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ELECTROWEAK AND BEYOND THE STANDARD MODEL PHYSICS

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We present an overview of the Electroweak and Beyond the Standard Model Physics working group of the DIS2004 conference.

1 Introduction

For more than a century, high-energy collisions of particles have been a golden method of investigating the ultimate structure of the matter. Along with precision studies of heavy meson decays, primarily at lower energy colliders, these experiments have led to the consolidation of the Standard Model (SM) as the theory of particle physics at energy scales up to $\mathcal{O}(10^2)$ GeV. Recent results from the high-energy colliders LEP, HERA, and the Tevatron, complemented by the extraordinary precision measurements from b-factories, display no significant deviations from SM predictions.

At present, intensive data taking continues, with measurements testing the Standard Model at higher levels of precision. LEP, which gloriously finished the data taking 3.5 years ago, continues to provide interesting results from a data sample corresponding to 2.8 fb^{-1} collected at energies up to 209 GeV. The HERA and Tevatron colliders are now taking data again after substantial upgrades of the machines and the detectors. In Run II at the Tevatron than 200 pb^{-1} has been delivered and up to 8 fb^{-1} is expected by the end of the programme in 2008. HERA has suffered delays mainly due to the high backgrounds related to the new high-luminosity beam optics. However, constant efforts have largely overcome these problems and the first results from HERA II using a data sample corresponding to an integrated luminosity of 17 pb^{-1} have been presented at this conference.

2 The status of the Standard Model

2.1 Electroweak precision tests

The parameters of the Standard Model were determined in a global fit including precision measurements [1] at LEP and SLC. The fitted values agree very well with the predictions as can be seen in figure 1(left).

A particularly interesting result is the measurement of asymmetries in the heavy quark production and the comparisons with the lepton asymmetry. The value of $\sin\theta_{eff}$ extracted from the heavy quark asymmetry differs by three standard deviations from the one derived from the leptonic asymmetry measured at SLD using polarised beams. The source of this discrepancy could be a statistical fluctuation or a neglected systematic effect. While anomalous quarks couplings could give rise to such differences, their effects on other observables would have been seen and therefore this explanation is unlikely.

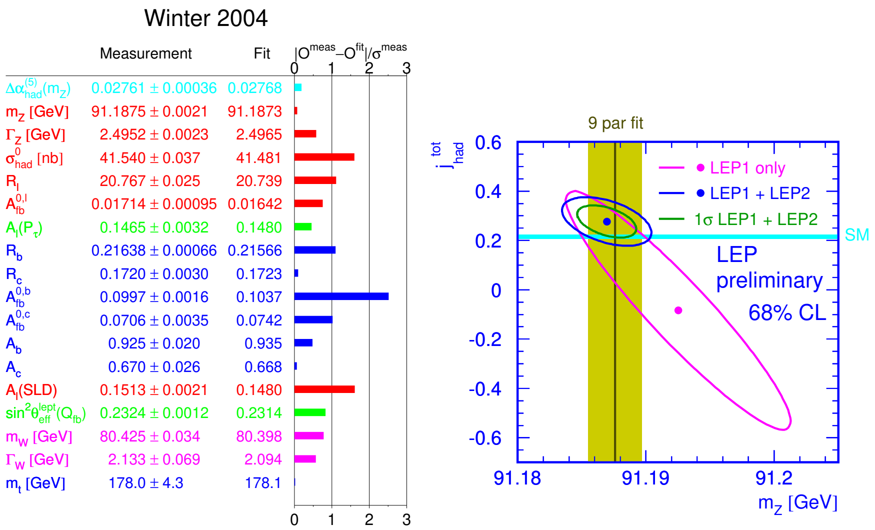

Figure 1. Left: the pulls of the 18 parameters in the electroweak fit. Right: the result of a 9 parameter semi-model-independent fit for the interference contribution j^{tot}_{had} versus M_Z.

Measurements of two fermion production at LEP are sensitive to new physics due to the fact that the entire center-of-mass energy is available at the production vertex of the fermion pair. Deviations from the Standard Model could be observed in a semi model-independent analysis, where the $\gamma - Z$ interference term in the production cross section (denoted by j^{tot}_{had}) is allowed to differ from the SM value. The result is shown in figure 1(right) in the plane $M_Z - j^{tot}_{had}$. The correlation between the two parameters is reduced by the use of LEP2 data and good agreement with the SM predictions is observed [2].

2.2 The Top and the SM Higgs

The $D0$ experiment at the Tevatron has recently used a new method to measure the top quark mass using Run I data [3]. In this method, all combinations of jets contribute according to a weight determined from the comparison with the $t\bar{t}$ signal. A probability is assigned to each event. The background which remains after an initial selection is reduced by a cut on the probability. The top mass (m_t) is extracted from the mass distribution obtained from the weighted combinations. Using Run I data, D0 obtained $m_t = 179.0 \pm 5.1$ GeV, to be compared with the old method where $m_t = 172.1 \pm 7.1$ GeV (statistical errors only). In addition to the upward shift in m_t, the new method yields improved statistical precision. The expected precision from the Tevatron Run II measurement is about 3 GeV, dominated by the systematic error [4].

