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The Next Linear Collider*

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Abstract

Progress in physics is driven by its experimental program. The Large Hadron Collider project is well advanced at CERN. Intensive R&D and advanced planning are already in place for the next large scale facility in particle physics: a 30 km long linear accelerator able to collide electrons against positrons at energies up to about 1 TeV. Its anticipated results, and those obtained at the LHC, will provide answers to some of the fundamental questions from the origin of mass to the relation between the particle physics and cosmology.

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1 Introduction

High energy physics is entering a new era where decisive experiments will yield deeper understanding of the fundamental questions regarding the basic building blocks of matter, their interactions and their relation to Cosmology. A series of experiments and theoretical developments over the last forty years has provided us with a coherent theory which has been verified with great precision. The "Standard Model" [1] of particle physics ascribes three of the fundamental particle interactions to the exchange of force particles, known as gauge bosons, with integer spin. *Strong interactions*, mediated by gluons bind the fundamental building blocks of matter, the quarks, into nuclei, such as the proton. *Electromagnetic interactions*, responsible for the binding of atoms and molecules, are mediated by photons. *Weak interactions*, mediated by the charged $W^{\pm}$ and the neutral Z^0 bosons, describe nuclear beta decays and the interactions of neutrinos. Weak interactions are effective over only a short range due to the large masses of the W and Z bosons, 80 and 90 GeV respectively, which are approximately 90 and 100 times larger than that of the proton.

The great triumph of the Standard Model was the correct prediction of these masses, before an accelerator of sufficient energy was available to produce them. The observation of the W and Z bosons at CERN in Geneva in 1983 and that of the top quark at Fermilab in Illinois a decade later, in proton-antiproton collisions, marked the successful end of a first phase of investigations as all the predicted matter and force particles had been observed. Two e^+e^- colliders, the SLAC Linear Collider (SLC) at the Stanford Linear Accelerator Center (SLAC) in California and the Large Electron Positron (LEP) collider at CERN operated throughout the 1990's and enabled the properties of the Z boson to be studied in great detail. Operation of LEP up to 209 GeV, the highest collision energy ever achieved in electron-positron collisions, provided detailed information on the properties of the W bosons, which were produced in W^+W^- pairs. The collision of point-like, elementary particle at a well defined and adaptable energy offers advantages for precision measurements, as those conducted at LEP and SLD, over proton colliders.

These successes force us to address an even more fundamental set of questions. The mechanism responsible for the masses of W and Z bosons, quarks and leptons, of which the electron is the most familiar, is not understood. In the Standard Model these masses arise from the particle interaction with a single, new, elusive particle: the Higgs boson. Each particle acquires a mass which is proportional to the strength of its coupling to the Higgs boson. These couplings are also believed to be the source of CP violation, first observed in the decays of K mesons, and presently extensively studied in B decays. The Higgs boson has not yet been observed. Extensive searches for it have been undertaken by many experiments. The absence of a significant Higgs signal at LEP shows that its mass exceeds 114 GeV. The Higgs boson also manifests itself indirectly, via quantum corrections to other measurable Standard Model quantities, such as the masses of the W and Z bosons and their decay properties. Their precise study indicates that the Higgs mass is less than approximately 250 GeV.

The next step in the exploration of higher energy scales will occur at the Large Hadron Collider (LHC) project, under construction at CERN in the same tunnel which housed LEP. This accelerator will collide protons with greater intensity and at an energy seven times larger than at the Tevatron currently operating at FermiLab. Operation is expected to start in 2007. The LHC was designed to observe the Higgs boson, irrespective of its mass, or exclude its existence. If the Higgs is discovered, its mass will be measured with great accuracy and some of its couplings to quarks and gauge bosons determined. Theoretical uncertainties in its production rates in the complex proton-proton interactions and the inability to observe some of its decays, due to the large backgrounds, will impact both the accuracy in the measurements of its properties and the extent to which its role in the generation of mass can be tested.

In the Standard Model, the specification of the Higgs boson mass is sufficient to predict all of its properties. In particular, the rates of its decays into different particle pairs are completely defined by the masses of the particles involved; see figure 1. An e^+e^- linear collider of sufficient energy to produce the Higgs boson will allow an exhaustive set of measurements of these decays to determine these couplings and prove that the Higgs mechanism in the Standard Model is, or is not, correct.

