PHYSICS AT LARGE p_{T}^2 AND Q^2: SUMMARY*

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We summarize the results presented in the "Physics at large p_{T}^2 and Q^2" working group at the DIS'2002 Workshop. Higgs searches, precision measurements as well as searches for physics beyond the Standard Model at current and future experiments are reviewed.

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1. Introduction

Over the past three decades the Standard Model (SM) of particle physics has been surprisingly successful. Although the precision of the experimental tests improved by orders of magnitude no significant deviation from the SM predictions has been observed besides the compelling evidence for non-zero neutrino masses. Still, there are many questions which the Standard Model does not answer and problems it can not solve. Among the most important

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ones are the origin of the electro-weak symmetry breaking, hierarchy of scales, unification of fundamental forces and the nature of gravity. Precise measurements of physics at highest p_{T}^2 and Q^2 values should finally help us to solve the puzzles of the Standard Model. The discovery of the Higgs particle and the measurement of its properties is the most important challenge of future experiments. However, the signs of "new physics" can be also looked for in many other channels.

In this paper we will report on the status of the experimental Standard Model tests, including searches for top physics and searches for the SM Higgs boson. Searches for supersymmetry, low-scale gravity, leptoquarks and other new phenomena beyond the Standard Model, are reviewed. Finally, the prospects for discovering "new physics" at existing and future colliders are discussed.

2. Precision tests of the Standard Model

Over the last decade the electro-weak physics has entered the era of precision measurements, resulting in experimental accuracies better than the per mille level [1]: examples are the W-boson mass, measured at LEP and the TeVatron, and the effective weak mixing angle at the Z resonance, measured by SLD and at LEP.

The comparison of electro-weak precision measurements with accurate theory predictions allows to test the electro-weak theory at the quantum level, where all parameters of the model enter. In this way it has been possible to obtain indirect constraints on the top-quark mass prior to the top-quark discovery, which turned out to be in remarkable agreement with the direct observation carried out at the TeVatron. With the knowledge of the top-quark mass and further improved experimental and theoretical precisions, it is now possible to obtain constraints on the Higgs boson mass within the Standard Model, which enters the precision observables in leading order only logarithmically in contrast to the quadratic dependence on the top quark mass.

As an example for the comparison between theory and experiment, Fig. 1 shows the currently most accurate prediction for the W-boson mass within the Standard Model [2], derived from the prediction for muon decay, in comparison with the current experimental value for M_W and the experimental exclusion limit on the Higgs boson mass, $M_H > 114.4\,\mathrm{GeV}$ at 95% C.L. The theory uncertainty is dominated by the experimental error of the top-quark mass, which enters the theory prediction as input parameter, while the present uncertainty from unknown higher-order corrections is smaller by about a factor 5 [2]. The figure clearly shows the preference for a light Higgs boson within the Standard Model; at the 1σ level there is no overlap between the allowed regions of experimental result and theory prediction for $M_H > 114.4\,\mathrm{GeV}$.

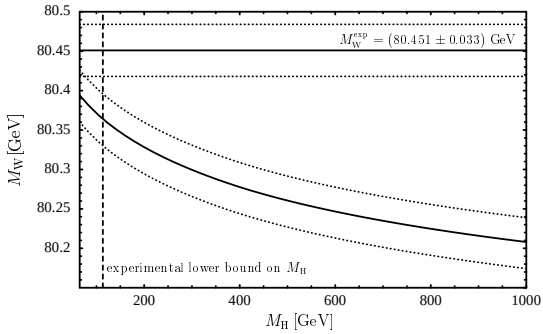

Fig. 1. Comparison of the theory prediction for M_W as function of the Higgs boson mass with the current experimental value. The experimental exclusion limit on the Higgs boson mass is also indicated (from Ref. [2]).

Fig. 2 displays the experimental values from LEP and the TeVatron and the world average obtained from combining these two measurements, as well as indirect predictions from a Standard Model fit to the LEP1+SLD data and the LEP1+SLD data supplemented by the m_t measurement. Furthermore, shown is the prediction within the Standard Model corresponding to the measurement from the NuTeV collaboration, which has recently published its final result on the ratio of neutral current to charged current reactions in neutrino–nucleon scattering. This measurement, when interpreted as a measurement of the mass of the W boson, shows an interesting deviation, at the level of three standard deviations, from the direct measurement. The NuTeV experiment has extracted the electro-weak parameter, $\sin^2\theta_W$, from the high precision measurement of the ratio of neutral-current to charged-current cross sections in deep-inelastic neutrino and anti-neutrino scattering off a steel target. Their measurement, $\sin^2\theta_W^{\mathrm{on-shell}} = 0.2277 \pm 00013(\mathrm{stat}) \pm 0.0009(\mathrm{syst})$, is 3σ above the Standard Model prediction.

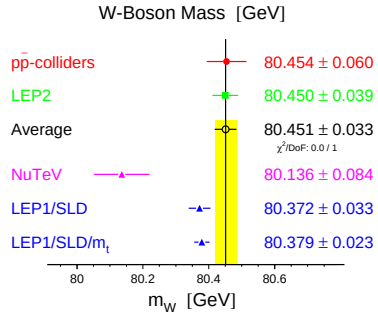

Fig. 2. The world average of the direct m_W measurements from $p\bar{p}$ colliders and LEP2. Also shown are indirect m_W determinations within the Standard Model by NuTeV, LEP1+SLD and LEP1+SLD with m_t measurement.

The plausibility of the hypothesis that this discrepancy is due to unaccounted QCD effects, especially a strange and anti-strange sea asymmetry has been evaluated by taking into account results from NuTeV, CCFR, and charged-lepton deep-inelastic cross section measurements. The NuTeV collaboration does not find support for this hypothesis [3].

The current result of the global fit to all data in the Standard Model is shown in Fig. 3, where the $\Delta\chi^2$ curve is given as a function of the Higgs boson mass. The blue band indicates the theory uncertainty from unknown higher-order corrections. The preferred value for the Higgs boson mass within the Standard Model, corresponding to the minimum of the curve, is around 81 GeV, while the 95% C.L. upper limit (one-sided, corresponding to $\Delta\chi^2 = 2.7$) obtained from the fit is about 193 GeV. It should be noted that the result for the Higgs boson mass from the fit is strongly correlated to the value of m_t. Changing m_t by 5 GeV, corresponding to the present 1σ error, gives rise to a shift in the upper bound for M_H of about 35%.

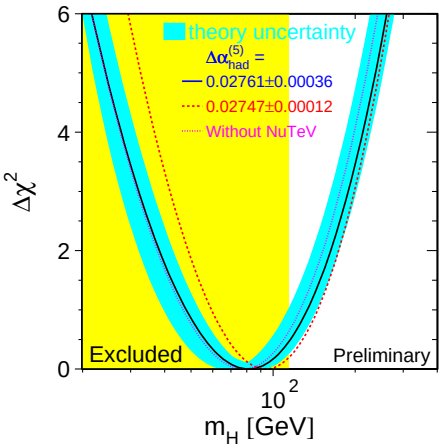

Fig. 3. Indirect Higgs mass constraints from a global fit to all data in the SM.

In the above fit results it has been assumed that the Standard Model provides the correct description of the data. A measure of how well the Standard Model describes the data is given by the fit probability. This probability is presently only 1.3%. It should be noted that the preference for a light Higgs boson within the Standard Model is not induced by those observables which significantly deviate from the Standard Model prediction. Omitting the NuTeV measurement from the fit leads to almost unchanged results for the fitted parameters, while the fit probability is improved to 11.4%. Enlarging the errors of different measurements entering the effective weak mixing angle at the Z resonance in order to take into account their spread by almost 3σ leads to a further significantly improved fit probability and a more pronounced tendency towards a light Higgs boson.

QCD is in a very good shape within the framework of the SM. Jet production has been measured at HERA for $0 < Q^2 < 10^4\,\mathrm{GeV}^2$ and $4 < E_T < 100\,\mathrm{GeV}$ [4] The jet data have then been used at HERA-I to test QCD and make precise measurements of the gluons and α_s. The detector and theory systematic errors have been well understood showing that jet measurements can be made to better than 10% level if the E_T is high enough (high Q^2 is needed also). Low Q^2 regime is rich but require more precise theoretical calculations. HERA II will start soon, and one can expect a large increase of the high E_T high Q^2 samples which will enable to measure the proton PDFs at higher x, measure α_s with better precision, BFKL and of course search for new physics.