When the new value of m_t is input to an electroweak fit, the allowed mass range of the Higgs boson is 117^{+67}_{-45} GeV, whereas the old value of m_t yielded the range 96^{+60}_{-38} GeV (direct searches at LEP give a lower limit of 114.3 GeV). The 95% confidence level upper limit of the SM Higgs mass has increased to 251 GeV from 219 GeV.

Studies of the top quark will enter the domain of precision measurements at the Large Hadron Collider (LHC), where a large sample of top quarks will be produced in pp collisions [5]. The precision on m_t will be $\sim$1 GeV. Together with an estimated precision of 15 MeV for the W boson mass this measurement will allow an indirect determination the SM Higgs boson mass with a precision of $\sim$20%. Many other measurements related to the top quark will be possible even in the low luminosity option at the LHC: rare decays, search for flavour changing neutral currents, or spin correlations.

Direct searches for the Standard Model Higgs production at the Tevatron [6] are underway. The most promising production mechanism is associated production with a W, which decays leptonically, $W \to \ell\nu$. The Standard Model Higgs boson decays mainly into $b\bar{b}$ for $m_H < 140$ GeV. Therefore, b-tagging plays a crucial role in separating the signal from the W+jets background. Despite the excellent silicon detectors at the Tevatron experiments, irreducible backgrounds from $t\bar{t}$ and Wbb processes strongly limit the sensitivity. The highest luminosity is required in order to discover Standard Model Higgs production: for a Higgs mass of 115 GeV, an integrated luminosity of 8 fb^{-1} is necessary for a 5σ discovery by the CDF and D0 experiments.

2.3 Other EWSB mechanisms

The electroweak symmetry breaking (EWSB) mechanism involves mass scales beyond 100 GeV, according to present experimental knowledge in the SM Higgs searches. It is possible that the first sign of physics beyond the SM will involve the mechanism of EWSB. This motivates searches for heavy bosons, belonging to the EWSB sector, which decay in channels not favoured or not allowed for the SM Higgs. A remarkably wide range of non-SM Higgs scenarios have been ruled out in searches at the Tevatron [6], LEP [7,9],and HERA [10].

An example is the search at the Tevatron for a Higgs boson decaying via $H \to WW^*$. Upper limits on the production cross section have been calculated in the range from 6 to 8 pb for Higgs masses between 140 and 200 GeV. Those limits are more than an order of magnitude above the prediction from the Standard Model, but in some cases only a factor of two above predictions from exotic models involving a hypothetical fourth fermion generation, as can be seen from the exclusion limits shown in figure 2(left). Searches for bosonic decays of the Higgs in models with fermiophobic couplings have also been performed in the cleaner (but lower energy) LEP environment [7]. Higgs masses up to 105 GeV have been excluded considering

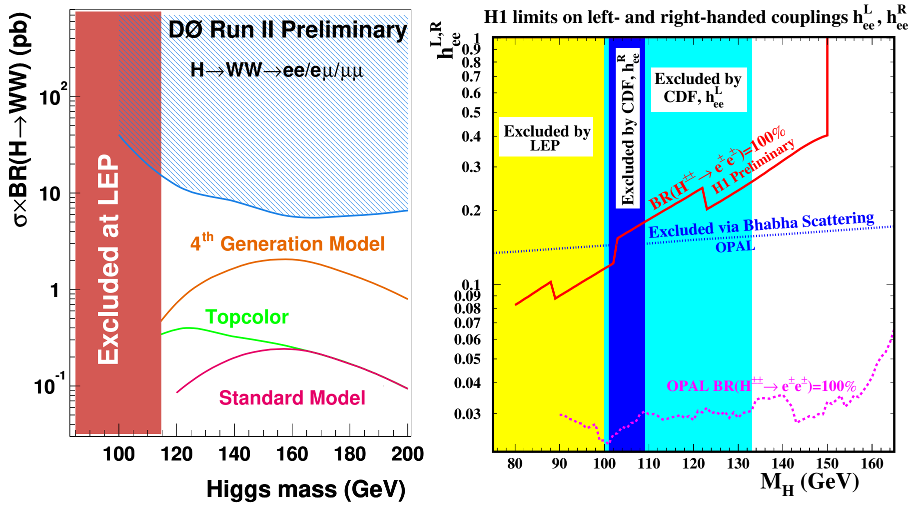

Figure 2. Left: exclusion limits of the Higgs decaying to a W pair from Tevatron. Right: exclusion limits of the couplings versus $H^{\pm\pm}$ mass from LEP, HERA and Tevatron.

full decay into a W boson pair.

One of the most popular SM extensions is Supersymmetry (SUSY) for which the Higgs sector includes five bosons in the minimal version. If EWSB is SUSY-like, the most favourable production scenario at the Tevatron requires large values of $\tan\beta$. Data from Run II have been analysed and values of $\tan\beta$ above 97(140) have been excluded for a Higgs mass of 90 GeV (150 GeV) [6]. The Tevatron analysis complements previous searches at LEP which established lower limits on $\tan\beta$ (typically below 10) in this range of Higgs mass [8].