The observation of the Higgs boson will exhaust the search for elementary particles predicted by the Standard Model. However, we have very compelling reasons to believe that the Standard Model is not the final theory of elementary particles and that new physics exists beyond it. As the mass of an elementary particle, or its energy, becomes larger, eventually its gravitational interactions become comparable to its weak interactions. This mass scale is referred to as the Planck mass ($\sim 10^{19}$ GeV). As the strong, weak and electromagnetic couplings are extrapolated to higher energies their values approach to each other, tantalizing evidence of the possibility of a further unification of the fundamental forces. Quantum corrections to the W, Z and the Higgs boson masses would inevitably drive their values up to the Planck mass, making the large hierarchy between their actual masses and the Planck scale difficult to understand. If new physics appears at some scale the Standard Model will become incomplete as new quantum corrections appear. The "hierarchy problem" will be vitiated if the scale of this new physics is around 1 TeV. There are several classes of candidates for this completion. One class is represented by theories with extra symmetries, such as Supersymmetry, which lessen the impact of the quantum corrections by introducing cancellations. Another class of models introduces new mass scales where the theory changes its character. For example, additional space dimensions could be present. Even though their size is too small to have been observed, they could invalidate the naive extrapolation of the Standard Model to the Planck scale. All these models have distinctive and definite predictions which will provide experimental signatures at a collider of sufficient energy to access the new scale. Data from astrophysical observations, such as the WMAP satellite in 2003, show that about 25% of the mass in the Universe is of unknown origin, the so-called "Dark Matter". It is tantalizing that, while no viable candidate for dark matter exists in the Standard Model, theories of new physics, which introduce new symmetries, predict the existence of weakly-interacting stable particles which might have been produced in the early Universe and survived through its evolution. One of the prime aims of the next generation of accelerators is to unveil signals of this new physics and understand its nature and its relation to cosmology.

Supersymmetry is regarded as the best motivated model of new physics. By introducing a supersymmetric partner for each Standard Model particle, a cancellation takes place in the quantum corrections responsible for the hierarchy problem. These new particles have opposite statistics to their Standard Model partners (for example the partner of the electron has spin 0) and larger masses. Supersymmetry also ensures that the couplings of the Standard Model evolve and meet at a high energy scale. Supersymmetry predicts a stable particle with about the right mass and couplings to account for the observed dark matter density and the large-scale structures of the Universe. If Supersymmetry is indeed realized in Nature, there is a large number of new particles to discover and measure. It is expected that the super-partners of the quarks (squarks) would be heavier than those of the leptons (sleptons), just as quarks are, on average, heavier than leptons. Particles with strong interactions will be produced copiously at the LHC and the production of squarks and gluinos (the partner of the gluon) of masses less than 3 TeV will result in their discovery and measurement. But the direct production of sleptons is more difficult, as they have only electroweak interactions and their observation can be compromised by the larger backgrounds. Supersymmetric models predict several Higgs particles. Again, the LHC will find at least one of these and measure some of its properties. An e^+e^- collider of sufficient energy could measure all of them and complete the picture. In particular, the accurate determinations of the mass of the lightest supersymmetric stable particle and those of the sleptons will be crucial for understanding whether supersymmetry is indeed responsible for the dark matter in the Universe.

The event rate at an e^+e^- collider is determined by the intensity of the collisions (luminosity) and the production cross sections. The latter are conveniently expressed as a few "units of R", where $R = \frac{22\ fb}{E^2_{Beam}}$ where E_{beam} is the energy of one beam in TeV. A constant event sample therefore requires that the luminosity increase with the energy. To obtain an event sample of 10000 events in 10^7 seconds of operation (corresponding to one year of operation) requires a luminosity of $\sim 50 \times E_{beam}^2 \times 10^{33}\text{cm}^{-2}\text{sec}^{-1}$. For comparison, LEP operating at $E_{beam} \sim 100$ GeV had a peak luminosity of $10^{32}\text{cm}^{-2}\text{sec}^{-1}$ approximately four times its original design. Obtaining this luminosity is the biggest technical challenge facing a linear collider and will be discussed in the next section.

