E_T$, Same Sign or Opposite Sign di-leptons, no-jet or $\geq 2$ jets
- tri-leptons + missing $E_T$, no-jet or $\geq 2$ jets.

One can add: $\gamma$ (GMSB), $\tau$, $Z^0$, $h^0$ (in cascades), etc. No mass peaks are available, but one can determine various end points, the shapes of distributions, etc.

The respective rates of each topology determine a “footprint” of the model.

This “inclusive signature” is what the detector gives, provided problems of trigger, acceptance, reconstruction, identification, etc, are solved.
The game would be to compare the experimental footprint with those of hypothetical models, e.g. a SUSY model defined at very high energy, correctly evolved (RGE) to the electroweak scale, correctly generated, viable with respect to low energy observables, respecting EWSB, etc.

The background to the signal comes from SM processes, but also from beyond–SM ones, e.g. from SUSY itself in our example.

Such a strategy is obviously more general than for SUSY search.

![Figure 22](image.png)

Figure 22: Some features of SUSY. Decay chains and end-point spectrum, distributions of $M_{\text{eff}}$ for signal and background with different generators.

In SUSY search, $E_T^{\text{miss}}$ is the key quantity and must be well understood. This implies to use the right generators (see figure 22) to evaluate the SM background (15). Guidance from Tevatron or HERA is important. However, for the final answer, one may have to wait for the information of LHC data themselves. Experimentally, one will use hard cuts against fake $E_T^{\text{miss}}$ and reject events with $E_T^{\text{miss}}$ along a jet or opposite to it.

One should note and exploit the possible occurrence of $h^0$ in cascades (figure 24 left). Since sparticles are pair-produced one should attempt to separate the hemispheres (16).

Different regions of the SUSY plane $m_0/m_{1/2}$ will have different footprints (figure 24 right). Prospective studies should consider a variety of test points, and go beyond the strict MSUGRA frame.

A personal remark: all physics analyses will need as a prerequisite to perform “experimental tasks”. These activities are of general interest, quite vital and should be considered, publicized and felt as “glorious” as analysis work. Let me quote as examples: evaluation of generators, detector
alignment, track/shower matching, muon inner/muon outer matching, $V^0$ reconstruction, conversion, reinteractions, jet scale, cracks, $E_T$ miss reconstruction, combined calorimetry, b tag, (c tag), pile up, etc, a key objective being to achieve a good $E$ flow.

Figure 23: the reach in the MSUGRA plot

Figure 24: impact of $h^0$ production in cascades. MSUGRA plot, showing the various regions.
Figure 25: Drell-Yan, a well-mastered process, and some of the promises it offers.

6. The LHC Machine
Figure 26 gives the nominal parameters of the LHC and shows the huge step it represents compared to previous and existing machines. More than a decade of intensive R/D allowed to master the various technical problems. I am indebted to various reports from our LHC colleagues (17).

| Table 1: Main parameters of the LHC with protons |
|-----------------------------------------------|
| Circumference                | 26.7 km |
| Beam energy at collision     | 7 TeV   |
| Beam energy at injection     | 0.45 TeV|
| Dipole field at 7 TeV        | 8.33 T  |
| Luminosity                   | $10^{34}$ cm$^{-2}$s$^{-1}$ |
| Beam current                 | 0.56 A  |
| Protons per bunch            | $1.1 \times 10^{11}$ |
| Number of bunches            | 2808    |
| Nominal bunch spacing        | 24.95 ns |
| Normalized emittance         | 3.75 mm |
| Total crossing angle         | 300 μrad |
| Energy loss per turn         | 6.7 keV |
| Critical synchrotron energy  | 44.1 eV |
| Radiated power per beam      | 3.8 kW  |
| Stored energy per beam       | 350 MJ  |
| Stored energy in magnets     | 11 GJ   |
| Operating temperature        | 1.9 K   |

Figure 26: table of LHC parameters. The “jump” from past or present machines to the LHC.
6.1. Beam optics, vacuum, collimation

With, per beam, ~3000 bunches of ~ $10^{11}$ protons, the LHC beam optics must take into account:

λ Incoherent single particle effects:
   - beam-beam interaction, namely the effect of the electromagnetic field of one beam on the particles of the other beam.
   - intrabeam scattering, for instance multiple Coulomb scattering within the same beam (most important for a lead ion beam).
   - The beam should be viewed as a relativistic gas, not in equilibrium: its radial emittance increases and remedial action is needed (18).

