DESY'S FUTURE HIGH ENERGY PHYSICS PROGRAMME*

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The future accelerator related high energy physics programme of DESY is reviewed: After the successful completion of the HERAI data taking in 2000 and the upgrade of HERA and the HERA experiments in 2000–2001, the priority for DESY's high energy programme until 2006 is HERAII: $1\,\mathrm{fb}^{-1}$ of luminosity for the collider experiments H1 and ZEUS and data for HERMES and HERAb. After the completion of the HERAII programme the priority will shift to experimentation at a high energy linear e^+e^- collider.

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1. Introduction

As one of the 15 research centers of the Herrmann-von-Helmholtz Gesellschaft, DESY's mission is to conceive, develop and operate accelerators as large research infrastructure for German and international research groups. Most of the research at DESY is done by external users: DESY's own in-house research represents about 7.5% of its budget. Thus DESY is successful if the users perform excellent and highly visible research; the discussions with the users on the present and future programme — as taking place at this workshop — are essential for the planning and decision making of DESY.

DESY's scientific programme rests on 3 pillars: Accelerators, high energy particle physics and research with synchrotron radiation.

At present about 2200 scientists perform research with synchrotron radiation at DESY. The work is centered at DORIS. In addition there is an exciting, hard X-ray programme at PETRA, when it is not used as injector for HERA. First experiments are also being performed at the VUV-FEL

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(Free-Electron-Laser) of the TTF (TESLA-Test-Facility). After the demonstration of the SASE (Self Amplified Spontaneous Emission) laser principle at wavelengths below 100 nm at the TTF, it is planned to upgrade the TTF to TTFII, a user facility with photon wavelengths down to 6 nm from 2004 onwards.

In order to maintain its role as synchrotron radiation laboratory, DESY plans to transform PETRA in 2007 into a dedicated synchrotron radiation source (PETRAIII), which however will require additional funding for manpower and investments.

DESY's high energy physics research is presently centered at HERA with the four experiments H1, ZEUS, HERMES and HERAb. About 1200 physicists participate in this programme. After the upgrade of HERA and of the HERA-experiments (HERAII), DESY is dedicated to deliver until 2006 1 fb^{-1} of ep luminosity (approximately equally shared between electrons and positrons of both helicities) each to H1 and ZEUS, in addition to polarized electrons and unpolarized protons for HERMES and HERAb, respectively. In addition some beam time could be devoted to running at lower energies.

The programme beyond 2007 depends on the decision on the LC (Linear Collider) which is DESY's first priority for high energy physics beyond 2006. Any programme beyond HERAII will require additional resources. For reasons of manpower, it is at present not possible to work out new ideas, like options for PETRAIII which are compatible with a high energy physics programme and efficient synchrotron radiation research. The same holds for polarized protons or light ions in HERA. Nevertheless, the high energy physics science case is looked at by several users. By 2003 the situation on the LC and PETRAIII should be more clear. The possibility to realize a HERAIII programme will depend on the progress in the LC decision making, the quality of the science case, the strength of the community and the situation of manpower and funding.

The TESLA TDR contains in its appendix options for a scientific use of TESLA and HERA as an extension of the ongoing programme.

2. R&D on superconducting linear accelerators and free electron lasers

In 1992, shortly after the completion of HERA and the observation of the very first (and still low) luminosity by ZEUS and H1, the R&D programme towards superconducting linear accelerators has been started within the framework of the international TESLA (TeV Superconducting Linear Accelerator) collaboration hosted at DESY.

The aim was to develop the superconducting technology to the level that the construction of a linear collider (LC) in the 0.5 to 1 TeV range would become feasible. The target defined by B.H. Wiik has been an increase in accelerating gradient by a factor 5 and a reduction of the cost per meter by a factor 4. An integral part of the R&D programme has been the TESLA Test Facility (TTF) with which the long term performance of all components could be demonstrated under realistic conditions. From the beginning TESLA has been conceived as collider for high energy particle physics research and as a fourth generation photon source. The requirements for both fields have been defined by the TESLA collaboration in close contact with the world-wide user community.