The availability of the associated $e^+e^- \to ZH$ production makes e^+e^- collisions an ideal laboratory to study the Higgs boson properties in details. Since the momentum of the Z can be accurately measured from its disintegration into lepton pairs $Z \to e^+e^-$, $\mu^+\mu^-$ and the beam energy is precisely known, the invariant mass of the Higgs system recoiling against the Z can be inferred, independent of its decay properties. The presence of a Higgs signal would be revealed by a distinctive peak in this mass distribution *even if none of the Higgs decay products were observable* (see Figure 2). The strengths of the couplings of the Higgs boson to force and matter particles can be determined accurately from the study of their yields in Higgs decays. Knowing the particle masses, it will be possible to perform the fundamental test of the proportionality between these masses and the coupling strength, required by the Higgs mechanism. Interactions of Higgs bosons with each other are known once the Higgs mass is defined. These too can be measured at the linear collider. These measurements will definitively establish that the Higgs boson of the Standard Model provides **both** force and matter particles with their masses. Should there be more than one Higgs-like particle, discrepancies would be evident and the determination of their properties will be essential for revealing the nature of the underlying theory.

If the collider were operated at collision energies near the Z mass with a much larger luminosity than LEP, then the powerful precision measurements of the LEP program could be further improved and the quantum nature of the Standard Model probed much more rigorously (see Figure 1). These measurements provide independent information about the nature of the new physics, once the Higgs boson mass is known and its quantum corrections calculated.

In the case of the LHC, the composite nature of the proton means that not all of the energy is available to produce new particles. Furthermore, the masses of such particles that can be reached depends on their interactions (strong *vs.* electroweak, for example). Large event rates are possible for particles of mass below 1 TeV. Many detailed studies show that there is complementarity between the LHC and a linear collider of appropriate energy. In the case of Higgs bosons, a collision energy of 150 GeV above the Higgs mass optimizes the cross section for ZH production. In most models of Supersymmetry, particles such as sleptons are expected to have masses of order of a few hundred GeV. A linear collider that could operate at collision energies from a few hundred GeV to 1 TeV would make significant discoveries.

2 The Linear Collider: Accelerator and Detector

e^+e^- collisions at these high energies cannot be achieved at circular storage rings, due to excessive energy losses by synchrotron radiation. Therefore a linear accelerator is the only possibility. The e^+e^- collider is expected to cover a vast, diversified physics program spanning measurements at the Z energy with much larger event samples than those already obtained by LEP and SLC, precise determination of the mass the top quark and its couplings, and searches for new phenomena at constituent energies comparable to those explored at the LHC in proton-proton collisions. This corresponds to collision energies from 90 GeV up to about 1000 GeV, the widest kinematic range ever covered by a particle collider. The luminosity of the collider must be increased along with the energy in order to compensate for the falling cross-sections. Accelerating the beams to these energies within a manageable accelerator length - approximately 30 km - and with an acceptable power consumption - of order 200 MW -, requires accelerating cavities of high gradient and good efficiency. The generation of beams of small transverse size, their preservation during acceleration and their focusing to spots of nanometer size at the interaction region, needed to achieve the required luminosities, represent powerful challenges. For more than a decade, three accelerating technologies have been under development. Design optimization and technological validation is performed in large test facilities presently operating in several of the leading accelerator laboratories around the world. These activities aim at the proof of existence for the basic building blocks of the linac, the damping ring and the final focus systems (see Figure 3).

High frequency, room temperature copper cavities are a natural evolution of the technology successfully applied at the SLC, the only linear collider operated so far. An X-band linear collider would be able to reach 1 TeV of collision energy, with over 12000 cavities operating at 11.4 GHz for an accelerating field of $\simeq$50-60 MV/m. This approach is implemented in the NLC [5]and GLC [6] designs, jointly developed by SLAC and KEK in Japan. The X-band technology has recently reached an important validation of the last two outstanding issues to get a proof of principle.