λ Collective effects:
   - single bunch effects, from short range wakefields due to the interaction of the beam with its environment, like the transverse slow head-tail instability.
   - multibunch instabilities due to long range wakefields: the most important is the transverse resistive wall instability: $\propto \sqrt{\rho}, \ r^{-3}$ ($\rho$ is resistivity, $r$ is radius). The inside of the beam screen is coated by 50μ of copper. A major programme of reduction of impedance has been undertaken (figure 28). Crossing at an angle and, if necessary, a larger interval between bunches (75 ns available) decrease the long range effects.

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Figure 27: LHC experiments and an artist view of the underground arrangement.

Figure 28: effect of the impedance reduction on the bunch length. The LHC crossing scheme.
The dynamic aperture is defined as the maximum useful betatron amplitude over a long time. It is limited by imperfections in the superconducting magnets: non-linear field errors due to persistent currents, coil geometry, redistribution of current between strands during ramping. These errors are dominant at injection field level. Figure 29 shows as an example the residual sextupole component of the dipoles. Concerning the magnetic field quality of the magnets, solid warm-cold correlations have been established, which allow to test in the cold only a fraction of the magnets. Since they present slightly different features, one should pair them in order to smooth out the variations. A special installation strategy is foreseen for this purpose (19).

A tune spread is due to beam-beam interaction and the corresponding tune footprint must fit between resonances (figure 29).

The magnets (see below) operate at 1.9°K. Actually most of the heat loads (0.8 W/m from image currents, 0.6 W/m from synchrotron radiation), have to be intercepted at higher temperature. This is the role of a special screen inside the vacuum chamber (figure 30). Warmer than the chamber and punched with holes, it acts as a cold trap.

Beam induced multipacting may build up an electron cloud (figure 30). “Scrubbing” runs will be needed. An elaborate strategy is devised to clean and condition the machine with γ and electrons.

To improve the vacuum in the experimental sectors all warm sections of the vacuum chamber will be coated by a non-evaporable getter (figure 31).

Figure 29: the sextupole component. The tune footprint in the resonance pattern. The final focusing and a high gradient quadrupole. Performances of the 75 ns crossing scheme.
Figure 30: the screen intercepting synchrotron radiation. Electron cloud building up. Effect of scrubbing on the residual pressure and on the yield of secondary electrons.

Figure 31: C. Benvenuti, father of NEG. Getter pumping at LEP. Its principle. Deposition of getter for LHC vacuum chamber.
The energy stored in the beam is huge (up to 300 MJ). Protection of the beam elements and of the experiments requires a most elaborate collimation scheme, as well as a safe dump procedure in a dedicated section (figure 32). Both systems will come in two steps (see later).

Figure 32: various aspects of LHC collimation and dump.

Figure 33: the movable LHCb vertex locator (VELO)
Some elements of the LHC experiments will be located very close to the beam: the TOTEM detector, the LHCb vertex locator (figure 33), and, to a lesser extent, the pixel detectors of ATLAS and CMS, one more reason to proceed with care.

![Not Covered in this Talk](image)

**Background control** for the experiments:

- No request received to have collimators for background control.
- Background will be controlled as a side-product of minimizing particle losses in the SC magnets (quench prevention).
- Tertiary collimators in experimental insertions might be used for background also?
- Background control is outside of the collimation project: but strong concerns have been received in external reviews: Follow-up by TIS!

**Collimation of ions:**

- Will use the same collimators as protons, therefore no separate mentioning.
- Two-stage cleaning does not work for ions.
- Expect intensity limitations.
- No solution as far (the laws of physics are against us).