In addition to the "classical" role of EWSB mechanism, the Higgs sector can also reveal the gauge structure of the underlying theory. This is the case for left-right symmetric models, where Higgs triplets are predicted, including a doubly charged Higgs boson $H^{\pm\pm}$ which couples in the fermionic sector to leptons but not to quarks. The experimental signature of a doubly charged Higgs produced at colliders is a pair of same-charge high energy leptons. Searches for the $H^{\pm\pm}$ boson have been performed at LEP, HERA and the Tevatron [6,10]. No evidence for $H^{\pm\pm}$ could be established, despite a few spectacular dielectron events observed at HERA [10]. The lower limits on the boson mass are deduced as a function of the coupling to the lepton pair and are summarized in figure 2(right).

If not revealed by the data collected at Tevatron or HERA in the next few years, the EWSB mechanism has a good chance of being discovered at the LHC and precisely measured at the next linear collider. However, an SM Higgs boson with low mass (m_H below 140 GeV) remains difficult to find at the LHC. Due to the huge QCD background, the optimal search channel in this mass range is the diphoton decay $H \to \gamma\gamma$. For a SM Higgs mass of 130 GeV, only a 3σ excess would be obtained with 30 fb^{-1}, while a 6σ discovery requires 100 fb^{-1} [11]. At the next linear collider the Higgs mass could be measured with a precision of a few parts per thousand. For example, the expected error on the mass is below 70 MeV if $M_H < 130$ GeV and below 400 MeV if the Higgs mass exceed $2M_Z$ [12]. These studies make clear the role of the next linear collider in precision measurements of EWSB.

2.4 Production of weak bosons at LEP and Tevatron

Measurements of weak boson production at colliders allow powerful tests of the electroweak sector of the Standard Model. Both the properties of the W and Z bosons and the mechanisms of single and pair production have been studied at LEP and the Tevatron.

The precise determination of the W mass (M_W) provides an independent test of the consistency of the Standard Model due to the dependencies on the Higgs boson and top quark via radiative corrections. Averaging the direct measurements performed at LEP2 and the Tevatron yields $M_W = 80.425 \pm 0.034$ in good agreement with the value of 80.380 ± 0.023 obtained indirectly from the electroweak fit.

Measurements of weak boson pair production test the gauge structure of the Standard Model, due to the influence of the three-boson gauge coupling in the production mechanism. At LEP, W–pair production dominates the diboson production cross section with a typical value of 17 pb for $\sqrt{s}$ around 200 GeV [13]. Measurements of the W–pair production cross section at various $\sqrt{s}$ at LEP agree well with the SM prediction. The flattening of the cross section after the phase space rise around $\sqrt{s} \simeq 2M_W$ typifies and confirms the SM gauge structure.

Single boson production is a rare process at LEP with cross section below 1 pb [14]. Single boson production is a subprocess of the four–fermion production. The weak boson is identified in the leptonic or hadronic channels. The boson pair production is supressed by requiring no second candidate for a weak boson decay in the event. Both single and pair production of weak bosons are subprocesses of the four–fermion production. The two processes involve however different poles in the cross section. In particular, the single boson production is sensitive to triple gauge couplings and constitutes therefore an interesting test of the Standard Model. Besides, the final state topology is spectacular and considered as background in many exotic searches.

Processes involving three- or four-boson vertices may reveal new physics through the deviation of the effective coupling strength from the SM predictions [15,16]. The main process sensitive to the triple boson coupling is W pair production. In addition, single W or γ production may be sensitive to those couplings. At LEP triple gauge couplings have been measured to precisions of $\sim$2%. Improvements of two orders of magnitude are expected at the next linear collider [12].

Possible quartic gauge couplings have been studied at LEP using final states with two acoplanar photons that may be produced at a $WW\gamma\gamma$ vertex and accompanied by two neutrinos. Data are in good agreement with the SM prediction and constraints on the anomalous quartic gauge couplings have been derived.

The measurement of single weak boson production at the Tevatron is a precise

1994-2000 $e^{\pm}p$		Electron obs./exp. ($W^{\pm}$ contrib.)	Muon obs./exp. ($W^{\pm}$ contrib.)	Tau (H1:108 pb^{-1}) obs./exp. ($W^{\pm}$ contrib.)
H1 118.4 pb^{-1}	Full Sample	11 / 11.54±1.50 (71%)	8 / 2.94±0.50 (86%)	5 / 5.81±1.36 (15%)
	$P_T^X > 25$ GeV	5 / 1.76±0.30 (82%)	6 / 1.68±0.30 (88%)	0 / 0.53±0.10 (49%)
ZEUS 130.2 pb^{-1}	Full Sample	24 / 20.6 $^{+1.7}_{-4.6}$ (17%)	12 / 11.9$^{+0.6}_{-0.7}$ (16%)	3 / 0.40$^{+0.12}_{-0.13}$ (49%)
	$P_T^X > 25$ GeV	2 / 2.90$^{+0.59}_{-0.32}$ (45%)	5 / 2.75$^{+0.21}_{-0.21}$ (50%)	2 / 0.20$^{+0.05}_{-0.05}$ (49%)