The TeVatron hadron collider provides as well a unique opportunity to study QCD at the highest energies [5]. The results on jet production are used extensively to derive new parton distribution functions and photon data are used to discriminate between different approaches for understanding their disagreement of the theory with data relative to photon production at small transverse momentum, Fig. 4.

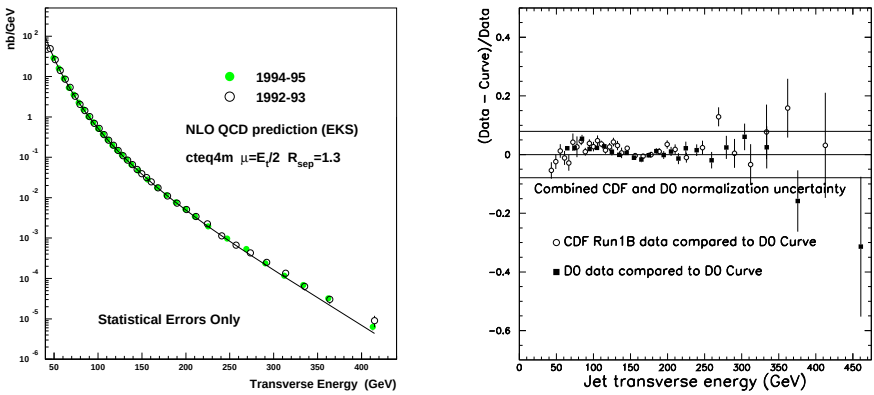

Fig. 4. Left: CDF inclusive jet cross section from Run1B data (1994–1995) compared to QCD prediction and to the published Run1A results. Right: Comparison of CDF and D0 data to D0 smooth curve.

3. Top physics

The top quark was predicted in the Standard Model of electro-weak interactions as a partner of the b-quark in a SU(2) doublet of the weak isospin, in the third family of quarks [6]. The top quark was observed at the TeVatron by the CDF and D0 collaboration during the Run I data taking (1992–1996). The CDF and D0 top mass averages, obtained from measurements in several channels and based upon $100\,\mathrm{pb}^{-1}$ of data from $p\bar{p}$ collisions at $\sqrt{s} = 1.8\,\mathrm{TeV}$

collected by each experiment in Run I. The combined TeVatron measurement of the top quark mass is $M_{\rm top} = 174.3 \pm 3.2$ (stat)± 4.0 (sys) GeV/c^2. The CDF measurement of the $t\bar{t}$ cross section (assuming $M_{\rm top} = 175\,{\rm GeV}/c^2$) is $\sigma_{t\bar{t}} = 6.5^{+1.6}_{-1.4}$ pb and the D0 value (assuming $M_{\rm top} = 172.1\,{\rm GeV}/c^2$) is $\sigma_{t\bar{t}} = 5.9 \pm 1.7$ pb.

All mass measurement techniques assume that each selected event contains a pair of massive objects of the same mass (top and anti-top quarks) which subsequently decay as predicted in the SM. A variety of fitting techniques use information about the event kinematics. A one-to-one mapping between the observed leptons and jets and the fitted partons is assumed [6]. Of course, it is assumed that the selected sample of events contains just the $t\bar{t}$ events and the SM background. This is the simplest and the most natural hypothesis since top quark is expected in the SM. On the other hand, the samples of $t\bar{t}$ and single top candidates are among the best places to look for new physics. Because of the top quark mass being large, event selection cuts in top analyses are practically identical to those applied in many analyses looking for physics beyond the SM (Supersymmetry, Technicolor, Leptoquarks, *etc*). Both CDF and D0 made numerous comparisons between various distributions of the reconstructed top quarks, and especially those of the $t\bar{t}$-system, with the SM predictions. No significant disagreements were found.

The increased integrated luminosity expected at the TeVatron Run II (about a factor of 20 in respect to Run I), combined with improvements to CDF and D0 detectors and larger $t\bar{t}$ cross section, will allow the experiments to collect a number of reconstructed top events 20–70 times larger than in Run I, depending on the final state and tagging requirements. The systematic effects will dominate uncertainties in the measurements of σ_{tt} and m_t. Both experiments estimate that the error on m_t will reach $\Delta M_{\rm top}$= 2–3 GeV/c^2 (compared with 7 GeV/c^2 in Run I). The $t\bar{t}$ cross section should be measured with an error of about 8% (about 30% in Run I). Analysis of single top production offers a direct access to the Wtb vertex and should allow the measurement of the $|V_{tb}|$ element of Cabibbo–Kobayashi–Maskawa matrix. Anomalous couplings would lead to anomalous angular distributions and larger production rates. The expected SM cross sections are of the order of 1–2 pb. Of course the increased statistics will allow the TeVatron experiments to finally test the underlying hypothesis that the top candidate events are just the $t\bar{t}$ events and not events from new physics [7].

4. The quest for the Higgs boson

The Higgs mechanism is one of the basic ingredients of the SM theory of fundamental interactions, allowing the introduction of masses for the observed particles, without violating the local gauge invariance. Still the Higgs

boson is probably the most elusive particle to be found. Within the SM a single neutral scalar is predicted, whose mass is an arbitrary parameter, although unitarity of the model imposes an upper limit of about 1 TeV. Precision electro-weak measurement indicate that the mass of the Standard Model Higgs boson should be around 81 GeV/c^2 and the 95%CL upper limit is set at 193 GeV/c^2. The Higgs boson has still to be found. It has been searched for extensively at LEP. In particular, in the years 1998–2000 the four LEP collaborations have collected 2465 pb of data from e^+e^- collisions at $\sqrt{s}$ between 189 and 209 GeV. The SM Higgs boson is produced via Higgs-strahlung or vector boson fusion and decays mainly into $b\bar{b}$. The searches at LEP are based on the following topologies: fully hadronic decay ($H \to b\bar{b}Z \to q\bar{q}$), decay of the Z into $\nu\bar{\nu}$ and decays of the Z into $l\bar{l}$ or $\tau\bar{\tau}$. The fully hadronic channel has the largest cross section and the possibility of detection is dominated by the b-tagging capabilities of the detectors.

The Higgs search at the highest c.m. energies at LEP resulted in an excess of signal-like events above the background expectations with a statistical significance of about 1.7σ, compatible with the production of a Standard Model Higgs of about $M_H = 116$ GeV. The exclusion bound on the Standard Model Higgs obtained by combining all LEP data is $M_H > 114.4$ GeV at 95% C.L. [8].

The quest for Higgs will now move to the TeVatron, where a new data taking phase started in March 2001 (Run II) [9] At the TeVatron Run II the $gg \to H$ production mode dominates over all mass ranges, but the huge irreducible QCD background makes it impossible to use this production channel for a measurement. So, for low Higgs mass ($M_H < 130$ GeV/c^2) the associated production with a vector boson (W or Z) and the subsequent decay into $b\bar{b}$ is the most promising channel, with an estimated cross section production of order 0.1 pb. The double b-tagging of the 2 jets coming from the Higgs decay, together with the signature of the additional boson helps to discriminate from the background. From the trigger point of view, channels with one high p_T lepton coming from the vector boson decay are not a concern, since the rate can be easily controlled. On the other hand channel where the vector boson decays into quarks (W/Z) or neutrinos (Z) have an higher branching ratios and trigger strategies need to be devised to control data taking rates. It has been shown in preliminary studies [10] that a trigger strategy based on the use of SVT tracks is crucial in selecting a sample enriched in heavy flavors, keeping the rate at a reasonable level. Improved offline b-tagging efficiency (a factor 1.3 is already achieved only due to the increased geometrical coverage of the silicon detector) will then help in discriminating signal from background.