**Transfer line collimation**

![Figure 34: some warnings from a specialist (R.Assmann).](image)

**Figure 34:** some warnings from a specialist (R.Assmann).

![Figure 35: the rationale of the LHC parameters.](image)

**Figure 35:** the rationale of the LHC parameters.
6.2. Magnets and cryogeny
LHC will use very high field 15 m long SC magnets, of a most innovative design, “two-in-one” (figure 36). They are superconducting and use superfluid liquid helium cryogeny at 1.9 °K. 1232 of them are needed. One needs 400 SC quadrupoles operating above 200 T/m and more than 4000 SC corrector magnets of various types. Overall the LHC represents about 40000 tons of “cold mass”, a cold surface area of 50000 m² and 1250 tons of Nb-Ti superconductor (80% of the world’s yearly production) cooled by close to 100 tons of He. After the tokamak Tore Supra (figure 37), LHC is the first very large scale instrument using superfluid helium.

The dipole field of 8.5 Tesla is well beyond the saturation limit of any kind of steel. So the field configuration and quality (10⁻⁴) rest entirely on the geometry of the coil, arranged in the so-called “cosθ” distribution and whose accuracy (~0.1 mm) and stability must be excellent.

Besides the main magnets, quadrupoles of the low-beta triplet at the experiments are the most challenging: 215 T/m, high heat loads and radiation dose, large cold bore, excellent field quality requirements (KEK, Fermilab).

Let us note that the leads bringing the current (1.7 MA overall) from the warm to the cold are realized using SC with a high critical temperature (up to 50°C) (figure 41). One gains a factor 3 on the energy loss. This represents one of the first large scale application of these materials in the field of high currents.

The String installation (figure 39) allowed a thorough test of a chain of elements.

Figure 36 : scheme of a LHC magnet
Figure 37: the tokamak Tore Supra in Cadarache

Figure 38: cooling scheme of the magnets and characteristics of the superconducting conductors.

Figure 39: the String Test, a magnet under measurement, magnets and cryoline in the tunnel.
Figure 40: pictures of LHC magnets, equipment, storage, transport. Dashboard for cryodipoles at the time of Corfu meeting.

Figure 41: details on the structure of the SC cables. The “warm” SC current leads. The connections between two magnets.
8 large refrigeration units will be used, of unitary power equivalent to 18 kW at 4.5°K. We recall that one needs 950 watt at 300K per watt at 1.8K. One of the critical issues was the design of the cold compressors shown in figure 42, components of 8 refrigeration units, each of 2.4 kW at 1.8°K.

On the critical path for the first collisions it the installation of the LHC in the tunnel, in particular due to delays in the cryogenic services lines (QRL), which initially had problems, and for which a recovery plan was implemented successfully.

See P. Lebrun CERN LHC/96-02

Figure 42: A refrigeration unit. Cold compressors. The cryogenic line inside the tunnel.

The problem of acceleration is easier at LHC than it was at LEP. Indeed, due to the heavy mass of the proton, the energy loss by synchrotron radiation (figure 43) is very small. A few RF cavities are sufficient, instead of the large park of cavities of LEP2. The critical energy of synchrotron radiation is low (40 eV). On the other hand the number of radiated photons is huge and this has important consequences, as we saw.
**Synchrotron Radiation**

- **Power and critical photon energy:**
  \[ P \propto \frac{\gamma^4}{\rho^2} \cdot q^3 \cdot N \]
  \[ <E_\gamma> \propto \frac{\gamma^3}{\rho} \]

- **Electron:**
  \[ e = \frac{\omega}{2\pi} \cdot \lambda \]

- **If the bunch dimensions become comparable or smaller than the radiation wave length, a bunch can radiate like a single macro particle!**

- **Free Electron Laser (FEL) machines**

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**Table:**

|     | \( E \) [GeV] | \( \rho \) [km] | \( N \) \( \times 10^{12} \) | \( U \) [MeV] | \( P \) [MW] | \( E_\gamma \) [keV] |
|-----|---------------|----------------|-------------------------------|--------------|--------------|-------------------|
| LEP 1 | 45            | 3.1            | 4.7                           | 260          | 2.1          | 90                |
| LEP 2 | 100           | 3.1            | 4.7                           | 2800         | 23           | 715               |
| LHC  | 7000          | 3.1            | 312                           | 0.007        | 0.005        | 0.04              |

**Figure 43:** Information about synchrotron radiation.

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**Figure 44:** the principle of RF acceleration. RF SC cavities of LEP.
Figure 45 illustrates the large variety of components of the LHC machine, the construction of which presents a worldwide dispersion. One understands that the realization may thus be affected by “business instabilities” (P.Lebrun, in 20).