Table 1. Summary of the results of searches for events with isolated leptons, missing transverse momentum and hadrons with large transverse momentum P_T^X at HERA. The number of observed events is compared to the SM prediction. The $W^{\pm}$ component is given in parentheses in percent. The statistical and systematic uncertainties added in quadrature are also indicated.

test of the SM, due to the progress achieved both in theoretical calculations, available to NNLO in QCD, and in experimental technique [17]. Study of the leptonic decay channels of the W allow tests of lepton universality. The measured ratio $(\sigma(W) \times BR(W \to \ell\nu))/(\sigma(Z) \times BR(Z \to \ell^+\ell^-))$ can be related to the total W width, which is found to agree well with the theoretical prediction.

Although pair production of weak bosons ($W\gamma$, WW, $Z\gamma$) is a rare process, cross section measurements have already been reported from the Tevatron [17]. For instance, W pair production has been measured using a Run II data sample corresponding to an integrated luminosity of 200 pb^{-1}. The cross section, measured using leptonic W decays, is 14.3 ± 5.6 pb, in good agreement with the NLO theoretical calculation of 12.5 ± 0.8 pb. This measurement is a direct test of the SM triple gauge couplings. The spectacular final states of these processes constitute backgrounds for many exotic searches.

2.5 Events with high P_T isolated leptons at HERA

Events with isolated leptons (electrons, muons or taus) and missing transverse momentum have been observed in the HERA I data [18,19,20,21]. The results are summarised in table 1. The only SM process which yields events with isolated high-transverse-momentum leptons and missing transverse momentum in ep collisions at HERA is W boson production. Of particular interest are the events where P_T^X, the transverse momentum of the hadronic final state, is large. Although no significant deviation from the SM prediction is observed, some atypical events with prominent jets have been observed in the electron and muon channels by the H1 Collaboration and in the tau channel by the ZEUS collaboration. At present, it is still possible to explain the differences in event yields between the H1 and ZEUS measurements as a statistical fluctuation.

The incoming HERA II data will certainly solve this puzzle. Three events with isolated electrons and missing transverse momentum have already been observed in the prelimnary analysis of a HERA II data sample coresponding to an integrated luminosity of 17 pb^{-1} [22]. The P_T^X distribution of these events is compared to the SM prediction in figure 3. Two new events with $P_T^X > 25$ GeV are seen.

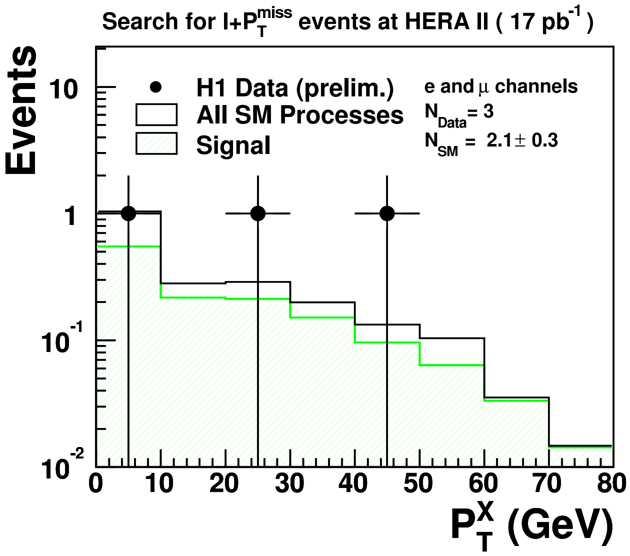

Figure 3. The hadronic transverse momentum distribution in the electron and muon channels combined: data (HERA II, $\mathcal{L} = 17$ pb^{-1}) are compared to the SM expectation (open histogram). The signal component of the SM expectation, dominated by real W production, is given by the hatched histogram. $\mathrm{N_{Data}}$ is the total number of data events observed, $\mathrm{N_{SM}}$ is the total SM expectation.

Multi-lepton production has also been studied at HERA. Here, the main production mechanism is photon–photon collision. Events with two electrons or two muons with transverse momenta up to 50 GeV have been observed, including a small sample of events containing two or three electrons for which the invariant mass of the highest P_T electron pair exceeds 100 GeV [10]. A possible interpretation of those events in terms of doubly charged Higgs has been discussed above. The analysis has been repeated on the HERA II data sample (17 pb^{-1}) but no new events at large invariant mass were observed [10].