The TESLA TDR (Technical Design Report), which has been published and presented in a Scientific Colloquium at Hamburg in March 2001, demonstrates that above R&D goals have been achieved. The TDR has been written by 1134 authors from 304 institutions in 36 countries. The TTF has been successfully set-up and operated at DESY with major components and manpower coming from several countries in a truly global collaboration.

In the following two recent R&D highlights from the TESLA collaboration are presented.

Fig. 1 shows a photo of a 9-cell TESLA Nb cavity. So far about hundred 9-cell cavities, six 7-cell and twenty-two 1-cell cavities have been produced. The average accelerating gradient could be steadily increased and the cavity-to-cavity spread reduced. For the last production series an average of 26 MV/m has been achieved with all cavities above 23.5 MV/m, the value required for a center-of-mass energy of 500 GeV for a 33 km long TESLA collider. In a collaboration between CERN, DESY, KEK and Saclay the electropolishing of Nb cavities has been developed. Encouraging accelerating gradients in excess of 40 MV/m at Q-values of 5×10^9 have been achieved. Recently a full 9-cell electropolished cavity has achieved 35 MV/m at 5×10^9. This corresponds to a TESLA energy of 800 GeV. The installation of cavities with gradients in excess of 35 MV/m opens the possibility to achieve

Fig. 1. Photo of a TESLA 9-cell Nb cavity.

energies between 500 to close to 800 GeV from the beginning, however at reduced luminosity (3 to 1 $\times 10^{34}$cm^{-2}s^{-1}) above 500 GeV. To achieve the full luminosity (6×10^{34}cm^{-2}s^{-1}) above 500 GeV then just requires an increase in RF-power and cooling for a second phase of TESLA.

The SASE principle (Self Amplified Spontaneous Emission) for Free-Electron-Lasers has been proposed in 1980 by Kondratenko and Saldin: The interaction between the photon field radiated by a small emittance electron beam in an undulator with the electrons can lead to a micro-bunching of the electron bunch resulting in laser type radiation. Different to undulator radiation, the radiated photon intensity is proportional to N_e^2, where $N_e \sim 10^9$ is the number of electrons per bunch. This results in an increase in photon intensity by 9 orders of magnitude. In addition the radiation is coherent and pulse lengths in the tens of femtosecond range can be reached.

With the TTF the SASE principle could be experimentally demonstrated at wavelengths around 100 nm and studied in detail. The laser radiation has been characterised in a number of experiments and the results agree with the theoretical expectations. A crucial prediction, the exponential growth of the radiation intensity along the undulator and finally saturation, has been achieved in September 2001. The results are shown in Fig. 2. These findings have paved the way to the X-ray free electron laser (XFEL) which is a part of the TESLA proposal.

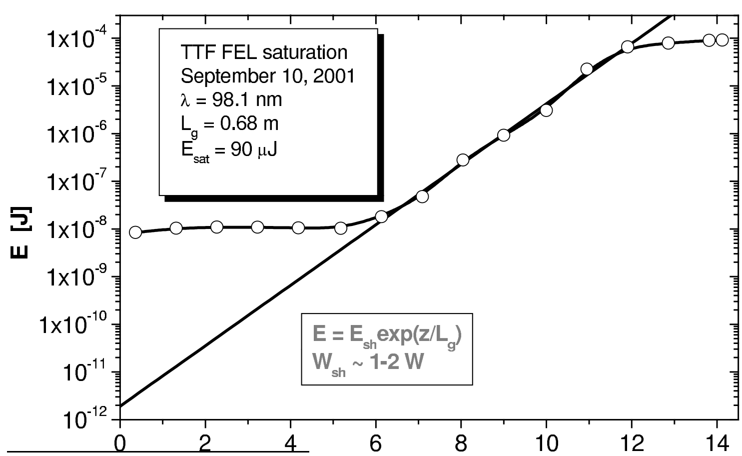

Fig. 2. Radiated power in the TTF-FEL as function of the longitudinal position in meters in the undulator.