Figure 45: the variety of LHC components. A breakdown of its cost (overall 2.2 Giga Euros).

Figure 46: the evolution with time of the luminosity of previous machines. The expected integrated luminosity range of the Tevatron.
6.3. LHC commissioning

Figure 46 illustrates the evolution in time of the luminosity of various machines. Figure 47 gives the same for LEP. During the excellent last year of LEP2 each experiment got 250 pb⁻¹. One year is 6 months running or ~ 1.5 \times 10^7 s. The peak luminosity was \(10^{32} \text{ cm}^{-2} \text{ s}^{-1}\). The mere product of the peak luminosity and the running time should lead to \(1.5 \times 10^7 \times 10^{32} = 1.5 \times 10^{39}\) i.e. 1500 pb⁻¹. This is a factor “2π” more! One must therefore introduce a running efficiency and use \(<L>\) instead of \(L_{\text{peak}}\).

Figure 47: the evolution with time of the integrated luminosity at LEP.

Figure 48: a hint of what could be the first stages of LHC commissioning.
For the commissioning of the LHC, figures 48, 49 and 29 (21) give a hint of what it could look like. A key point is that the beam power, even at reduced luminosity, is such that all care should be taken to avoid damaging machine components and the experiments. A reduced number of less intense bunches and a weaker focusing will be used at the start.

One should also note that the final dump system and collimator scheme, needed for the full intensity, will be installed only in the long shut-down 2009/2010.

Figure 49: a hint of what could be LHC commissioning in time.

From these figures I tried a personal guesswork, following crudely the commissioning plans, with 1 month ~ $N_{\text{sec}} \times \text{lum} / \pi$.

| Year | 1 month | $2 \times 10^{30}$ | 2 months | $10^{31}$ | 0.02 fb$^{-1}$ ?? |
|------|---------|-------------------|-----------|----------|------------------|
| 2007 |         |                   |           |          |                  |
| 2008 |         |                   |           |          |                  |

(75 ns, $\beta^*=2$, $4 \times 10^{10}$)

| Year | 3 months | $4 \times 10^{12}$ | ~1 fb$^{-1}$ |
|------|----------|--------------------|--------------|
| 2008 |          |                    |              |

(25 ns, $\beta^*=1$, $3 \times 10^{10}$)

| Year | 4 months | $1-2 \times 10^{13}$ | 4-8 fb$^{-1}$ |
|------|----------|---------------------|---------------|
| 2009 |          |                     |               |

Figure 50 : a personal guess (no more!) of the initial integrated luminosity at LHC.
However R. Teuscher in his talk at Lisbon conference foresees $6 \times 10^{31}$ to $10^{32}$ initially, then 7 months at $2 \times 10^{33}$ in 2008 giving a figure of 1 to 10 fb$^{-1}$ at the end of the year.

As Lyn Evans rightly says: “(It is) difficult to speculate further on what the performance might be in the first year. As always, CERN accelerators departments will do their best!”

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**Conclusion**

- The LHC is a demanding machine. Not only does its physics reach enter into new territory, but also the machine challenges advance the state-of-the-art in some respects by 2-3 orders of magnitude.
- Many interfaces between the machine and experiment interests: energy, luminosity, beam background, ...
- The LHC machine is designed to master all the known accelerator physics and operational challenges.
- We must proceed carefully in order not to hinder further progress (damage to the accelerator or the experiments).
- A plan has been laid out for commissioning of the LHC: 2 months until colliding beams and 5 years to nominal performance (like LEP).
- We have exciting times ahead of us...