In Fig. 5 the expected discovery reach in Run II for the Standard Model Higgs boson from the study carried out during the Run II workshop at Fermilab [11]. Based on a simple detector simulation, the integrated luminosity necessary to discover the SM Higgs in the mass range 100–190 GeV was estimated. The first phase of the Run II Higgs search, with a total integrated luminosity of 2 fb^{-1} per detector, will provide a 95% C.L. exclusion sensitivity comparable to the one obtained at LEP. With 10 fb^{-1} per detector, this exclusion will extend up to Higgs masses of 180 GeV, and a tantalizing 3 sigma effect will be visible if the Higgs mass lies below 125 GeV. With 25 fb^{-1} of integrated luminosity per detector, evidence for SM Higgs production at the 3 sigma level is possible for Higgs masses up to 180 GeV. However, the discovery reach is much less impressive for achieving a 5 sigma Higgs boson signal. Even with 30 fb^{-1} per detector, only Higgs bosons with masses up to about 130 GeV can be detected with 5 sigma significance.

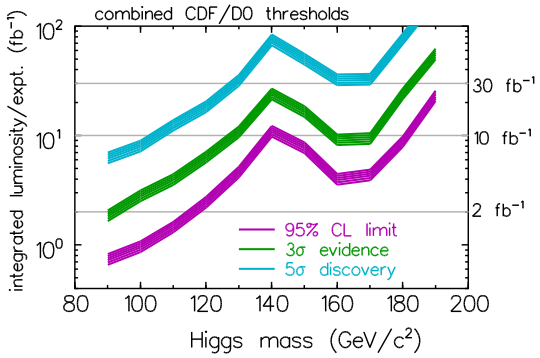

Fig. 5. Projected discovery/exclusion regions for SM Higgs as function of luminosity at Run II.

5. Beyond the Standard Model

Although the Standard Model is remarkably successful in describing all experimental results, there are theoretical arguments to believe that it is only a low-energy effective theory. Searches for "new physics", which could reveal the true fundamental theory of particles and interactions are among most interesting subjects in present and future colliders. Large variety of results was presented at this conference.

5.1. SUSY

Supersymmetry (SUSY) is believed to be the best motivated candidate for a theory beyond the Standard Model. It solves the hierarchy problem and provides a framework for consistent gauge unification [12]. Supersymmetry

predicts that for each fermion and gauge boson of the SM a supersymmetric partner with spin different by 1/2 unit exists. This opens a wide field for discoveries at present and future colliders.

The Minimal Supersymmetric extension of the Standard Model (MSSM) requires two Higgs doublets, giving rise to five physical Higgs bosons, h, H, A, $H^{\pm}$. In contrast to the Standard Model, the mass of the lightest CP-even Higgs boson in the MSSM is not a free parameter, but can be predicted within the model. This leads to the tree-level upper bound of $m_h < m_Z$, which however is affected by large radiative corrections. Taking into account corrections up to the two-loop level, an upper bound of about $m_h < 135\,\text{GeV}$ can be established [2]. This bound is valid for $m_t = 175\,\text{GeV}$ and is shifted upwards by about 5 GeV if m_t is shifted by $+5\,\text{GeV}$. The exclusion limits obtained from the Higgs search at LEP are shown in the plane of m_h and $\tan\beta$, the ratio of the vacuum expectation values of the two Higgs doublets, for two MSSM benchmark scenarios [2] in Fig. 6 [13]. Note that in these benchmark scenarios $m_t = 174.3\,\text{GeV}$ is used. A shift in m_t would significantly affect the upper bound on m_h as function of $\tan\beta$ (the "theoretically inaccessible" region for high m_h values in the plots). The Higgs searches at the TeVatron can probe a significant part of the MSSM parameter space. In fact, the discovery of a Higgs boson with non-SM couplings could be a first sign of supersymmetry. While the upper bound on m_h can be somewhat relaxed in non-minimal SUSY models (up to about 200 GeV), the prediction of a light Higgs boson is generic to all SUSY models which stay in the perturbative regime up to the GUT scale.

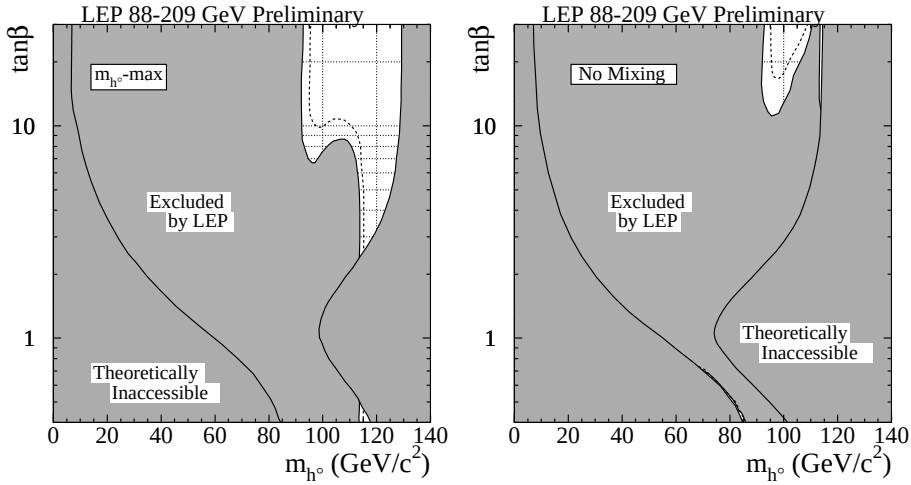

Fig. 6. LEP exclusion limits in $(m_h, \tan\beta)$ plane for the $m_h^{\max}$ (left plot) and the no-stop-mixing (right plot) MSSM benchmark scenario [14].

LEP covered most of the MSSM parameter space, but the Higgs boson was not found.

LEP searches for other supersymmetric particles have shown no evidence for a signal. Therefore exclusion bounds under certain model assumptions can be derived and *e.g.* stop, selectron and chargino masses are excluded up to 96, 99.4 and 103.5 GeV, respectively [15]. The lower 95% C.L. limit on the neutralino LSP mass is about 45 GeV. The LEP squark mass limits are compared with new CDF squark and gluino search results in Fig. 7 (left). New analysis of CDF data exclude gluino masses below about 180 GeV [16]. Complementary results are obtained by LEP and TeVatron as for the search for stop decaying to sneutrino ($\tilde{t} \to bl\tilde{\nu}$), as shown in Fig. 7 (right). Stop masses up to about 140 GeV are excluded by CDF under this assumption, whereas LEP experiments give limits for models with low stop-sneutrino mass difference.

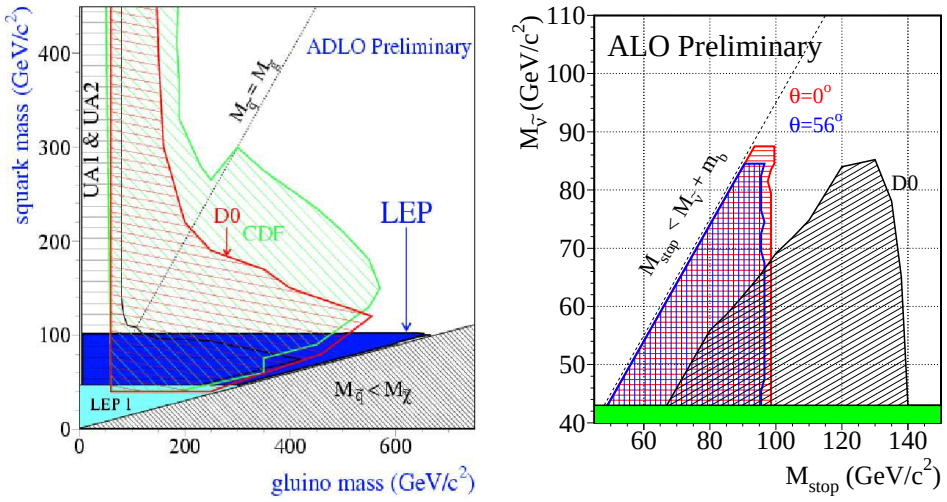

Fig. 7. Comparison of gluino and squark mass limits (left) and stop and sneutrino mass limits (right) from TeVatron and LEP.

In the SUSY models with R_P-violation resonant squark production is possible at HERA. Both HERA collaborations searched for squark production and investigated different possible decay channels [17]. Resulting limits on the R_P-violating coupling λ'_{1j1} as a function of the squark mass are shown in Fig. 8. For coupling of electro-magnetic strength (λ'_{1j1}=0.3) squark masses up to 260 GeV are ruled out.