2.6 CP violation

At BaBar, a multitude of rare B decay modes have been measured, with typical branching fraction accuracy of order 10^{-6} [31]. Charmless hadronic decays, which are CKM suppresssed, are sensitive to new particles in penguin loops. In addition the time-dependent CP asymmetry in B decays to $\pi^+\pi^-$ and $\rho^+\rho^-$ or ϕK^- and ϕK^* are sensitive the the CKM angles α and β respectively. Utilizing $B^0 \to \rho^0\rho^0$ and $B^0 \to \rho^+\rho^-$ decays, BaBar has measured $\alpha = 96^\circ \pm 10^\circ(\mathrm{stat}) \pm 4^\circ(\mathrm{syst}) \pm 13^\circ(\mathrm{penguin})$ [32]. An analysis of the time evolution of $B^0 \to D^{(*)\pm}\pi^\mp$ decays allows one to constrain the CKM angle γ by $|\sin(2\beta+\gamma)| > 0.69$ at 68% CL [32].

The LHCb detector will study production and decays of B mesons at the LHC [33]. An advantage of studying B mesons at a hadron collider over the e^+e^- b-factories is access to the B^0_s. After one year of data taking, LHCb should be able to make a 5σ measurement the $B_s - \bar{B}_s$ mixing parameter ΔM_s up to values of 68 ps^{-1}, well above the SM prediction. In addition, analyses of CP asymmetries in $B_s \to D_s^\pm K^\mp$ will allow the angle γ of the Unitarity Triangle to be measured to 14° [33].

3 Beyond the Standard Model

The HERA, LEP and Tevatron colliders provide complementary capabilities for the exotic searches. LEP and the Tevatron are "annihilation" colliders, which can produce any fermion-antifermion pair which couples to a boson produced in the s-channel. Therefore new particles which do not couple directly to the SM fermions can be produced. Furthermore, the rates for such processes will depend only on the SM guage couplings. In contrast, HERA is a "scattering" collider, where the exchanged SM boson is in the t-channel. Only new bosons that couple both to leptons and quarks could be produced in the s-channel of eq collisions and the rate would depend on the non-SM e-q-boson coupling.

This partially explains the dominance of LEP and the Tevatron in searches for pair production of new particles (*e.g.* sparticle production in R_p conserving SUSY) and the competitiveness of HERA in scenarios involving particles with lepton-quark couplings (*e.g.* leptoquarks or squarks in R_p violating SUSY). In addition, the QCD background, which is very difficult at the Tevatron, is less of a problem at HERA. This allows the investigation of a wider range of decay channels and extends the HERA sensitivity to regions of parameter space that are inaccessible to Tevatron analyses. LEP searches benefit from both low backgrounds and high luminosity due to the excellent machine performance, but are limited by the lower centre of mass energy compared to HERA or the Tevatron.

3.1 SUSY

A popular extension the Standard Model is supersymmetry (SUSY). SUSY unifies internal symmetries with Lorentz invariance and associates supersymmetric partners ($s$particles) to the known SM particles. Supersymmetric models provide solutions to many problems of the SM (hierarchy, fine–tuning, unification) and predict spectacular final states in high-energy particle collisions. Despite extensive studies at colliders and elsewhere, no trace of SUSY has yet been detected.

The production of single $s$particles is possible if the conservation of the multiplicative quantum number R_p is violated (R–parity is $R_p = (-\mathbf{1})^{3B+L+2S}$ where

B, L, and S denote the particle's baryon number, lepton number, and spin respectively). In R–parity violating models, s–channel squark production at HERA via the electron-quark-squark Yukawa coupling (λ) is possible. A special case is the stop ($\tilde{t}$) which in many SUSY scenarios is the lightest squark.

Searches for R_p violating SUSY at HERA [23] have excluded scenarios where $s$quark masses are below 275 GeV for a Yukawa coupling of electroweak strength. The searches involved all possible decays of the squarks (both direct R_p–violating and gauge decays) and are therefore sensitive to a large class of models, corresponding to a wide scan over the parameter space. A special class of models, in which the gauge decays are kinematically forbidden and the stop squark is heavier than the sbottom have been studied. The decay $\tilde{t} \to \tilde{b}W$ followed by $\tilde{b} \to d\bar{\nu}_e$ and $W \to \ell\bar{\nu}_\ell$ can lead to events with isolated leptons, missing transverse energy, and high P_T jets, similar to the events observed by the H1 Collaboration. However the analysis has shown that the observed events are incompatible with this scenario and limits on the squark masses and the coupling λ' were calculated. In this SUSY scenario (gauginos heavier than squarks and stop heavier than sbottom), stop squarks with mass below 260 GeV are excluded if the $\lambda' = 0.3$ independent of the sbottom mass.

Searches where R_p is conserved are mainly based on the presence of the lightest supersymmetric particle (LSP) in the final state, which usually involves large missing transverse momentum. In this case SUSY particles can only produced in pairs. In the case of squark pair production at the Tevatron, the subsequent decay to quarks and neutralino (considered as LSP) yield events with two acoplanar jets and prominent missing transverse momentum [24]. The large QCD background from dijet production is removed by harsh cuts on missing transverse momentum and its alignment with either of the jets. In absence of a signal, squarks(gluinos) are excluded with masses below 292(333) GeV (in mSUGRA scenario with $m_0 = 25$ GeV, $A_0 = 0$, $\tan\beta = 3$, $\mu < 0$, $m_{1/2} = 100 \sim 140$ GeV). If the lightest squark is sbottom, then $\tilde{g}\tilde{g}$ production (via an s-channel gluon) with the subsequent decays $\tilde{g} \to \tilde{b}\bar{b}$ and $\tilde{b} \to b\chi^0$ would lead to a striking signature with four b-jets and prominent missing transverse momentum. The search for such signatures using the b-tagging capabilities of the CDF detector demonstrated the unique sensitivity of the Tevatron experiments to this particular SUSY scenario.