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Figure 51: Some wise considerations about LHC commissioning.
7. The experiments

Figure 52: scheme of the CMS experiment.

Figure 53: scheme of the ATLAS experiment
7.1. Presentation and present status

It is commonplace to say that the large experiments ATLAS and CMS are indeed very big! However they are also very subtle. For instance one should remember that the goal is to reach a spatial accuracy of typically 100 μ at their periphery and 10 μ in their inner part, which implies an even more accurate alignment of their detectors, first mechanical, and ultimately refined using the particles themselves.

The requirements put on these detectors are phenomenal. To fix the ideas in a striking way, let us say that CMS, for instance, will have 210 m² of micron grade silicon detectors in its tracker, ~ 80 million channels in its pixel detectors, 80000 lead tungstate crystals as electromagnetic calorimeter, of the order of 10000 tons of iron recuperated from artillery shells from russian warships. As for ATLAS, at nominal luminosity, 10⁹ interactions will occur per second. This represents a volume of data equal to 10000 Encyclopedia Britannica per second, a data rate treated by its event builder equal to the data rate of the world’s telecom network in 2003. Only 100 of these events can be kept, which implies a rejection (in real time and with no allowance for mistakes) of a factor 10⁷. About ten petaBytes of data per year will be stored and analysed.

At the time of writing the largest components of both detectors are installed (however CMS is assembled at ground level and will have to be lifted down). The magnetic systems will be tested soon at full field. These are good news! But there is still a lot to do! As said once, “la route est droite, mais la pente est forte”.

Figure 55: the ATLAS combined test. Some of the results. Cosmic muons in ATLAS. Prospect for an early top mass measurement.

ATLAS has performed under beam a very useful combined test (figure 55) with a complete « slice » of their spectrometer. The detector commissioning is under study and even started with cosmic muons. As soon as the LHC beam comes, halo muons and beam gas interactions will be
exploited. Then basic SM processes, abundant even with low luminosity, like IVB production, will be used for calibration purposes. The first physics results could include a measurement of the top mass. As we said, before any claim for new physics, the main SM processes will have to be «rediscovered» and measured.

I briefly described already ALICE in 3. Figure 56 gives information about LHCb.

![LHCb Experiment](image)

Figure 56: the LHCb experiment. The rapidity coverage. The RICH identification. View of the LHCb magnet.

7.2. The four experimental challenges of the detectors
Let us see more precisely what are the implications of the huge interaction rate: 40 million crossings and 25 interactions per crossing, giving the $10^9$ interactions per second quoted.

The first is a very large number of hits, implying a very large number of independent channels, so that each of them is, at any moment, almost certainly «free» to register an interesting event if it occurs. As an example, the CMS Central Tracker (CT) will see ~ 1000 tracks per crossing, many of them spiralizing, leading to ~ 40000 hits in detector per typical event. The 210 m$^2$ of single sided p-on-n detectors of the CT comprise ~ 10 M channels and their mean occupancy level is only O(1%). Some of the tracker performances are shown by figure 57.
The second is the high level of irradiation of the central/forward components (figure 59). This was almost negligible at LEP. However the Tevatron, HERA, RHIC, and some fixed target experiments are already facing this problem, albeit under less severe conditions. For 500 fb$^{-1}$ or 10 years of nominal luminosity, the CMS barrel tracker and electromagnetic calorimeter receive the doses shown in figure 58 (1 Gy = 100 rad). All components of these detectors must be radiation hard, as we shall see later.

| radius   | kGy | CMS ECAL |
|----------|-----|----------|
| 4 cm     | 840 | $\eta$   |
| 11 cm    | 190 | kGy      |
| 75 cm    | 7   | 0-1.5    |
|          |     | 3        |
|          |     | 2        |
|          |     | 20       |
|          |     | 2.9      |
|          |     | 200      |

Figure 58: some irradiation levels in CMS sub-detectors.
The third, already alluded to, is the need for a highly selective trigger: One must go from $10^9$ to $10^5$ events /s. This is done in steps (figure 60). At level 1, $10^5$ Hz are kept. 3 $\mu$s of pipelining of the data are required. This raises severe synchronization requirements. Obviously, the criteria set to retain an event (high $p_T$ objet, $E_{T,\text{miss}}$, etc) at level 1 and higher level must be carefully thought and implemented.