Superconducting cavities produce improved power transfer efficiencies by accelerating particles on longer Radio Frequency (RF) pulses. Since their application at LEP, where accelerating gradients of 6 MV/m were achieved, superconducting cavities have been developed that exceed 25 MV/m. The TESLA project [3], whose R&D and design has been centered at DESY in Hamburg Germany, proposes a linear collider based on 21000 Niobum superconducting cavities, operating at 1.3 GHz and providing high luminosities and collision energies from 90 to 500 GeV, later upgradeable to 0.8-1.0 TeV. The TESLA project has demonstrated the feasibility of producing and operating cavities in a full cryomodule at the design gradient for a 500 GeV collider, thanks to results obtained at the Tesla Test Facility at DESY. A budgeted proposal based on the TESLA design was released in March 2001. Recently the German government has approved the construction of an X-ray light source that uses a 50 GeV electron linac, based on the same superconducting accelerating technology, which will provide an important initial test.

Technologies which would enable multi-TeV collisions are currently less advanced than the other technologies. The CLIC project [4] at CERN, is aiming at collision energies of 3-5 TeV at very high luminosity. This uses “two-beam” acceleration where a low energy, high intensity drive beam feeds power to the main beam achieving, in principle, gradients of order 150 MV/m at 30 GHz. CLIC still requires significant R&D to demonstrate its feasibility.

Several additional options are available to further increase the capabilities of the linear collider. As parity is not conserved in the Standard Model, interactions of electrons with left and right handed polarization are different. For example the production of W pairs in e^+e^- annihilation, which represents a background to some searches for new particles, is suppressed if the electron is right handed. Polarized electron beams were available at SLC and proved crucial in analyzing the structure of the Z boson couplings. Polarized positrons would provide a further tool analyzing the couplings of the Standard Model and new particles, and for reducing the systematic uncertainties. By backscattering a laser beam off the electron or positron beam, a photon beam, whose energy is more than 80%, of that of the electrons can be obtained. The resulting photon-photon collider could be used to produce the Higgs boson in isolation and further study its properties.

The ability of the linear collider to answer the questions on the origin of mass, new physics and the nature of dark matter depends not only on large event rates at high energies but also on the reconstruction of the produced particles with high accuracy. The detector will provide the precision in the reconstruction of each individual particle that make the linear collider a unique research facility. This accuracy must be preserved also in the presence of the beam induced backgrounds which, though lower than those at hadron colliders of comparable energy, are still significant.

Two examples will serve to demonstrate why a detector at the linear collider needs significant improvements on presently demonstrated performances. These are the Vertex Tracker and the Electromagnetic Calorimeter. Proving that the Higgs mechanism is indeed responsible for generating the masses of quarks and leptons requires measuring the Higgs boson couplings to each fermion species with high precision. Jets of particles arising from the production of the heavier bottom and charm quarks contain particles with lifetimes of order 10^{-12} seconds. By extrapolating the particle tracks back to the interaction vertex with great precision, this lifetime can be used to distinguish these jets from each other and from those arising from the lighter quarks and gluons, to determine the couplings of the Higgs bosons to these particles. Detectors at the LHC are not designed to identify charm jets and their efficiency for bottom jets is less than that needed at the linear collider. The less stringent constraints on radiation hardness than at the LHC, enable new solutions for Silicon pixel sensors to be considered for the linear collider where the aim is to improve by more than a factor of three on the best tracking precision obtained so far by the SLD experiment at SLAC.

The linear collider detector must be able to detect and precisely measure the energies of outgoing electrons, muons, as well as jets of particles, such as pions. The last represents the greatest challenge. The energies of the final-state particles span a range of approximately an order of magnitude over which precision must be maintained. At the LHC the energies of jets are measured by means of calorimeters in which all the energy is deposited and summed. In the less demanding conditions offered by the linear collider, the energy measurement can be performed by measuring separately the energies of the individual particles that make up the jets. Charged particles have their momenta measured in a large-volume tracker. Photons are measured from their energy deposition in a high-resolution electromagnetic calorimeter while neutral hadrons, such as neutrons, which represent a smaller fraction of the jet energy are measured in a hadron calorimeter. The jet energy is then obtained by adding these components. This method requires a spatial resolution of the calorimeter in excess of what is currently available, to avoid double-counting of energy deposits from charged particles whose energies have been measured, with much better resolution, in the tracker. Layers of Tungsten radiators interleaved with Silicon detecting planes are presently being studied in prototypes for the electromagnetic calorimeter. These would provide enough segmentation to match each energy deposition to its initiating particle even in the core of dense jets (see Figure 4).