At LEP, no evidence for sparticle production (sleptons, squarks, neutralinos, or charginos) has been found. The exclusion domain of sparticle masses approaches the kinematical limit of 100 GeV. Remarkably, a robust limit on the chargino mass at 92 GeV is obtained, independent of model assumptions. The neutralino mass limit is obtained indirectly from combined searches for Higgs bosons, sleptons and charginos. In the most constrained scenario, the neutralino mass is excluded below 50 GeV, while in a non-constrained SUSY scenario, no absolute lower bound can be claimed [25]. The searches for sparticle production can be combined in order to exclude complementary regions in the SUSY parameter space for a given constrained model. In figure 4, the exclusion domains obtained in the mSUGRA model from various search strategies are shown in the $(m_0, m_{1/2})$ plane.

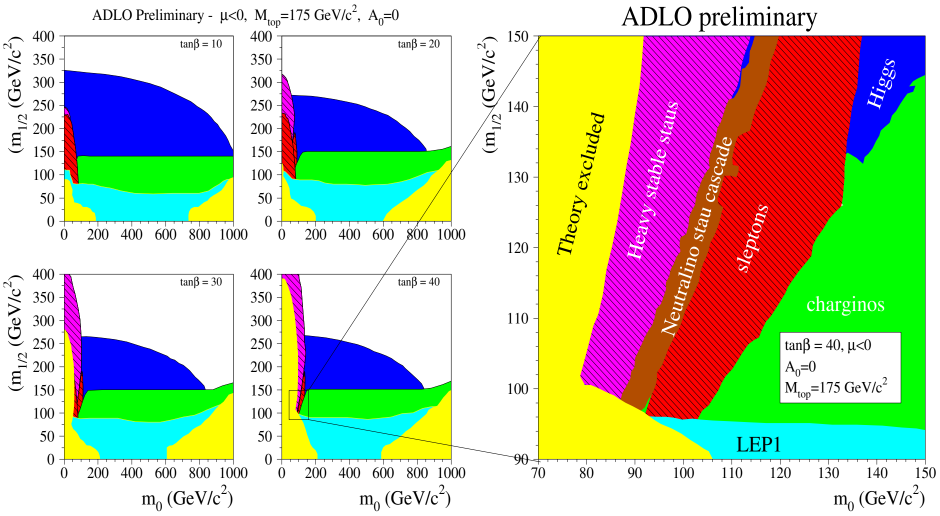

Figure 4. Exclusion limits in the plane $(m_0, m_{1/2})$ from combined interpretation of SUSY and Higgs searches.

3.2 Leptoquarks

Leptoquarks are hypothetical bosons which couple to a lepton and a quark via a Yukawa coupling (denoted λ). In the Standard model, both quarks and leptons occur in left-handed $SU(2)$ doublets and right-handed $SU(2)$ singlets. The symmetry between quarks and leptons leads to the cancellation of triangle anomalies which make the SM renormalizable. Leptoquarks appear in theories in which this symmetry is more fundamental.

Leptoquarks (LQs) are color triplets, which would be pair produced in either $q\bar{q}$ or gg interactions at $p\bar{p}$ or pp colliders. Because they carry electroweak charge, they would also be pair produced in e^+e^- collisions. Only standard model gauge couplings are involved in pair production; therefore the cross sections depend neither on the quark-lepton-LQ Yukawa coupling nor on the quark and lepton generations to which the leptoquark couples. In contrast, leptoquarks would be singly produced via the Yukawa coupling in a lepton-quark collision. Searches at electron-proton colliders are sensitive only to LQs which couple to electrons and the sensitivity to LQs which couple to second and third generation quarks is far below that of first-generation LQs. Leptoquarks are usually (but not always) assumed to be *generation diagonal*. Models in which LQs couple to more than one generation of quarks or leptons would induce flavor-changing neutral currents or lepton flavor violation respectively [28].

The model of Buchmüller, Rückl and Wyler[27] (BRW), in which leptoquarks couple to a single generation of SM fermions via chiral Yukawa couplings which are invariant under $SU(3) \times SU(2) \times U(1)$ is often used to classify possible leptoquark species. In the BRW model baryon and lepton numbers (B and L) are conserved; there exist ten possible leptoquark species characterized by the chirality of the coupling, the spin ($J = 0$ or 1), the weak isospin (T =0, 1/2, or 1), and the fermion number, $F = 3B + L = 0$ or 2.

For a coupling of electroweak strength $\lambda = 0.3$, leptoquarks lighter than $\sim$ 290 GeV are excluded by both ZEUS and H1 [26]. Combining the two HERA searches to effectively double the luminosity would be desirable.