The fourth is that, at all levels, the volume of information is gigantic. $\sim 10^9$ MB / s enters the front-end electronics. $\sim 100$ GB / s go to the Event Builder. The Farm requires $5 \times 10^6$ MIPS. Several TB / day must be stored, i.e several petabytes per year. We will examine later the computing challenges.

Figure 60: the volume of data to be treated at various steps, a sketch of the triggering scheme, trigger and DAQ requirements for various experiments.
Technically, as shown by figure 61, all expectations from industry in the various domains relevant for trigger and acquisition have been fulfilled. Moreover, meanwhile supercomputing has turned into PC farming, offering high speed interconnection, as needed in the on/off-line systems.

Figure 61: left: the performances needed for LHC (green polygon) and what was expected from industry along the years. Right: the achievements (red polygon).

7.3. A few remarkable sub-detectors

7.3.1. Silicon devices

Figure 62: evolution of Si devices from the eighties to the LHC time.
Figure 62 gives an idea of the fast evolution of semiconductor high resolution silicon devices, microstrips and pixels. From few cm$^2$ in the eighties, it went to a m$^2$ at LEP. At LHC, besides their traditional role in heavy flavour tag, they constitute part (ATLAS) or the totality (CMS) of the tracker. Overall, these experiments will include 287 m$^2$ of pixels and microstrips, 200 million diodes, 22000 modules, etc. The « jump » is indeed a very bold one!

![ATLAS Si tracker](image1)

![CMS](image2)

Figure 63: the ATLAS Si Tracker, sketch of CMS all-silicon tracker, its material budget.

The detectors nearest to the beam, usually pixels, have as a main function to tag heavy flavours and especially beauty. This turned out to be a key aspect of physics analysis at all previous machines, in particular the Tevatron, and will be vital at LHC, as nicely described by figure 64 (22).

Among radiation effects on electronic components one can distinguish:

1/ the effect of the total ionizing dose: it produces trapped charges in the Si dioxide gate insulator. For sub-micron devices, these can escape by tunneling. It also increases leakage currents.
2/ the displacement damage: this affects the function of atoms.
3/ single event effects (SEE), due to highly ionizing particles and nuclear interactions. ex. single event upset flipping the value of a digital signal.
Figure 65: performances of b-tag at Tevatron and some of its aspects and virtues at LHC (from V.Rizatdinova, ref.22).
Concerning electronics, 0.25 μ CMOS has become the preferred technology. Modern CMOS is intrinsically hard and meets LHC speed and power constraints. Its quality and uniformity are quite high. It dominates commercial electronics for which HEP represents a small community compared to industry. The 0.25 micron version will probably be on the market until 2009. 0.18 and 0.13 micron technologies are already available. The power consumption is however still a major issue.

Radiation qualification of the detectors and electronics implies exposures to X-rays, neutrons from reactors, proton beams. One must take into account annealing effects. SEE are statistical effects: one has to get a sufficient statistical assurance. Concerning safety factors, one can make an interesting comparison to space physics.

To improve the behaviour of detectors under radiation, the key factors are to guarantee a sufficient level of oxygenation of the material, to choose the proper crystal orientation and to keep the device at low temperature (−10° C).

Inversion of space charge sign will occur. This was observed in tests as shown in figure 66, by the curves giving the depletion voltage as a function of fluence. The figure gives more information and shows the beneficial effect of the various factors quoted above.

7.3.2. Calorimetry
Some bets were already made at LEP: for instance the BGO scintillating crystals of L3, offering an excellent energy resolution, were largely chosen in order to study the toponium spectroscopy, which unfortunately was absent. Similarly at LHC, the use of PbWO4 crystals in CMS was adopted to meet the requirements of the Higgs mode $h \rightarrow \gamma\gamma$ for a mass below 130 GeV.