3. High energy physics programme

Over the last year intensive discussions on the road-map of high energy physics have taken place which resulted in a world-wide consensus on the next high energy accelerator. As example the European position (ECFA/01/213) contains the following priorities for accelerator based particle physics in Europe:

- Allocation of all necessary resources to fully exploit the LHC Facility.
- Continued support for ongoing experiments.
- Realisation in as timely a fashion as possible of a world-wide collaboration to construct a high luminosity e^+e^--collider with a centre-of-mass energy exceeding 400 GeV.
- Strengthen the educational programme in accelerator physics, and increase the accelerator R&D at laboratories and universities.

DESY is fully committed to this road-map, by putting for the next years HERAII as its highest priority, by acting as crystallisation point for the superconducting TESLA collider and a focussed accelerator R&D programme in a global collaboration with universities and research laboratories.

3.1. Physics at HERAII

The physics programme of HERAII has been worked out during the HERA Workshop (1995-1996) which has defined the goals for the HERA upgrade: An increase by a factor four in luminosity to $7.5 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and polarized electrons and positrons for the two collider experiments H1 and ZEUS. To achieve this goal the interaction regions had to be completely rebuilt: Special superconding magnets had to be installed inside the detectors about 1 m from the nominal interaction point in order to achieve the required focussing of the beams. As a result the synchrotron radiation produced close to the experiments has increased by a factor of about 20 and HERA is significantly more sensitive to misalignments of the beam and of the magnetic elements.

The HERA upgrade was completed in summer 2001. In autumn 2001 a specific luminosity within 20 % of the design value has been achieved. The running-in, however, has been significantly slower than expected. At present (July 2002) HERA is able to deliver luminosity reliably. The outstanding problem is the large amount of background, which prevents the experiments H1 and ZEUS from data taking and forbids to increase the currents in HERA because of radiation damage to sensitive detector components. The

HERMES experiment, which has set-up a transversely polarized proton target, has already taken physics data. The HERAb experiment has commissioned most of its detector components and has taken high statistics p–A total cross section data for calibration and physics studies.

The HERAII physics programme of H1, ZEUS and HERMES has been discussed extensively at this workshop. I will just highlight a few topics and refer to the much more extensive contributions from other speakers.

3.1.1. QCD at HERAII

HERA will continue to make significant contributions to many aspects of QCD, like the structure of the proton and the photon, the value and the scale dependence of the strong coupling constant and QCD at high parton densities.

A major effort of H1 and ZEUS is devoted to a precision measurement of the strong coupling constant α_S and its energy dependence from the scaling violation of the structure functions and from final states. The aim is to achieve an experimental uncertainty of ± 0.001 from HERA data alone — this will require a continued close collaboration with the theoretical community.

HERA will continue to study the regime of high parton densities and diffraction at low x-values. Particular emphasis is presently put on the study of exclusive reactions like DVCS (Deeply Virtual Compton Scattering), where HERMES and the collider experiments cover center-of-mass energies from 7.5 to 350 GeV. Already the present measurements give a first access to the recent field of Skewed Parton Distributions. Given the small cross sections precise measurements require HERAII luminosities. HERMES is preparing a Recoil Detector made of silicon strip detectors, scintillating fibres, scintillator strips and a solenoid surrounding the target, to cleanly identify exclusive reactions. H1 will install the VFPS (Very Forward Proton Spectrometer) 200 m away from the interaction point in the cold region of the HERA-proton ring. This new detector will open a new quality for the high statistics study of diffraction using tagged protons.

On the topic of the unpolarized parton distribution functions (pdfs) of the proton, the increased luminosity and the availability of polarized electrons and protons will allow a precise and direct measurement of the u/d ratio in the proton at high x-values. With the additional HERAII statistics a precision "HERA-only" determination of the pdfs will become feasible.

In the field of polarized structure functions, HERMES, using a transversely polarized proton target, will measure the so far unmeasured quark transversity distributions δq.

As confirmed at this meeting with data from pp, $\gamma\gamma$ and real and virtual γp-scattering, beauty production remains a puzzle, with cross sections a factor two to twenty above the QCD predictions. The increased luminosity of HERA and the improved micro-vertex detectors will allow a precision, high statistics study of this question in photoproduction and deep inelastic scattering. HERAb will also contribute by a precise measurement of the b-production-, charmonium- (J/ψ-, ψ'-, χ-,...) and open charm-cross section in pA-interactions. These data will also provide valuable input to the understanding of charmonium suppression in nucleus–nucleus interactions.