Searches for pair production of leptoquarks from each of the three generations were performed at the Tevatron using Run II data. Decays to both charged leptons and neutrinos were studied. No evidence for leptoquark pair production was found in searches by $D0$ and CDF for final states involving at least two jets and either two charged leptons or one charged lepton and significant missing transverse momentum. The most stringent limits are obtained for the first generation leptoquarks and are directly comparable with the HERA result. Using a Run II data sample corresponding to an integrated luminosity of $\sim$120 pb^{-1}, leptoquarks decaying to eq and with masses below 238 GeV are excluded at 95% C.L., independent of the coupling. This result already improves upon the Run I result.

3.3 FCNC in the top sector

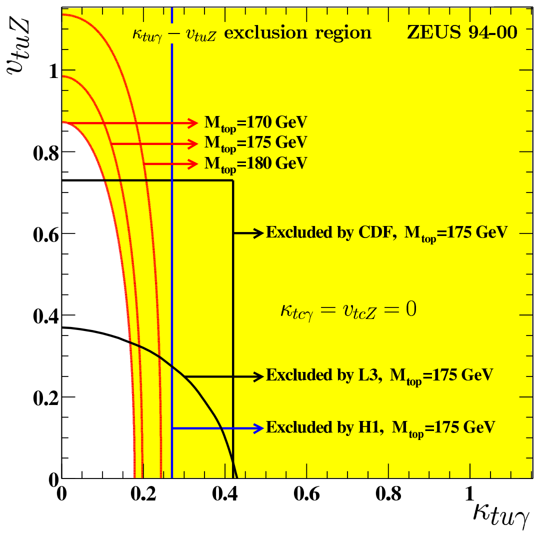

Figure 5. Exclusion limits at the 95% confidence level on the anomalous $tq\gamma$ magnetic coupling $\kappa_{tu\gamma}$ and the vector coupling v_{tuZ} obtained at the Tevatron, LEP (L3 experiment is shown, which currently gives the best limit of the LEP experiments) and HERA (H1 and ZEUS experiments). The anomalous couplings to the charm quark are neglected $\kappa_{tc\gamma} = v_{tcZ} = 0$.

A possible interpretation of an anomalous $W + jet$ production at HERA is provided by the anomalous single top production via flavour-changing neutral currents [28]. Recently published analyses from HERA complement previous searches at LEP and the Tevatron. No signal is observed although H1 does observe a 2σ excess due to the observed events with isolated leptons mentioned above.The sensitivity to new physics signals is expressed in terms of the effective couplings of the top quark to the light quarks and the photon $\kappa_{tu\gamma}$ or to the Z boson v_{tuZ} ($\kappa_{tu\gamma} = v_{tuZ} = 0$ in the Standard Model). Figure 5 summarizes the present status of exclusion limits from colliders in the $(\kappa_{tu\gamma}, v_{tuZ})$ plane.

3.4 Other searches

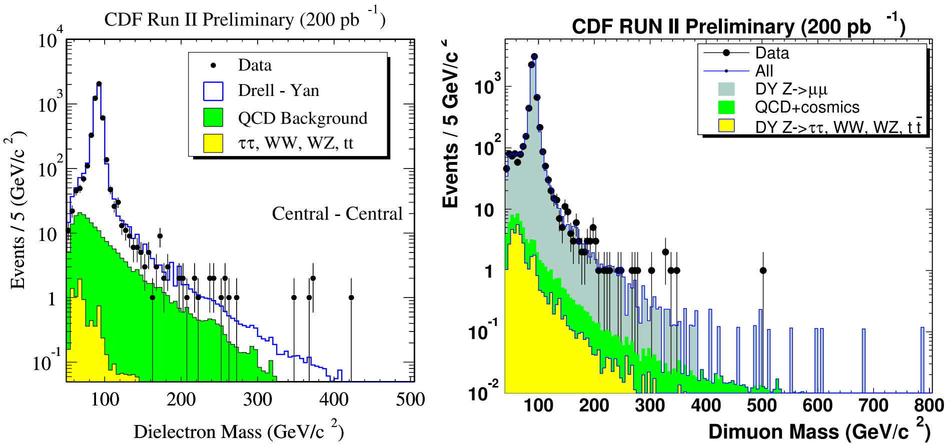

Figure 6. The dilepton invariant mass distribution at Tevatron in the case of dielectrons (left) and dimuons (right)

Many extensions of the SM predict new neutral heavy bosons which couple to leptons. In the simplest ("sequential") model, the neutral boson Z' has the same couplings to leptons as the SM Z boson. In a more sophisticated unification model based on the compact group E_6, four neutral bosons are predicted (Z_I, Z_ψ, Z_χ and X_η). Direct searches at the Tevatron [29] of the dielectron and dimuon spectra are shown in figure 6. No significant deviation from the SM is found and limits on various models have been extracted. In particular, a sequential Z' boson with a mass of 780 GeV is excluded at 95% by the dielectron analysis performed by the $D0$ collaboration. This limit is less stringent than the indirect limit of 1787 GeV obtained from the difermion studies at LEP. The interpretation in terms of E_6 unification models yield limits for the four neutral bosons ranging from 575 GeV to 680 GeV from the $D0$ analysis, better in this case than the indirect limits obtained from LEP.