PbWO4 crystals have been adopted for their short radiation and Moliere lengths, reasonable light yield, fast answer and tolerance to radiation. For reasons which are not all physical nor technical, the delivery of the 80000 crystals required is longer than foreseen and became a critical path for CMS planning.
Figure 67: the CMS crystals, raw, cut, equipped, mounted in a super-module. The APD read-out, the electronic chain.

Figure 68: the effect of radiation on the crystals. The demonstration that laser calibration works.

Considering the effect of radiation on crystals:

1/ radiation creates colour centers which decrease the transmission of the light
2/ there are various recovery mechanisms, with different time scales
3/ the behaviour of the crystal under radiation depends on its quality, in particular the correctness of its stoechiometry. One can correlate this behaviour to some precise optical properties.
4/ most important, the scintillation mechanism is not affected by radiation. This means that a proper monitoring of the transmission properties of the crystals is an adequate, although quite demanding, way to correct for the effect of radiation.

Nevertheless the mastering of 80000 crystals to a fraction of a % will not be a straightforward task. Again the last word about calibration will come from the data themselves, like the $Z\rightarrow e^+e^-$ channel.

Figure 69 gives the principle and several views of the original liquid argon electromagnetic calorimeter of ATLAS, which is already installed and under test in the experiment.
7.3.3. A plea for a continued R&D

I would like to insist on the vital need of a continued R&D in detector matters, so that we can hope to correct the defects still existing, improve their performances and meet still more severe experimental requirements in the future.

As microvertex detectors, we should aim at some version thinner than hybrid pixel sensors.

A Si tracker would benefit, for its pattern recognition, of the introduction of real 3-D detectors, like macro-pixels, instead of stereo detection, which generates ghost hits, the use of microstrips being limited to provide a few accurate points. The material budget (figure 63) should be reduced and the radiation hardness still increased.

From my point of view, calorimetry should also be reconsidered with a good Energy Flow as a main objective. This implies a sufficiently large radius, more granularity at an accessible cost, a better resolution, less material in front of it, a better integration of electromagnetic and hadronic calorimetry, a better match between calorimetric clusters and charged tracks, to recognize neutral clusters with more efficiency. Ideally all of these improvements should coexist. The CALICE R&D for ILC is a good example of such an attempt.
7.3.4. A few side remarks

Let me come back to synchrotron radiation, but now of electrons inside the detectors. The critical frequency is \( \omega_c = 3 \gamma^3 c / (2R) \) and the critical energy is \( E_c(\text{keV}) = 0.67 E^2(\text{GeV}) B(\text{T}) \). The number of photons emitted is \( N_\gamma = (5 \pi / \sqrt{3}) \alpha \gamma \text{ electrons} \) or \( N_\gamma = 6.2 \text{ per T.m.} \). The mean energy per photon is \( 0.31 E_c \). One thus find in CMS (1.25 m of 4 Tesla):

| P(electron) | 100  | 300  | 1000 | 1500 | 2000 | 2500 |
|------------|------|------|------|------|------|------|
| \( E_c \)  | 27   | 243  | 2700 | 6000 | 10800| MeV  |
| Energy loss| 0.26 | 2.3  | 26   | 58   | 104  | GeV  |

as about 30 photons of mean \( E = 0.3 E_c \) emitted over the tracker length, half or so converting in the tracker material. These photons are more numerous than bremsstrahlung ones. It would be amusing to visualize the track of such objects.

We can also consider Landau-Migdal-Pomeranchuk effects which concern electrons and photons at very high energy. The physics is that ultra-relativistic electromagnetic interactions occur gradually over “long” distances. During this, factors can accumulate enough to disrupt the interaction. Bremsstrahlung and pair production can be suppressed.

As an example, for a 100 GeV electron radiating a 100 MeV bremsstrahlung gamma, the formation length is 160 \( \mu \)m. Bremsstrahlung is suppressed by multiple scattering for \( k < k_{LPM} \)

\[ \sim E^2 / E_{LPM} \] (see 24). Similarly, due to the effect of magnetic field (1 TeV electron in 4 T), photons below 900 MeV are suppressed.