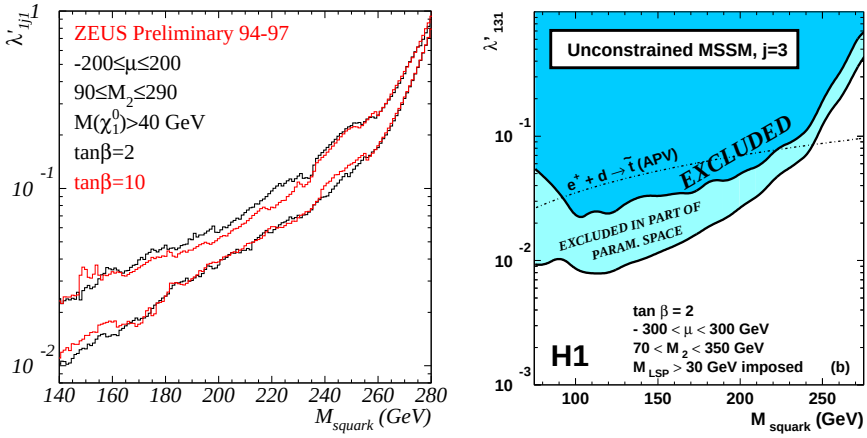

Fig. 8. ZEUS and H1 limits on the coupling λ'_{1j1} as a function of the squark mass in the R_P-violating SUSY. Coupling values above the upper curve are excluded on 95% CL for all values of μ and M_2, whereas those above lower line are excluded only in the part of parameter space.

5.2. Large extra dimensions

Another possibility of solving the hierarchy problem of the Standard Model has been proposed recently. The problem is avoided if additional compactified spacial dimensions are introduced. If the extra dimensions are large the effective Planck scale M_S can be in the TeV range [18].

The propagation of graviton in extra dimensions n can lead to effects observable at high energy colliders. The signature for real graviton production is single vector boson or monojet with large transverse momentum and large missing transverse momentum due to escaping graviton. For $n = 2$ limits on M_S between 1 and 1.4 TeV are set by LEP experiments from search for $e^+e^- \to \gamma G$ events [19]. For $n \geq 5$ best limits on M_S of the order of 600–650 GeV (slowly decreasing with n) are obtained from monojet events at the TeVatron [20].

Virtual graviton exchange could also contribute to fermion-pair and boson-pair production at LEP and TeVatron, as well as to NC DIS at HERA. Fig. 9 (left) shows the cross section for Bhabha scattering $e^+e^- \to e^+e^-$ measured by L3, compared with the SM predictions and predictions of the ADD (Arkani–Hamed, Dimopoulos, Dvali) model [21]. From analysis of e^+e^- and $\gamma\gamma$ events combined LEP limit on M_S is 1.13 (1.39) TeV, for positive (negative) coupling [19]. Similar analysis of e^+e^- and $\gamma\gamma$ events at the TeVatron resulted in the 95% CL limit on M_S of 1.1 (1.0) TeV [20]. A combined analysis of the e^+p and e^-p data at HERA resulted in M_S limits of about 0.8 TeV from H1 and ZEUS. H1 e^-p data compared with 95% exclusion limits for M_S is shown in Fig. 9 (right).

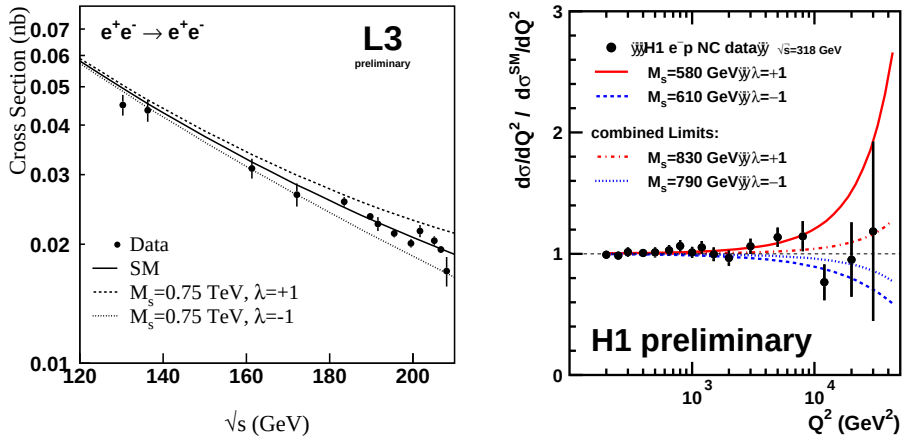

Fig. 9. Left: comparison of the Bhabha cross section measured at L3 for $\sqrt{s} =$ 130–209 GeV with SM predictions and predictions of the ADD model. Right: H1 e^-p data compared with 95% exclusion limits for the effective Planck mass scale in models with large extra dimensions.

5.3. Leptoquarks

The striking symmetry between quarks and leptons suggests that there could exist a more fundamental relation between them. Such lepton–quark "unification" is achieved for example in different theories of grand unification and in compositeness models. Quark–lepton bound states, called leptoquarks, carry both color and fractional electric charge and a lepton number. A general classification of leptoquark states used in many analyses has been proposed by [25], where 7 scalar and 7 vector leptoquarks are considered.

At HERA leptoquarks could be resonantly produced via fusion of the incoming lepton (electron or positron) and a quark (or antiquark) from the proton, with subsequent decay into $e^{\pm}$-quark or $\nu(\bar{\nu})$-quark. For large leptoquark masses, $m_{\mathrm{LQ}} > \sqrt{s}$ the u-channel leptoquark exchange and the interference with SM processes become important. Both experiments H1 and ZEUS see no evidence for a resonant LQ production or cross section deviations due to high mass LQ exchange [26]. Fig. 10 compares the H1 and ZEUS results for two scalar leptoquarks with results from LEP and TeVatron. The combined analysis of CDF and D0 data exclude scalar leptoquark masses below 242 GeV, for leptoquarks decaying to electron–quark only ($\beta = 1$) [20]. This limit is based on leptoquark pair-production in strong interactions and is independent on the leptoquark Yukawa coupling λ. Included in Fig. 10 are also indirect limits from LEP, based on the measurement of $q\bar{q}$ production cross section, which is sensitive to the virtual t-channel leptoquark exchange [19]. In the high mass region, beyond the kinematical limits, HERA and LEP provide comparable limits.

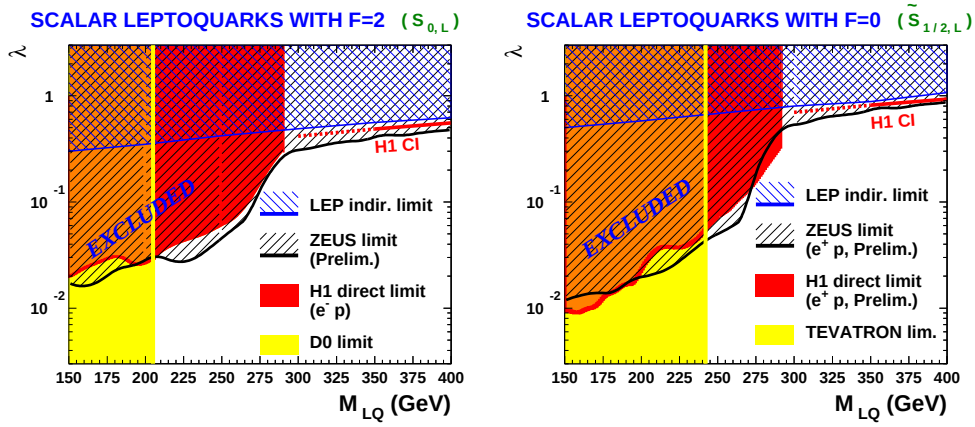

Fig. 10. Comparison of scalar leptoquark limits from HERA, TeVatron and LEP.

5.4. Other searches

Effects coming from "new physics" at high energy scales can be described in the most general way by four-fermion contact interactions. This includes the possible existence of second generation heavy weak bosons, heavy leptoquarks as well as electron and quark compositeness. At HERA, *eeqq* contact interactions would modify NC DIS cross sections at high Q^2. Since no deviations from SM predictions are found, exclusion limits on the compositeness scale Λ of 1.8 to 7.0 TeV are set by H1 and ZEUS experiments, based on the data collected in 1994–2000 [27]. Comparable limits are also obtained from measurement of Drell–Yan lepton-pair production at the TeVatron [28] and hadronic cross section and charge asymmetries at LEP [19]. Limits on four-lepton contact interactions *eell* set by LEP experiments range from 8.5 to 26.2 TeV.