Studies carried out over almost a decade in Europe, the US and Japan have established a general consensus on the detector design. This consists of a detector of size approximately 15 m in diameter and length, with a large cylindrical central tracker followed by the calorimeters inserted inside the superconducting coil, providing a $\simeq$ 3-5 T solenoidal magnetic field. A high resolution vertex tracker surrounds the beam pipe at the point of collision to precisely reconstruct the charged particle trajectories near their production vertices. Much still needs to be accomplished. In particular, the tracking detector must have as little material as possible, otherwise scattering and possible photon conversions will compromise the precision in the measurement of the vertex position and particle momentum. In contrast to the case of the LHC, where a strict preselection of events to be recorded is required in order to reduce the amount of recorded data to a manageable level, the event rate at the linear collider allows all events to be logged for later off-line analysis, ensuring sensitivity to all processes, irrespective of their experimental signatures.

3 Realizing the Linear Collider Project

In the last two years the Linear Collider has made significant steps towards its full maturity as a project to be considered for approval. The state of the different designs and the required accelerator R& D effort was summarized in a report by a panel set up by the International Committee on Future accelerators (ICFA), released in February 2003 [8]. Since then both the superconducting and warm accelerating technologies have been demonstrated to be viable candidates for a collider of initial energy of order 500 GeV, which could be extended to double this energy. The CLIC technology, with its ability to go to higher energies, is presently less mature and CERN has engaged in a significant R&D effort to address the outstanding issues.

Given its cost and complexity, the linear collider will have to be realized as a world-wide project with the host country or region bearing a substantial fraction of the cost. The ITER fusion program, which is of similar cost and complexity, is also being planned as an international project. An international linear collider steering committee was therefore formed under the auspices of ICFA in 2002. Among its members are the directors of the major high-energy-physics laboratories. It has begun the steps towards a world-wide formal project proposal and development of a model of inter-regional collaboration for its construction and operation. Remote operation of the accelerator and detectors from control centers, located world-wide is being considered, a first for a major project. The linear collider R& D has now reached the time at which a final decision on the technical feasibility of the project and an informed choice of the most advantageous technology can be taken. The particle physics community has already expressed an overwhelming support to its realization as the next large scale facility, needed to advance our understanding of nature from the quarks to the Cosmo. The linear collider potential in the future development in scientific research has been praised in recent assessment by the OECD. In its recent long-term plan, the Office of Science of the US Department of Energy has ranked the linear collider at the top of its mid-term projects.

By the end of the year, a review committee will have delivered a recommendation on the RF technology for a 500 GeV collider upgradeable to about 1 TeV. In the next few years, considerable R&D will be concentrated on the remaining accelerator issues. A budgeted project proposal, based on the designated technology, should follow the final phase of development and optimization of all the accelerator components. Surveys of potential sites for the linear collider are being conducted. These consider both the geophysical stability, over the length of the installations, the easy of access and issues such as land acquisition. R&D activities for the detector components will need to be increased during this phase. The project could then proceed towards approval, around the time when the first results from the LHC are expected, with the aim of having the first collisions by the middle of the next decade.

High energy physics is at the dawn of a new era of decisive results. These will shape our understanding of the fundamental questions on the origin of particle masses and electro-weak symmetry breaking, the nature of new phenomena beyond the Standard Model and their relations to Cosmology. The LHC is guaranteed to bring us closer to answering these questions but we already know that there will be measurements which will be limited in accuracy, while others will not be possible at all. The linear collider project will bring the accuracy which is needed to complete the picture. The synergy of the data provided by an e^+e^- collider of comparable constituent energy with that from the LHC will therefore be crucial in providing the experimental basis to answer the questions arising at the overlap of particle physics and cosmology, just as experiments at the e^+e^- LEP/SLC and at the Sp$\bar{\text{p}}$S/Tevatron were needed to bring us the current understanding of the Standard Model. If the picture provided by experiments at linear collider and at the LHC will validate the Higgs mechanism and the characteristics of new physics will match the data on dark matter emerging from satellite missions, it will be a great triumph for both particle physics and cosmology. The next few years will be crucial for turning what has been the goal of an intense world-wide development effort, for almost two decades, into a successful international facility for fundamental research.