EM showers develop differently. This is very important in cosmic ray physics. But already for a 1 TeV electron in 1 rad length (a preshower), one gets 3 photons above 1 MeV instead of the 14 expected neglecting the effect (24).

Admittedly the effects mentioned here are marginal, and, in calorimetry, may be masked by more dramatic ones, like saturation or leakage.

7.3.5. Some peculiar signatures: are we equipped?

In case of heavy charged long-lived or stable objects, e.g. long lived gluino in Split SUSY (25) (hep-ph/0507137), long lived NLSP in GMSB, etc, a good time of flight measurement would be most useful. It exists inside the detectors at the ns level but on a relatively short flight length. For amusement, one could dream, if needed one day, of a comfortable (but with reduced acceptance) TOF set up suspended in the access pit….

![Figure 70: a TOF detector in the shaft?](image-url)
8. The Challenge of LHC computing (from P. Messina, ref. 26)
As already emphasized, the LHC computing needs are enormous. Compared to the past, the need for a change of nature of the computing was felt. Different approaches were considered, and the distributed grid computing approach chosen. The MONARC strategy led to a multi-Tier hierarchical model.

A few rules were adopted: that resources outside CERN should be about twice the resources at CERN, that Tier0 would be ~ the sum of Tier1 and ~ the sum of Tier2. Some Tier1 and 2 will have other communities to satisfy, which raises technical and managerial challenges.

The LHC Grid (LCG) mission is to develop and deploy the software, methodologies and policies needed to create this environment.

The Network infrastructure seems adequate. ex. GEANT, Teragrid networks
The technical challenges come from the scale, the heterogeneity, the physical distribution, the dynamic variations of resources and analysis tasks.
Informatics research advances are also required.
Managerial challenges are dominated by political and cultural considerations: how to balance specificity versus “community”, and to realize joint projects with companies.

9. SLHC (10^{-35}): an upgrade of an upgrade!
As already said, reaching a luminosity of 10^{34} is already a challenge, which may take several years.

One can consider two ways of going beyond the nominal LHC: by increasing the energy or the luminosity. I will not discuss here the former, although I hope that some R&D on more powerful magnets (Nb–Sn, etc) is going on in the world.

As for the second option, figure 72 (27) describes the various factors which could be gained, starting with an increased number of protons per bunch and a still stronger final focusing, for which new quadrupoles are already under study.

However, the figure shows also the potential problems: the increased heat load and the expected decrease of the lifetime of the coasted beam, reducing the effective gain in accumulated luminosity. As for the detectors, most of the microvertices and trackers must be redone. One may also be concerned by the radiation and activation issues.

Furthermore, one should keep in mind that the brand new LHC machine is the last of a chain of older ones, which will also need rejuvenation and improvements. This should never be forgotten in planning the future of Cern.
Finally it is worth considering what these upgrades can bring, and put it in perspective with other potential programmes. Since one does not know what will be found at LHC, one can envisage a few possible outcomes and use them as indicators (28). The comparison of columns 1, 2 and 3 show the improvement to be expected. They are relatively modest, compared to what a VLHC or a multi-TeV lepton collider could offer. On the other hand, evidence for a signal at LHC may give a very strong incentive to push its performances.

Let me conclude by repeating that with the LHC we are entering an era which will probably not be an easy one, but certainly will be a fascinating period.

I thank warmly the organizers – and old friends – for the warm hospitality in Corfu. I thank G. Dissertori (29) and several colleagues for discussions. I also thank all the authors from whom I borrowed nice material, hoping that I quoted them properly.
Figure 71: brief history of computing at CERN. The WEB celebrated. LCG deployment. The multi-Tier hierarchical model.
Figure 72: few considerations on a luminosity increase of LHC (from O.Bruening, ref.27)

Figure 73: for a few scenarii the reach of LHC, its upgrades, and other hypothetical machines (from F.Gianotti, ref.28).
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