A field, which I personally find very exciting and which in my view deserves a larger effort, is the study of QCD-instantons, which could well lead to a discovery unique to HERA.

Above incomplete list exemplifies the rich QCD programme accessible by HERAII.

3.1.2. Electro-weak physics at HERAII

So far the luminosity of HERA has been marginal for precise studies of electro-weak physics.

For the charged current (CC) reaction the present results and the expectations for $1\,\mathrm{pb}^{-1}$ of data are shown in Fig. 3. This textbook measurement,

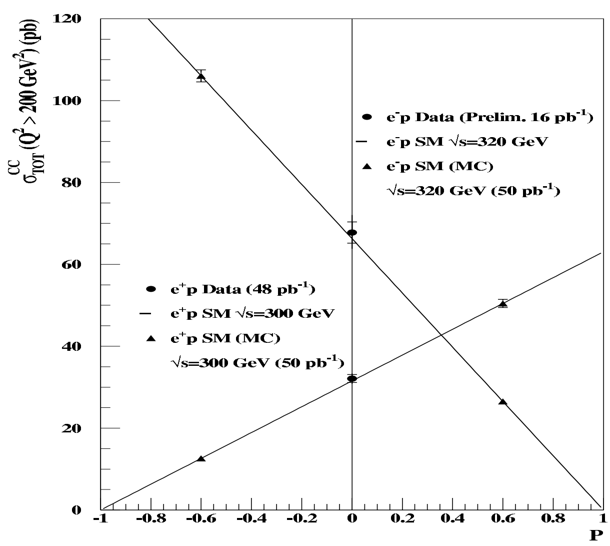

Fig. 3. Comparison of the present accuracy of the charged current cross section measurement for zero polarization and the expectation for 50 pb-1 in different charge and polarization states.

which demonstrates the V–A structure of the weak interaction in the space-like region, allows a precise determination of the W-propagator mass and sets a lower limit for a right handed W_{R} of about 400 GeV. As shown in

Fig. 4, HERA will measure the electro-weak couplings of the light quarks with an accuracy similar to the LEP measurements for the heavy quarks. For a luminosity of $250\,\mathrm{pb}^{-1}$ for electrons and positrons in two polarization states and a (too optimistic) 70 % polarization value, the uncertainty of the axial-vector coupling will be 6 % for the u- and 17 % for the d-quark. The corresponding numbers for the vector couplings are 13 % and 17 %, respectively. HERA will also allow a precise measurement of the weak mixing angle $\sin^2\theta_{\mathrm{W}}$ in a way which is complementary to LEP/SLC.

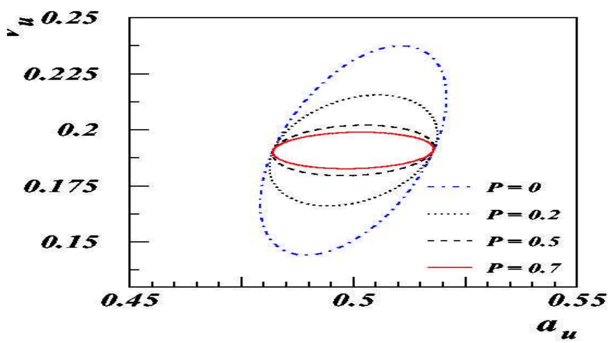

Fig. 4. Measurement accuracy of the measurement of the vector *versus* the axial vector coupling for u-quarks as function of the electron/positron polarization for a total luminosity of $1\,\mathrm{fb}^{-1}$.

Above measurements rely on precision polarimetry at the 1 % level or better. HERA has two Compton polarimeters: A transverse one close to the W-Hall, which has an upgraded data acquisition system, and a longitudinal one just downstream of the HERMES target. The latter has been upgraded with a new calorimeter. A cavity to boost the laser intensity for the longitudinal polarimeter is under preparation at Saclay. This will make a high speed bunch by bunch polarization measurement possible.