Observation of the Lepton Flavor Violation (LFV) in the neutrino oscillations suggests that LFV processes could also be observed in the charged lepton sector. Both H1 and ZEUS experiments searched for events with high-transverse-momentum muon or tau production, $ep \to \mu(\tau)X$. LFV at HERA could be due to the s-channel production or u-channel exchange of a leptoquark coupling to different lepton and quark generations. No events consistent with LFV LQ production or exchange were found. Fig. 11 (left) shows the upper limit on the LFV leptoquark Yukawa coupling, for $S^{\mathrm{L}}_{1/2}$ scalar leptoquark decaying into μq. HERA results are competitive with those from low energy experiments when heavy quarks are involved. Assuming the Yukawa coupling $\lambda_{\mathrm{eq1}} = 0.3$ LFV leptoquarks with masses up to about 300 GeV can be excluded at HERA.

The observation of heavy excited fermions would be a clear evidence for fermion substructure. H1 and ZEUS experiments reported results from excited electron and excited neutrino searches at HERA [29]. Decay channels involving γ, Z and W boson emission were considered. No excess of data events over the expected background has been observed. Limits on the excited electron coupling over the compositeness scale ratio, f/Λ are shown in Fig. 11 (right). Combined LEP limits from direct production $e^+e^- \to e^\star e$ and from indirect searches in $e^+e^- \to \gamma\gamma$ (virtual $e^\star$ exchange) are included for comparison.

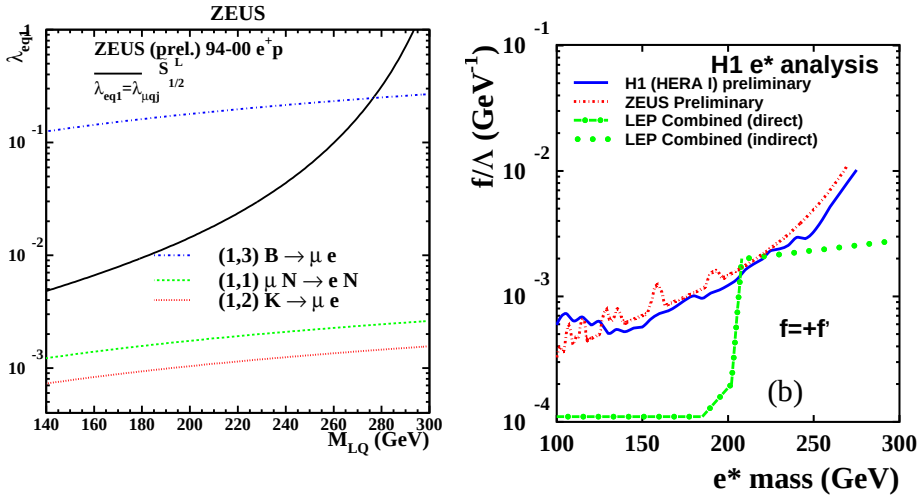

Fig. 11. Left: ZEUS 95% CL upper limit on the LFV leptoquark Yukawa coupling, for $S^{\rm L}_{1/2}$ leptoquark decaying into μq. Right: H1, ZEUS and LEP combined upper limits on f/Λ for $e^\star$.

First measurement of the high-$p_{\rm T}$ multi-electron production at HERA was reported by the H1 Collaboration [30]. The dominant Standard Model contribution is the interaction of two photons radiated from the incident electron and proton. The observed events are in general agreement with Monte Carlo predictions. However, for highest $p_{\rm T}$ and electron pair invariant masses above 100 GeV three events classified as di-electrons, and three tri-electrons are observed, where from the SM only 0.25±0.05 and 0.23±0.04 are expected, respectively. The distributions of the mass M_{12} of the two highest $p_{\rm T}$ electrons for di-electron and tri-electron events are shown in Fig. 12. This observation, which could be the hint of "new physics" beyond SM, needs confirmation with independent data samples[1].

[1] ZEUS Collaboration presented results on multi-electron production at HERA in July 2002 [31]. In the combined 1994–2000 data sample two di-electron and no tri-electron events are observed, compared to SM expectations of 0.77 ± 0.08 and 0.37 ± 0.04, respectively.

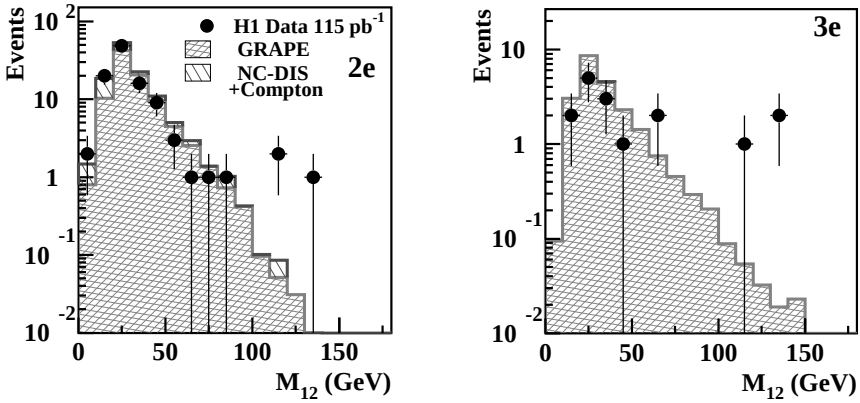

Fig. 12. Distribution of the invariant mass M_{12} of the two highest p_T electrons, for H1 events classified as di-electrons (left) and tri-electrons (right).

6. Future prospects

Both the TeVatron and HERA underwent major upgrades of the machines in the last several years, and are currently coming online with a new phase of data taking. At HERA it is now also possible to carry on experiments with polarized lepton beams. In Sections 6.1 and 6.2 the physics potential of these two upgrades is discussed.

In addition we have an outlook on future machines, the LHC and a future LC. LHC is scheduled to have its first run in 2007, and physics results will follow within a year or two as the energy frontier will be extended in the following years. In particular for searches for physics beyond the Standard Model the LHC will have great impact mainly in searches for scalar quarks and gluinos in SUSY. As for scalar leptons as well as the gaugino/higgsino sector additional help could be provided by a future Linear Collider (LC) with its first phase in the energy range of $\sqrt{s} = 500\,\mathrm{GeV}$ and upgrade possibilities to about 1 TeV. Due to the clean environment, the LC will provide measurements with unprecedented precision so that the underlying structure of the physics can be unambigously revealed. We summerize in Sections 6.3 and 6.4 some highlights about the expected physics potential of these future machines.

6.1. HERA upgrade

The luminosity system of H1 and ZEUS as well as the detectors itself have been decisively improved [32]. The expected integrated luminosity of HERA II will be 1000 pb^{-1}. Moreover, new spin rotators and polarimeters have been installed at Zeus and H1 so that also colliding experiments

with longitudinally polarized $e^{\pm}$ beams will be done. The luminosity will be equally shared between e^+p and e^-p and L and R polarizations. The detectors have both been improved, *e.g.* by introducing new or upgraded micro-vertex detector and improved triggering. In addition for both experiments the tracking in forward direction has been upgraded.

Within the SM the NC and CC cross sections are affected by the charge and by the longitudinal polarization of the incoming lepton. Therefore the use of polarized leptons is very promising. With different choices of the lepton charge as well as the polarization one can get complementary information about PDFs as well as the electro-weak couplings in NC in particular at high $Q^2\mathrm{GeV}^2$, see also Fig. 13.