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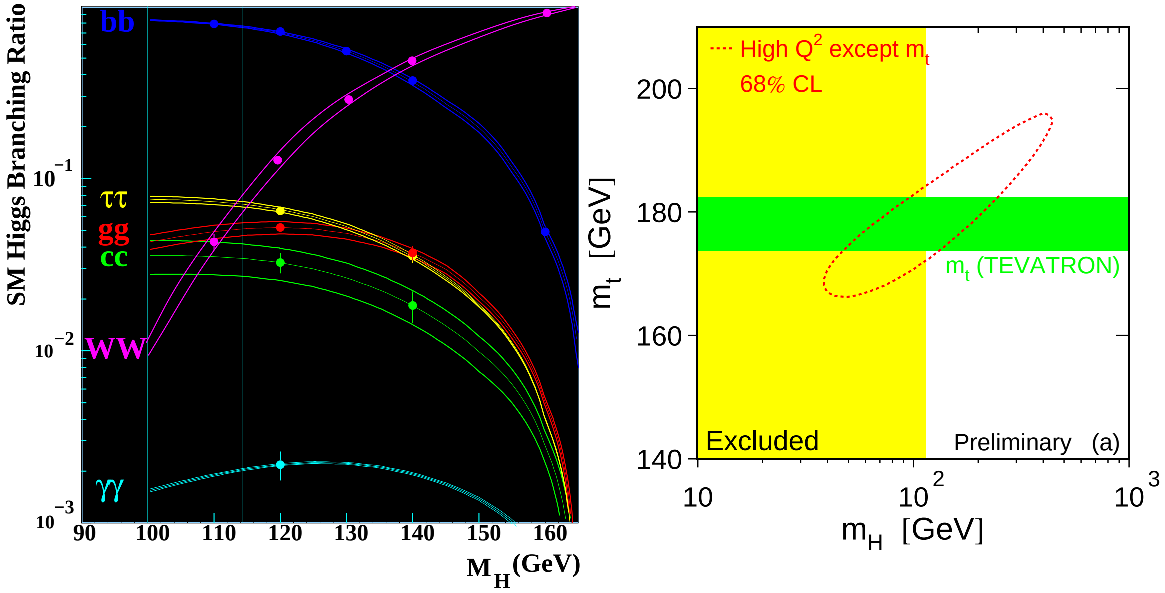

Figure 1: The Higgs boson: the left plot shows the decay branching fractions of the Standard Model Higgs boson as a function of its mass. The bands indicate the theoretical uncertainties and the points the size of the expected errors from a linear collider experiment. For masses larger than 200 GeV, the WW and ZZ final states dominate. On the right plot, the red contour shows the inferred constraint on the Higgs and top quark masses from fits to the quantities measured in lower energy experiments. The green band shows the top quark mass measurement from the production of top quarks at the Tevatron and the yellow region is excluded by direct searches for the Higgs boson at LEP. In the Standard Model, the figure strongly indicates that the Higgs boson is lighter than approximately 250 GeV.