3.1.3. Physics beyond the Standard Model at HERAII

There is a limited number of physics corners where HERA has a unique sensitivity to physics beyond the Standard Model. The HERAI results and the opportunities for HERAII have been discussed in detail at this Workshop and I will just list some of them.

As electron quark collider, HERA is the ideal tool for the discovery and the study of eq-contact interactions, leptoquarks, excited electrons and neutrinos, lepton flavour violation and R_P-violating supersymmetry.

The present HERA limits on compositeness are — depending on the type of couplings — between 2 and 5.5 TeV at 95 % confidence level. Similar limits come from LEP and the TeVatron. However without an increase of center-of-mass energy the limits improve only slowly with luminosity. HERA has a unique sensitivity to leptoquarks — especially if the branching ratio to the *eq*-channel is small. This is shown in Fig. 5 where the limits for scalar *eu*- and *ed*-leptoquarks expected for HERA (for an integrated luminosity of 400 and 800 pb^{-1}) are compared to the TeVatron limits for 1.5 fb^{-1}. In the field of excited leptons HERA has no competition from the TeVatron. Already with HERAI the sensitivity achieved exceeds the LEP-results for excited lepton masses above 200 GeV. This is shown in Fig. 6 for excited electrons neutrinos.

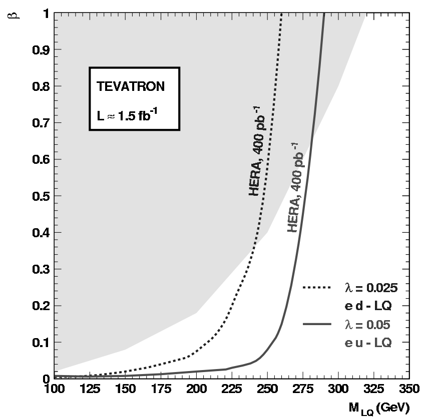

Fig. 5. Sensitivity of HERA *versus* TeVatron to *ed*- and *eu*-leptoquarks as function of the *eq*-branching ratio and the leptoquark mass.

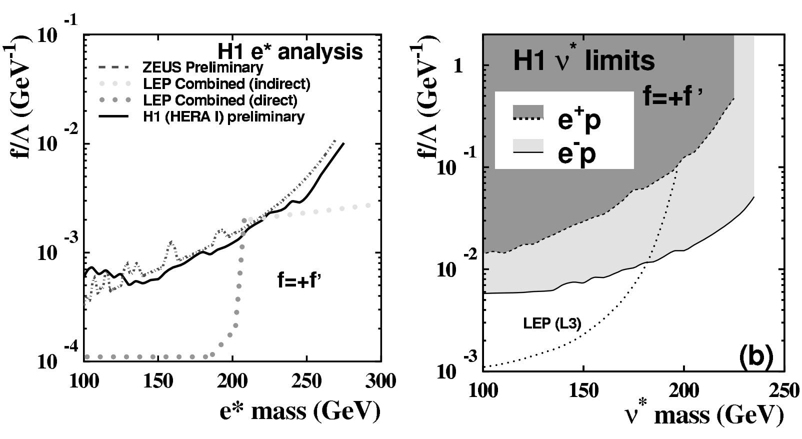

Fig. 6. Sensitivity of HERA *versus* LEP to excited electrons and neutrinos as function of coupling over energy scale *versus* excited fermion mass.

HERA also allows a sensitive search for flavour changing neutral currents (FCNC) — as example in Fig. 7 the presently achieved sensitivity for the anomalous top coupling $\kappa_{tu\gamma}$ from HERA is compared to the results from LEP and CDF. Also in the future HERA will be able to set the most stringent limits for the transition $e \rightarrow \tau$. Competition comes from the measurement of rare B-decays at B-factories.

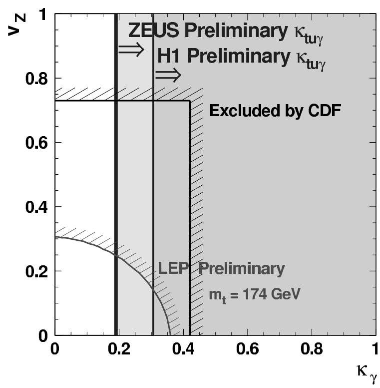

Fig. 7. Sensitivity of HERA *versus* LEP and TeVatron to flavour changing neutral currents for the coupling $tu\gamma$.