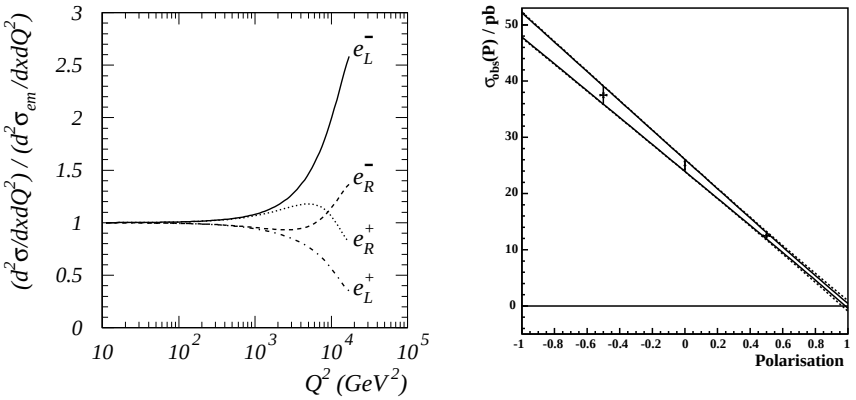

Fig. 13. Left: Sensitivity at high Q2 on electro-weak effects due to difference of cross section for different lepton charges and different polarizations. Right: CC cross section for e–p scattering as a function of polarization; $P = 0$: measured point (incl. 4.2 systematics). Errors due to polarization given by solid (dashed) line corresponding due to 0.2 % (2 %) polarization uncertainty.

For the measurements of the Z^0 boson couplings to light quarks u, d the beam polarization improves significantly the accuracy. A run with 250 pb^{-1} will lead to $\delta(a_u) = 0.04, \delta(a_d) = 0.10$ and with an $e^{\pm}$ polarization of $\geq 50\%$ a precise extraction of the vector couplings with $\delta(v_u) = 0.015$ and $\delta(v_d) = 0.04$ will be reachable. The measurements of HERA are complementary to those of LEP where c-quark couplings were probed.

Furthermore, also for the analysis of the left-handed charged currents the use of polarized beams will be decisive. Cross sections of charged currents depend linearly on the beam polarization and any deviation from this behavior would be a sign for physics beyond the SM, Fig. 13 (right).

6.1.1. Polarization at HERA

The HERMES fixed gas target experiment used successfully polarized beams since 1994. In a storage ring the $e^{\pm}$ beams become "naturally" polarized via the Sokolov–Ternov effect. In an exactly planar ring, *e.g.*, the (time-dependent) polarization is vertical orientated. Spin rotators before and after the intersection region turn the polarization in the longitudinal direction. Since the storage ring is not only planar at high energies depolarization effects occur and turn the natural polarization of about 90% into 50–70% degree which is expected to be reached at HERA. For the HERA upgrade there are two more regions with spin rotators at H1 and ZEUS are foreseen where a stable running of the ring and the luminosity has to be provided and the machine commissioning is still very challenging. For further details see [33].

As mentioned before not only the degree of polarization is decisive but also the accuracy with which this polarization can be measured at the experiments. For this purpose significant improvements of the Longitudinal Polarimeter (LPOL) as well as the Transversal Compton Polarimeter (TPOL) have been made. The LPOL needs only an energy measurement of the Compton scattered photon, whereas the TPOL measures the up-down asymmetry.

At the HERA II upgrade the LPOL is improved by a very efficient Fabry–Perot cavity in order to run in a few photon mode which leads to a high statistics. The TPOL on the other hand is upgraded in a two-fold way. In order to improve the angular resolution a silicon strip detector has been installed in front of the calorimeter which allows a continuous position calibration during the measurement. Furthermore, due to a new data acquisition a bunch to bunch measurement will be possible so that altogether an accuracy of $\delta P/P \sim 1\%$ can be reached. Further details can be found in [34].

6.1.2. Searches at HERA II

For an integrated luminosity of more than 500 pb^{-1} the upgraded HERA II experiment could make a discovery if the H1 effects for the isolated leptons with p_T^{miss} persists in W production.

Also other regions of physics beyond the Standard Model, comparable to the reachable regions at TeVatron II, are open at the run HERA II. In particular for the search for scalar leptoquarks the search can be increased up to a mass scale of about $M_{\mathrm{LQ}} \sim 300$ GeV. But also in the search for R-parity violating mSUGRA the limits for large $\tan\beta$ parameters are competitive to the other experiments.

Very interesting channels are those of excited leptons, in particular neutrinos. For low masses $M_\nu^* \leq 200\,\text{GeV}$ HERA II will be unique to discover this physics beyond the Standard Model. For higher masses the DELPHI results will overtake.

Concluding, one can state that after the detector commissioning the HERA II upgrade is complete and has real chance of discovering new physics beyond the Standard Model. The use of polarized beams will provide an important tool.

6.2. TeVatron upgrades

The Run I data taking period at the TeVatron ended in February 1996. Since then the collider and both the detectors (CDF and D0) underwent substantial upgrades.

The energy of the beams has been increased from 900 to 980 GeV. A new synchrotron ("main injector") has been built in a new tunnel. The main injector together with a debuncher-accumulator-recycler complex allows for faster production of antiprotons and the possibility of reusing them after they are rescued in the recycler. In Run I the luminosity reached $1.5\times10^{31}\text{cm}^{-2}\text{sec}^{-1}$ and was obtained with a 6 on 6 proton–antiproton bunches in the collider with an interbunch time of $3.5\mu\,\text{sec}$. The luminosity ultimately planned for Run II is $2.0\times10^{32}\text{cm}^{-2}\text{sec}^{-1}$ and it will be obtained with 36 on 36 proton–antiproton bunches with interbunch time of 396 ns. Eventually, in order to decrease the number of average interactions per bunch crossing below 2, the number of bunches in the antiproton beam will be increased to 108 with 140 bunches in the proton beam and a reduced interbunch time of 132 ns.

We have already mention that the quest for Higgs will be the main topic of research at the TeVatron in the next several years.

For top physics an extra 30–35% in the cross section is gained (1.8 to 2 TeV). There will also be a gain from acceptance and efficiency: $100\,\text{pb}^{-1}$ in Run II is equivalent to $150\text{–}300\,\text{pb}^{-1}$ in Run I). At this time work is still ongoing to finalize b-tagging software algorithms and the complete understanding of associated background. Top mass and W mass measurements will be updated from Run I results in winter 2003. The precision expected on the W mass is of order 20–30 GeV/c^2. The top mass measurement will be improved to a level of 2–3 GeV/c^2. Indirect constraints on the Higgs mass will be of course derived. In addition one of the goals of Run II is to search for $t\bar{t}$ resonances, rare decays and deviations from the expected patterns of top decays. The decay mode where both the W's from top decay leptonically will be the first to be looked at: in fact a moderate excess of events in Run I, especially at large missing energy is driving the investigation with an eye to signal for new physics [35].

Beauty and charm physics will also receive special attention at the TeVatron, since the new capabilities of the detectors (possibility of triggering on displaced vertex tracks) are making the TeVatron comparable to a dedicated b/c factory. CP violation in the b sector is of particular interest as evidence of physics beyond the SM. In the framework of the Standard Model, the source of CP violation and B mixing are the transitions between quarks described by the Cabibbo–Kobayashi–Maskawa matrix. In this model CP violation arises due to the irreducible phases in the CKM matrix. A precision measurement of the B_s^0 flavor oscillations is very important for testing the unitarity of the CKM matrix [36].The measurement of $\sin 2\beta$, one of the angles of the unitarity triangle, is obtained by extracting the amplitude of the CP asymmetry in the decay $B^0/\bar{B}^0 \to J/\psi K_s^0$. CDF has measured $\sin 2\beta$ with a precision comparable to that of dedicated B-factories and the TeVatron Run II will provide the conditions to perform this measurement with better precision [37]. The Standard Model favors a value of the parameter x_s between 22.55 and 34.11 at 95% C.L. CDF plans to use the fully reconstructed hadronic B_s^0 decays ($B_s^0 \to D_s^- \pi^+ \pi^- \pi^+$ with D_s^- reconstructed as $\phi\pi^-$, K^{0*}, K^- and K_s^-, K^-). These signals will come from data taken with the triggers based on displaced-vertex tracks. CDF expects 75000 reconstructed B_s^0 decays in 2 fb^{-1} using the above decay modes for an estimated signal-to-background ratio in the range 1:2 to 2:1. In Fig. 14 the expectations for an integrated luminosity of order 50pb^{-1} are shown. The proper time resolution is expected to be in the range 45–60 fs and the flavor tag effectiveness (εD^2) around 11%. This value includes same-side tagging, soft lepton tagging and opposite-side jet tagging, as well as kaon tagging now made possible by the use of the TOF detector.