Further Reading

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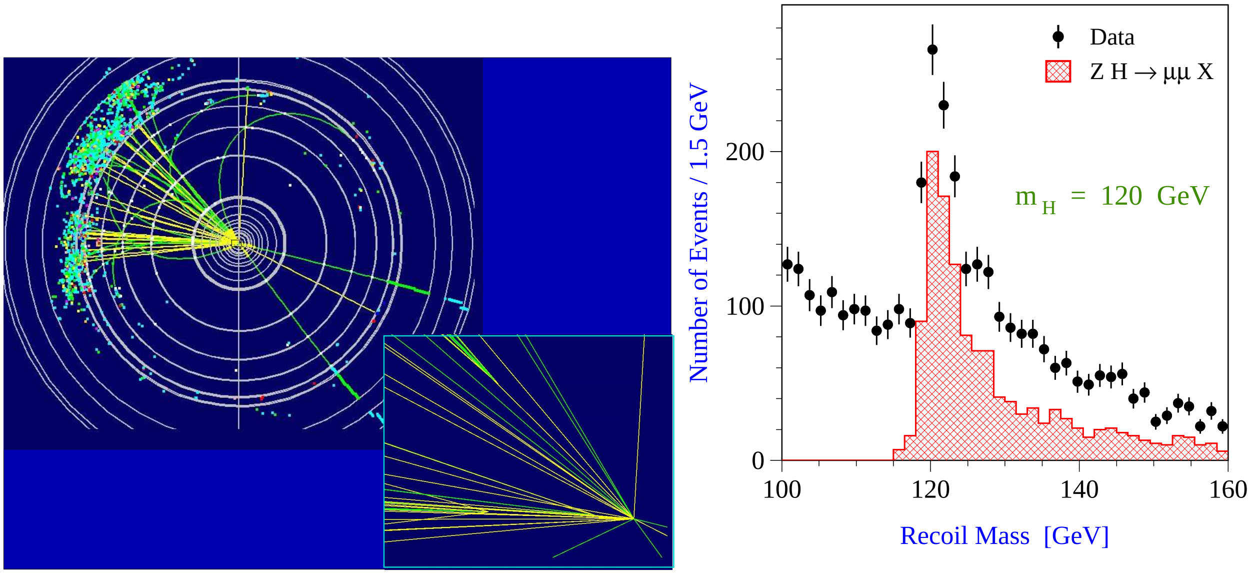

Figure 2: Detection of the Higgs boson at a Linear Collider: the left figure shows an event display from a simulated e^+e^- collision. The event is projected on a plane perpendicular to the beam, from a detector simulation of the process $e^+e^- \to HZ \to b\bar{b}\mu^+\mu^-$. The detector consists of a central tracking system inside a solenoidal magnetic field surrounded by a calorimeter and a set of muon chambers. The high momentum muons appear as stiff tracks at the lower right and penetrate through the calorimeters. The b and $\bar{b}$ quarks manifest themselves as jets of hadronic particles. The magnified view of the interaction region, clearly shows the structure of vertices originating from the cascade decays of the bottom hadrons. The right plot shows the reconstructed mass of the system recoiling against the muon pair in events of this type. The red histogram arises from the production of a Higgs boson of mass 120 GeV. The black dots include also the backgrounds and show that the signal is clearly identifiable.