Another field where HERA will be competitive is supersymmetry with R_P-violation. As an example we compare in Fig. 8 for minimal supergravity R_P-violation the present sensitivity of HERAI with results from L3 and D0.

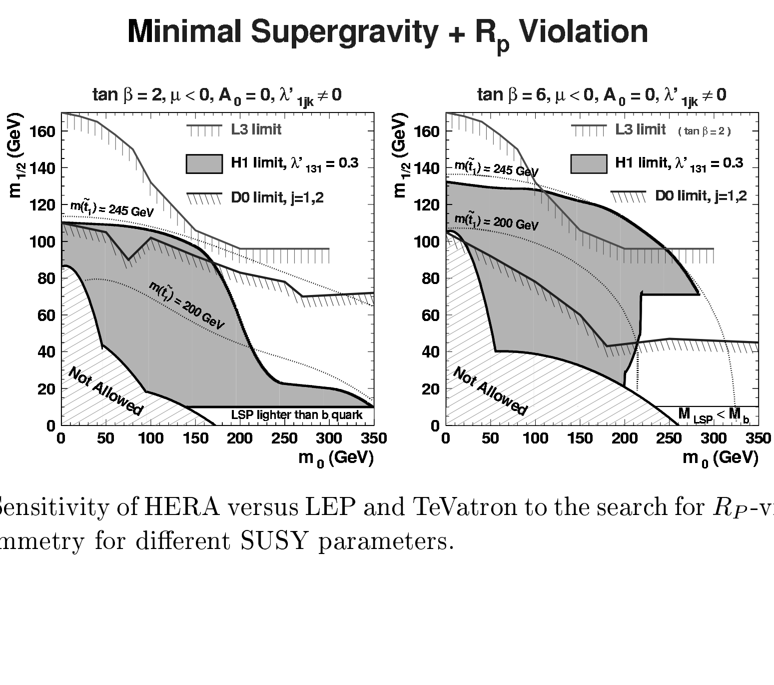

Fig. 8. Sensitivity of HERA versus LEP and TeVatron to the search for R_P-violating supersymmetry for different SUSY parameters.

Last but not least it is worth to mention the excess of events with a lepton, missing energy and large transverse hadronic energy from H1, which still awaits confirmation and explanation. At this workshop H1 showed an excess of di- and tri-electron events with masses above 100 GeV. The high luminosity of HERAII is clearly required for settling these questions.

3.2. Physics at TESLA

After the completion of HERAII physics a high energy e^+e^- linear collider (LC)is the priority of DESY's high energy physics programme. The physics and a conceptual detector design are well documented, for example in the TESLA TDR and the proceedings of the ECFA/DESY Workshops. We thus will be fairly brief here.

We start by reminding some of the events which have happened since the presentation of the TESLA TDR in April 2001 at Hamburg. First of all, there is now a world-wide consensus that a high energy e^+e^- LC overlapping in time with the running of the LHC is needed as the next high energy accelerator. It can only be built in a global collaboration.

The mandate of the ECFA/DESY Workshop has been prolonged by ECFA for another two years. The collaboration on the study of the physics questions and on the preparation of the experiments between the American, Asian, and European groups has significantly intensified by common working groups, workshops and conferences. Detector R&D programmes have been set-up both in Europe (reviewed by the DESY PRC-Physics Research Committee) and in the US (DoE).

An ICFA Technical Review Panel, headed by G.Loew, assesses the technical status, the potential to reach energies in excess of 500 GeV and the required R&D for CLIC, JLC, NLC and TESLA. The final report is expected for October 2002. An International Steering Committee (ILCSC) has been formed recently with the mandate to promote the LC within a global collaboration. One of its important tasks is to develop a coherent approach towards the national governments for the realization of a LC.