The expected total integrated luminosity for Run II will allow to search more efficiently for physics beyond the Standard Model. CDF will search for SUSY particles in first place. Assuming that SUSY breaking results in uni-

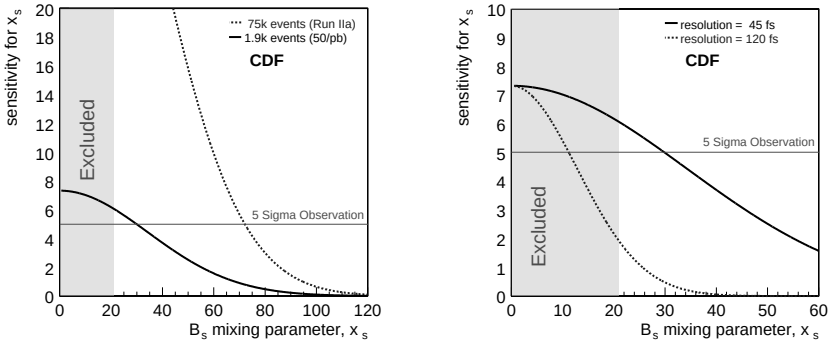

Fig. 14. Left: x_s reaches as function of number of events expected in Run IIa and with 50 pb^{-1}. Right: x_s reaches as function of time resolution.

versal soft breaking parameters at the grand unification scale, and that the lightest supersymmetric particle is stable and neutral, with 30 fb^{-1} luminosity and one detector, charginos and neutralinos, as well as third generation squarks, can be seen if their masses are not larger than 200–250 GeV, while first and second generation squarks and gluinos can be discovered if their masses do not significantly exceed 400 GeV [38].

Models where SUSY is broken at low scale including gauge-mediated supersymmetry breaking are generally distinguished by the presence of a nearly massless Goldstino as the lightest supersymmetric particle. The next-lightest supersymmetric particle(s) (NLSP) decays to its partner and the Goldstino. Depending on the supersymmetry breaking scale, these decays can occur promptly or on a scale comparable to or larger than the size of a detector. A systematic analysis based on a classification in terms of the identity of the NLSP and its decay length has been presented for example in [39]. The various scenarios have been discussed in terms of signatures and possible event selection criteria. Analysis are starting in CDF with the aim of understanding the datasets in terms of background contribution and possible deviation from it as a sign of new physics. Signatures involving photons are of particular interest to look for deviations from the SM predictions in the context of GMSB models. CDF is also using photon signatures as a first follow-up and check of strange events seen in Run I: in Fig. 15 the spectra of single photons candidate is reported using approximately 8 pb^{-1} of Run II data.

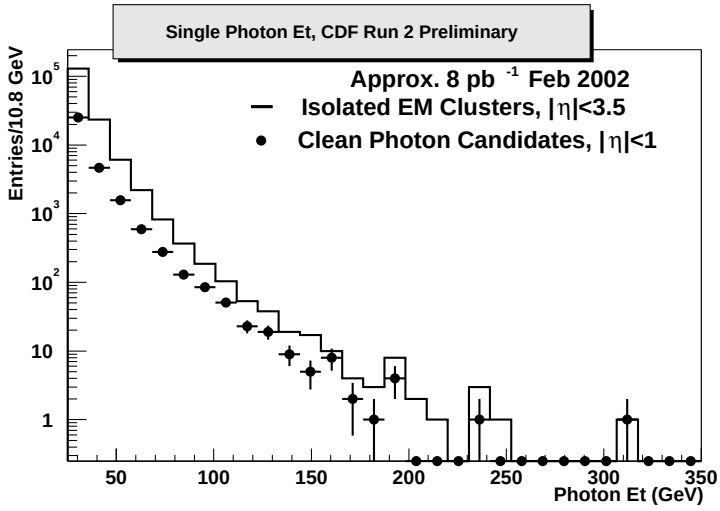

Fig. 15. First photon candidate events from CDF Run II.

6.3. LHC

The LHC will offer a large range of physics opportunities due to the high energy, $\sqrt{s} = 14\,\text{TeV}$, and a high luminosity, up to $\mathcal{L} = 10^{34}\,\text{cm}^2\text{s}^{-1}$. The first physics run is foreseen to start in 2007. The cross sections and expected production rates of many relevant physics processes are large, as can be seen in Fig. 16. Event samples, which will be collected at the LHC, will allow to perform many precision measurements of the Standard Model and possible beyond-SM scenarios [40].

Large $t\bar{t}$ samples will allow to measure the top quark mass up to 1–2 GeV and the production cross section of about 5% and also the detailed study of branching ratios, couplings and rare decays such as the flavor-changing neutral current reactions down to branching ratios of about 10^{-4}. The SM Higgs boson production cross section is larger than 100 fb up to 1 TeV, and the discovery is possible over the full mass range from the LEP2 lower limit up to the TeV range, already with $10\,\text{fb}^{-1}$. After few years of LHC running with high luminosity ATLAS+CMS would measure the Higgs boson mass and width, as well as production rates (with a precision of ∼10%), and moderate measurements of some couplings with certain model-assumptions (∼10–25%).

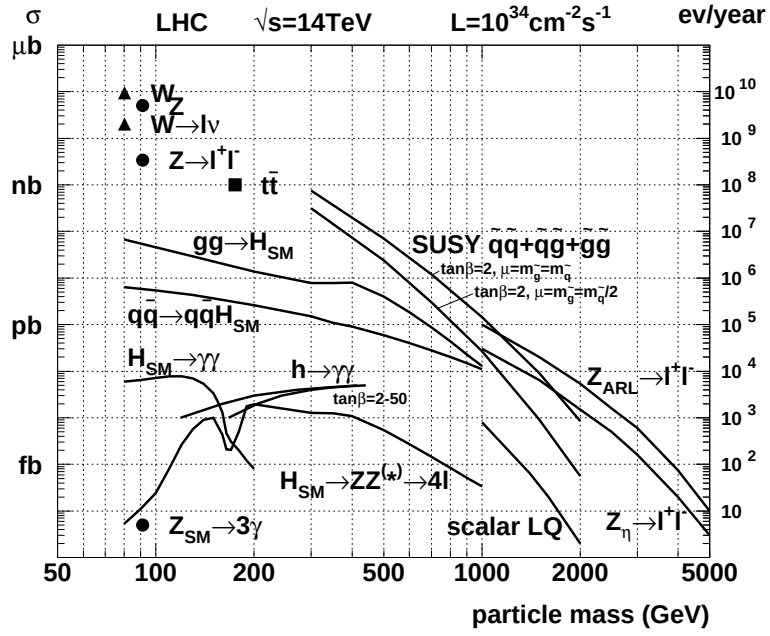

Fig. 16. Cross sections and event rates (per one year of LHC running at nominal luminosity) for different SM and beyond-SM processes which can be studied at LHC.

Searches beyond the Standard Model are among the important goals of the ATLAS and CMS experiments. LHC has a large discovery potential for Higgs bosons in the MSSM Higgs sector, two or more Higgs bosons should be observable over large portions of parameter space. However, there remains a region at $m_A > 200\,\text{GeV}$ and $4 \leq \tan\beta \leq 10$ where only the h^0 would be seen and it would be indistinguishable from a SM Higgs.

Excited quarks and leptons should be observable in different channels up to masses of about 7 TeV. New gauge bosons can be discovered up to masses of 5 TeV. The existence of right-handed W or heavy Majorana neutrinos can be assessed up to a few TeV, and charged heavy leptons can be discovered up to masses of about 1.1 TeV.

In theories of large extra dimensions the fundamental Planck scale can be of the order of TeV. Large effects from real graviton production or virtual graviton exchange are expected at LHC. Jets or photons in conjunction with missing transverse energy are considered as a signature for graviton emission. A signal will be observable at LHC if the Planck scale in $4+\delta$ dimensions is below 9 TeV, for $\delta = 2$, or 6 TeV if $\delta = 4$. The decay mode $G \to l^+l^-$ gives a good signal of narrow graviton resonances up to 2.1 TeV, if the Randall–Sundrum scenario is used. The presence of the virtual graviton exchange contribution to Drell–Yan processes can lead to a significant excess in the production of dilepton and diphoton events, if the fundamental Planck scale is below 8 TeV.