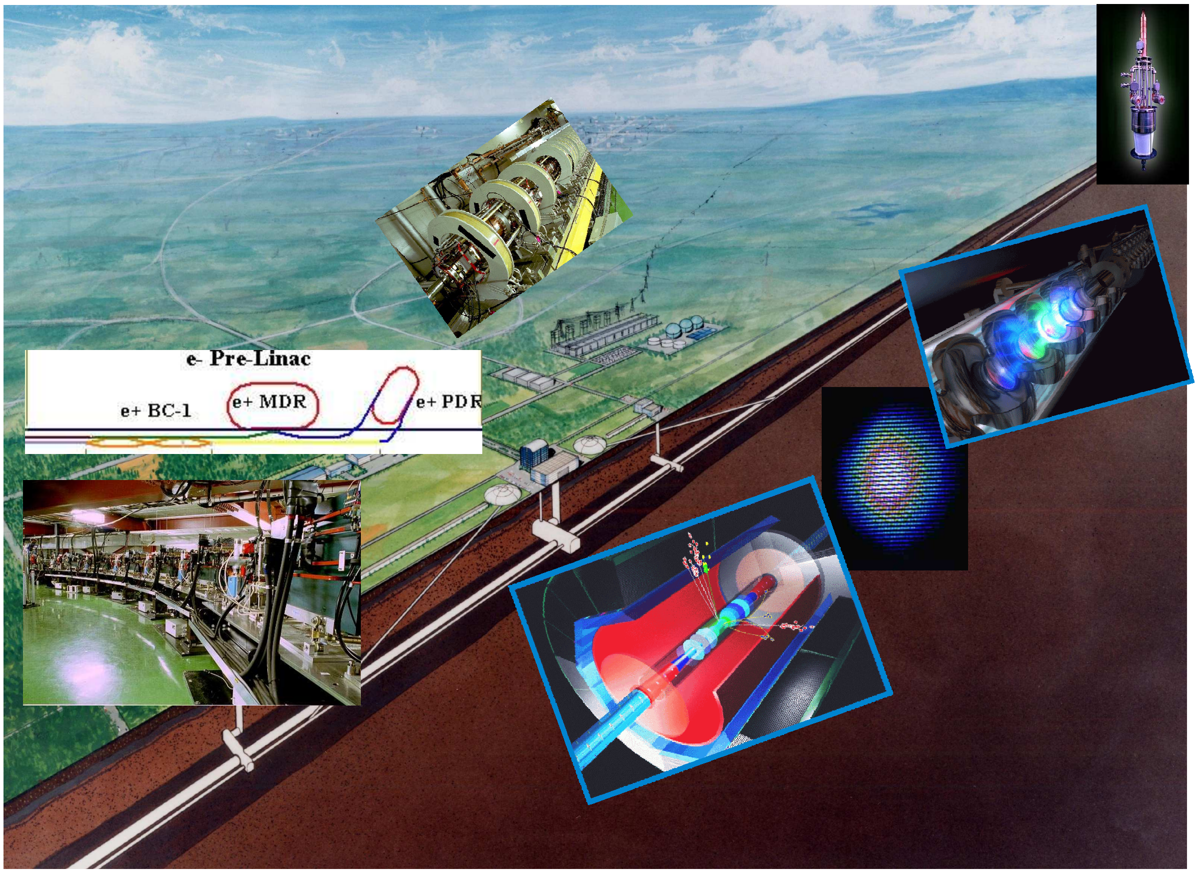

Figure 3: Schematic layout of a linear collider. The complex consists of a tunnel of approximate length 30 km. The injection complex is schematically indicated on the left and consists of a low energy source and injector (upper photograph showing prototype from KEK) and the damping ring (lower photograph of the ATF test facility at KEK) used to compress the beam. A second injector complex at the opposite end also includes a facility to produce, and collimate the positrons The main accelerator tunnel is filled with klystrons (prototype from SLAC shown in upper right corner) generating the RF to be fed into the accelerating structures (artist impression of superconducting structure from TESLA shown on the left below the klystron). Beams are accelerated up to their nominal energy of 45-500 GeV, squeezed to nanometer size (photograph of beam measured at SLAC Final Focus Test Facility) and brought into collision. Products from the collision are observed by the detector indicated by the conceptual drawing in the center of the figure.

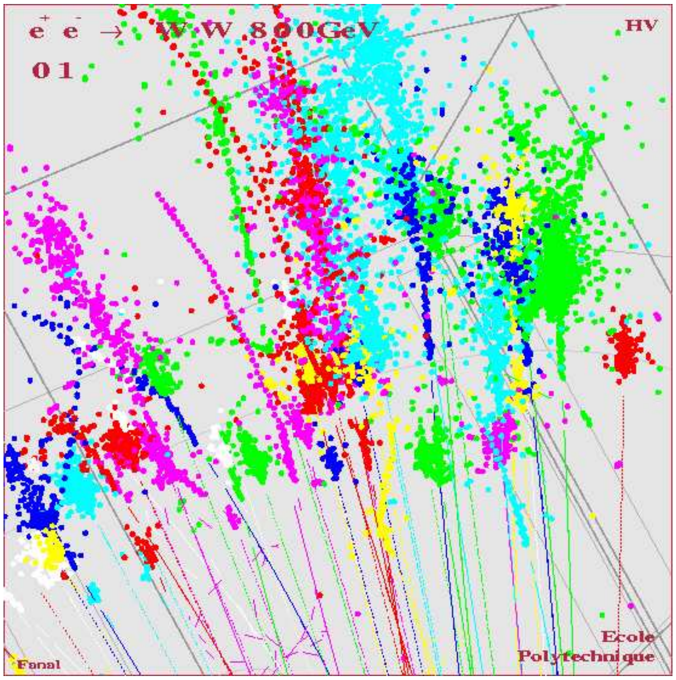

Figure 4: Display of a simulated particle jet detected in a Silicon-Tungsten calorimeter. The energy deposited by each individual particle is well distinguishable due to high segmentation of the sampling layers. A calorimeter with similar performances needs to be designed and constructed for the linear collider.

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