In Germany the TDR for TESLA, the superconducting electron-positron LC with an integrated X-ray laser laboratory, has been submitted to the German Science Council (Wissenschaftsrat). In a detailed report endorsed on July 12th 2002, the Wissenschaftsrat acknowledges *"the particular high gain of knowledge in fundamental questions of the micro- and macrocosmos expected from the TESLA linear collider"* and *"due to the high brilliance and time resolution of the X-ray laser a new quality of experiments expected in many fields of natural, bio-, geo- and material sciences".* The Wissenschaftsrat has asked the German Federal Government for an early, binding commitment for a German participation in a LC, once a more concrete proposal towards international financing and international collaboration has been submitted by DESY. A commitment by the German Government may be expected in 2003. In the meantime the preparations for the TESLA site in Hamburg and Schleswig-Holstein are proceeding according to plans.

3.2.1. Higgs physics

It is expected that the Higgs particle(s) will have been discovered by either the LHC or the TeVatron before the start-up of the LC. But it will need the cleanliness and precision of the latter to firmly establish the Higgs as mechanism for generating the mass of fundamental particles. This will require, besides a precision measurement of the Higgs mass and its couplings, the determination of the quantum numbers, the total width and most important the Higgs potential. It has been shown that this is possible with TESLA.

In case the branching ratios of the Higgs are completely different from expectations, Fig. 9 demonstrates that, by using the missing mass technique in the reaction $e^+e^- \to Z(\mu\mu) + H$, the Higgs mass and cross section can be precisely measured without model assumptions.

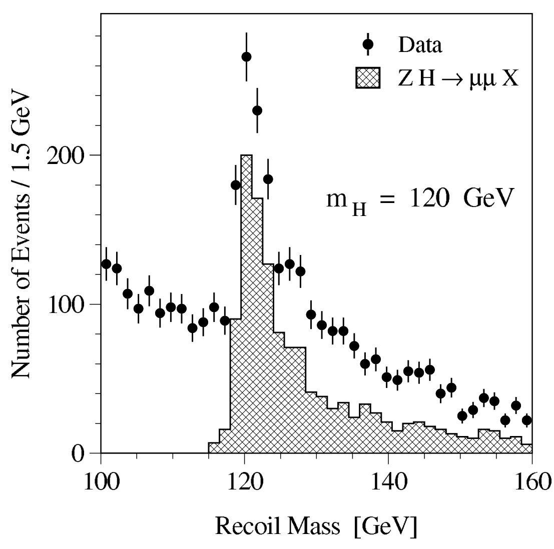

Fig. 9. Recoil mass spectrum for the reaction $e^+e^- \to Z(\mu\mu)+$ H at $\sqrt{s} = 350$ GeV for a luminosity of $500\,\mathrm{fb}^{-1}$.

3.2.2. Supersymmetry

It is generally agreed that supersymmetry (SUSY) is the best motivated extension of the Standard Model. A high energy LC is the ideal tool to study the question how SUSY is broken and how its breaking is communicated to particles. For SUSY particles in the accessible energy range a LC allows to measure the masses with an accuracy of $\sim 10^{-3}$, determine the production cross sections and spin-parity and extract the basic SUSY parameters like gaugino-, higgsino-, scaler masses and the mixing- and coupling-parameters. Fig. 10 shows the importance of precision measurements to understand the origin of the SUSY breaking by extrapolation to high energies.