If the fundamental Planck scale is below few TeV, LHC could then turn into a black hole factory. The non-perturbative process of black hole formation and decay by Hawking evaporation gives rise to spectacular events with up to many dozens of relatively hard jets and leptons [18,41]. For production of black holes more massive than 5 TeV at the LHC, with $M_p = 1\,\text{TeV}$ and $\delta = 10$, the integrated cross section function would be of the order of 10^5 fb, corresponding to a production rate of a few Hz. Even for black holes more massive than 10 TeV a production rate of a few per day might be expected. With TeV scale gravity, black hole production could become the dominant process at hadron colliders beyond the LHC.

6.4. Linear collider

An e^+e^- Linear Collider with $\sqrt{s} = 500 \ldots 1000\,\text{GeV}$ has been recognized to be the next major machine to be built for high energy physics research. It offers the possibility of a very precise analysis of the physics at the TeV scale. In this context the recently formed LHC/LC Study Group [42], which works out the optimal path for a hand-in-hand research of the hadron machines and the LC, has already revealed a large number of topics where using the results of one machine as input for the analysis at the other machine can be very fruitful.

The use of polarized beams [43], tunable center of mass energy as well as the different options e^+e^-, e^-e^-, $e^\pm\gamma$, $\gamma\gamma$ [44] offers a high degree of flexibility.

6.4.1. Top physics

Due to the high precision reachable at the LC, the mass and couplings of the top quark will be improved by at least one order of magnitude w.r.t. the LHC. At a threshold scan with an integrated luminosity of about $100\,\mathrm{fb}^{-1}$ and both beams polarized ($|P_{e^-}| = 80\%$, $|P_{e^+}| = 60\%$) the mass will be measured with an accuracy of about $\delta(m_t) = 100$ MeV, Fig. 17, and $\delta(\Gamma_t)/\Gamma_t = 0.05$. The vector coupling to a relative precision of 2% (or even 0.8% with $300\,\mathrm{fb}^{-1}$) [44] will become sensitive to quantum corrections.

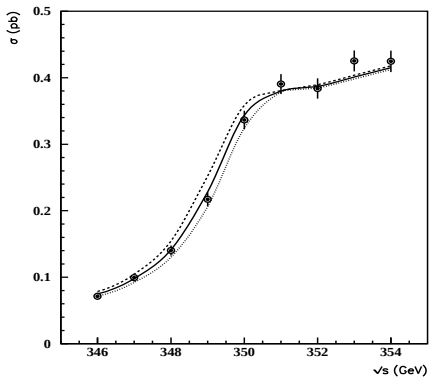

Fig. 17. Excitation curve of $t\bar{t}$ (including errors bars for $100\,\mathrm{fb}^{-1}$). The dotted curves indicate shifts of the top mass by ± 100 MeV.

6.4.2. Higgs physics

The properties of the Higgs bosons can be determined with high precision and all essential elements of the mechanism of electro-weak symmetry breaking can be established. The model independent determination of the mass, Fig. 18, and total width and the measurement of all relevant couplings to bosons and fermions can be performed at the per cent level. The quantum numbers (J^{CP}) can be uniquely determined. Even all self-coupling of the Higgs boson, which proves the shape of the Higgs potential, can be measured.

A very interesting option is the use of the $e^\pm\gamma$ and the $\gamma\gamma$ beams at a LC where in particular the production of the Higgs bosons in the s-channel is possible, Fig. 20.

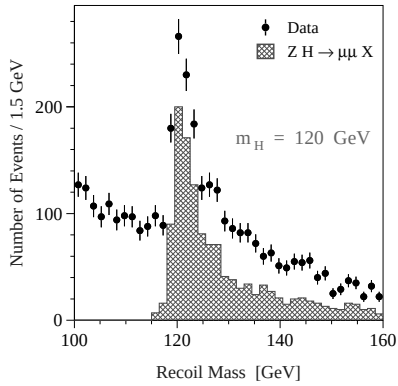

Fig. 18. The $\mu^+\mu^-$ recoil mass distribution in the process $e^+e^- \to HZ \to X\mu^+\mu^-$ for $M_h = 120\,\mathrm{GeV}$ and 500^{-1} at $\sqrt{s} = 350\,\mathrm{GeV}$. The dotted error bars are MC simulation of Higgs signal and background. The shaded histogram represents the signal only.

6.4.3. Anomalous gauge couplings

Triple gauge couplings can be measured with an superior accuracy at a LC providing a high sensitivity to any kind of new physics effects. In Fig. 19 the accuracy for triple gauge couplings at different LC energies are compared to the TeVatron and LHC potential.

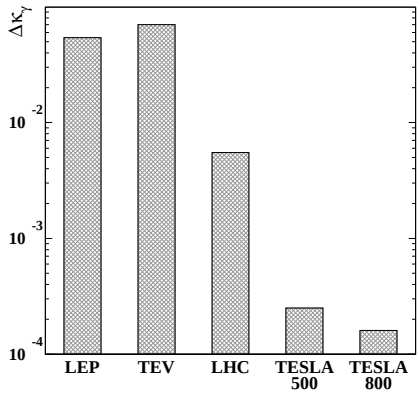

Fig. 19. The precision for anomalous gauge couplings in comparison at different machines. For LHC and TESLA three years of running are assumed. (LHC: $300\,\mathrm{fb}^{-1}$, TESLA $\sqrt{s} = 500\,\mathrm{GeV}$: $900\,\mathrm{fb}^{-1}$, TESLA $\sqrt{s} = 800\,\mathrm{GeV}$: $1500\,\mathrm{fb}^{-1}$.)

6.4.4. Physics beyond the SM

As for physics beyond the SM, the LC has a large discovery potential for supersymmetric particles, in particular for the non-colored particles. Due to its clean signatures and low background processes, a LC can shed light on the structure of the underlying theory very precisely.

Since SUSY is not an exact symmetry, but has to be broken at low-energy, there are about 105 new SUSY parameters in addition to the free 19 SM parameters. Therefore the LC is a unique tool for revealing the underlying structure of the model and has the challenging task of the precise determination of the parameters. Experimental and theoretical strategies have been worked out to determine precisely the low-energy electro weak parameters and after determining these free parameters powerful consistency tests are possible in order to understand the SUSY breaking scheme.

A lot of studies for other kinds of physics beyond the SM as phenomena of R-parity violating SUSY, large extra dimension, extended gauge boson sectors have been made and demonstrate the rich physics program of a LC [44].

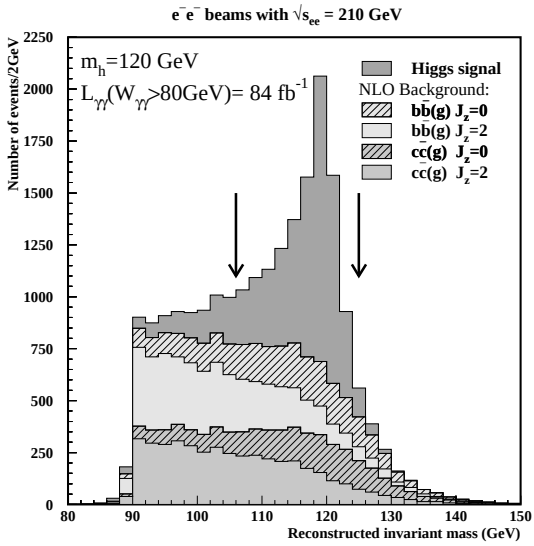

Fig. 20. Distribution of the reconstructed mass for Higgs boson production in $\gamma\gamma$ interactions at TESLA, for m_h=120 GeV [45].

7. Conclusions

It has been a very interesting session and we look forward to new data from HERA2 and the TeVatron! Let's thank all our speakers: J. Böhme, S. Chivucula, N. De Filippis, P. Deglon, K. Desch, M. Ellerbrock, C. Foudas, C. Genta, E. Gianfelice, S. Grijpink, J. Haller, M. Helbich, J. Kalinowski, M. Krawczyk, Z. Lalak, N. Malden, S. Mattingly, A. Mehta, C. Mesropian, S. Moch, M. Moritz, M. Petteni, K. Piotrzkowski, T. Pratt, T. Saeki, S. Schmidt, K. Sliwa, P. Spentzouris, R. Ströhmer, J. Sztuk, C. Vallee, A. Weber, G. Weiglein, M. Wolter, G. Wrochna, P. Zalewski.

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