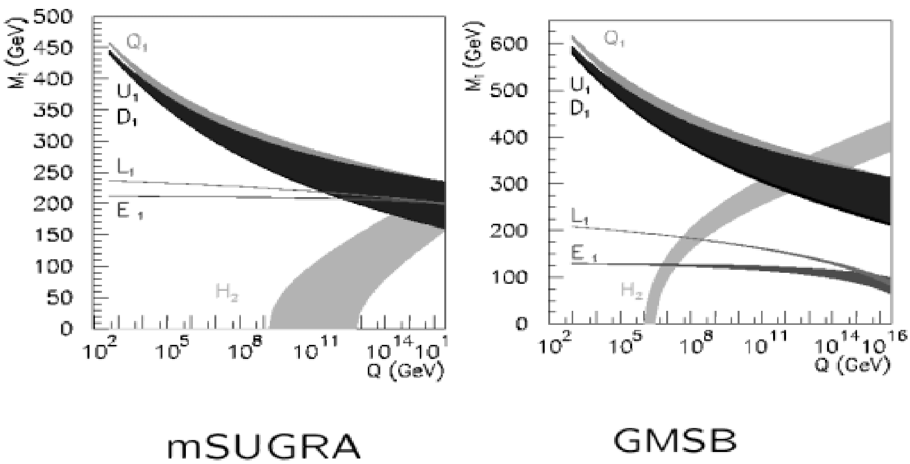

Fig. 10. Evolution of the precision measurements at a linear collider to the GUT scale.

3.2.3. Physics beyond the Standard Model and GIGA-Z

There are many ways in which physics beyond the Standard Model will be probed at a high energy e^+e^- LC. As illustration, the triple gauge couplings $WW\gamma$ and WWZ can be determined to an accuracy of a few 10^{-4} in single W and W-pair production. The precision of the anomalous couplings $\Delta\kappa_\gamma$ and $\Delta\lambda_\gamma$ achievable at the TeVatron, LHC and a LC at 500 and 800 GeV are compared in Fig. 11.

Another way to explore the consistency of the Standard Model and thus search for deviations, is to run TESLA at the Z-pole (GIGA-Z) which extends the precision measurements of the SLC and LEP at the Z-Pole by an increase in statistics by two orders of magnitude. As an example, the experimental uncertainty of the value of the effective weak mixing angle $\sin^2\theta_{\rm eff}$ from the measurement of the asymmetry $A_{\rm LR}$ can reduced to 0.000 013, an order of magnitude lower than presently achieved with the data from LEP, SLC and the TeVatron. To illustrate how measurements at GIGA-Z will improve the accuracy of the consistency check of the Standard Model, Fig. 12 shows the χ^2 of the electro-weak fit versus the Higgs mass for the present data and the expectations from GIGA-Z. The increase in sensitivity is truly impressive.

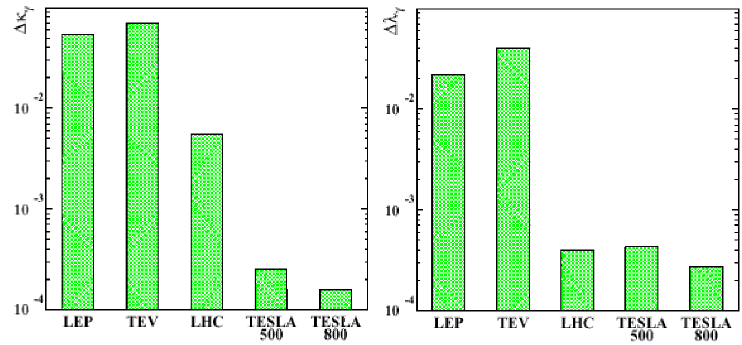

Fig. 11. Accuracy with which the anomalous triple gauge couplings for $WW\gamma$ can be measured at different colliders.

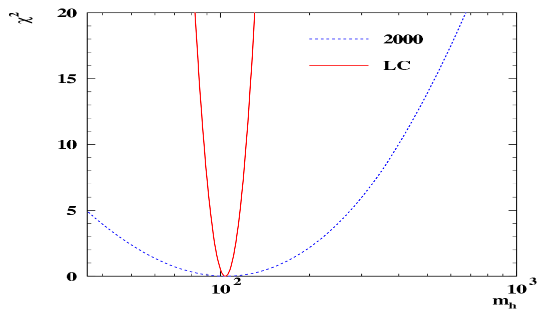

Fig. 12. Comparison of the χ^2-sensitivity of the electroweak fits to the consistency of the Standard Model at LEP and GIGA-Z ($100\times$ luminosity).

4. Conclusions

With HERAII, one of two high energy accelerators in operation until the start up of the LHC, DESY has a rich particle physics programme in QCD, electro-weak physics and physics beyond the Standard Model. Beyond HERAII DESY intends to play a leading role in a high energy e^+e^- linear collider, preferentially TESLA at Hamburg.