New physics can be manifested at large transverse momenta and possibly in various channels via different final state topologies. The H1 Collaboration performed a general search for new phenomena at large transverse momentum [30]. The events are classified according to the presence of highly energetic particles (electrons, muons, photons, neutrinos and jets). Classes of events with up to five high P_T particles are investigated. The analysis revealed a very good agreement in this phase space at large transverse momentum ($P_T > 20$ GeV) between data and MC prediction. The search for anomalies in the data has been performed using a model independent statistical method. The already observed excess of events with isolated leptons and missing transverse energy is also detected in this analysis. Besides the impressive control that this analysis provides for all exclusive searches at large transverse momenta, it also acts as a "watchdog" over many channels for manifestations of new physics at large P_T.

3.5 New physics from low energy measurements

SUSY can manifest itself also in the rare decays of the B mesons. An example is provided by the FCNC decay $B \to \mu^+\mu^-$, predicted to have a branching ratio of 3.4×10^{-9} in the Standard Model. The rate of decay can increase by up to three orders of magnitude in SUSY scenarios at large $\tan\beta$. A search for such decays of the B_d and B_s was performed at CDF [24] using $\mu^+\mu^-$ pairs with an invariant mass close to the nominal meson mass yielded no excess over the Standard Model prediction and a 90% confidence level upper limit on the branching ratio of $Br(B_s \to \mu^+\mu^-) < 5.8 \times 10^{-7}$ was obtained. The limit obtained for $Br(B_d \to \mu^+\mu^-) < 1.5 \times 10^{-7}$ improves the limit obtained by Belle $Br(B_d \to \mu^+\mu^-) < 1.6 \times 10^{-7}$ [35].

Another example of B meson decays sensitive to new physics are the radiative ("penguin") decays of the B mesons. The exclusive ($B \to K^*(\rho,\omega)\gamma$) and semi–inclusive $B \to X_s\gamma$ modes are measured at b-factories, for instance by BaBar [31]. Exclusive and semi-inclusive electroweak processes (*e.g.* $B \to X_s\ell^+\ell^-$) have been measured with branching ratios below 10^{-6}. The CP asymmetry is predicted to be zero in those decays within the SM, but can be substantially enhanced by new physics effects [34]. Good agreement with the standard model prediction is still observed in those extraordinary precise and spectacular measurements.

4 A theoretical perspective

4.1 Electroweak corrections to neutrino-nucleon scattering

New results on the electroweak corrections to deep-inelastic neutrino-nucleon scattering have been presented with particular emphasis on the results of the NuTeV experiment [36]. A complete determination of the NLO electroweak corrections has been performed and the residual theoretical uncertainties analyzed in detail. The radiative corrections imply a shift of about 5% on the Weinberg angle extracted from NuTeV data. The correct size of the corrections, however, depends on the procedure of handling the radiation of soft and collinear photons from the initial- and final-state charged particles. Initial-state radiation from the quark lines requires the introduction of a particular mass factorization scheme which will affect the DGLAP evolution of the parton densities, too. The $\overline{\mathrm{MS}}$ scheme has been chosen in complete analogy to QCD, which, however, cannot be treated in a fully consistent way, since the QED effects on the parton densities are not included in any of the available parton density fits. Thus, this aspect contributes to the theoretical uncertainties. The major source of uncertainty originates from the sizeable dependence of the results on the cut imposed on the final hadronic energy. In addition, the dependence on the input parameter scheme turns out to yield a significant contribution to the total uncertainties. The main conclusion is that the theoretical uncertainties estimated by the NuTeV collaboration seem to be smaller by an order of magnitude than the results obtained in this work. Based on this conclusion a reanalysis of the NuTeV data has been initiated which will include the most up-to-date theoretical tools. Moreover, it has been pointed out that the old results of Ref. [37] could not be reproduced. The origin of the discrepancies is presently under investigation.

4.2 NLO QCD results and beyond

Higher-order results for W boson production at large transverse momenta at hadron colliders have been discussed [38]. This process constitutes one of the major backgrounds for new particle searches at the Tevatron and LHC. The NLO QCD corrections have been computed long ago [39]. The aim of the work is an approximate determination of the corrections beyond NLO by taking into account the leading and sub-leading logarithms originating from soft gluon bremsstrahlung. The resulting approximation works well at NLO so that one can expect this to be true even at higher orders. Building on this assumption the approximate NNLO results for W boson production at large transverse momenta and the residual dependence on the factorization and renormalization scales have been studied. The scale dependence turns out to be very small after including these approximate NNLO corrections thus signaling an important theoretical improvement. Moreover, the NNLO corrections turn out to be moderate.

Starting from the same approach, approximate NNLO results for anomalous top quark [40] and charged Higgs boson production [41] at hadron colliders have been presented. Anomalous couplings between the top quark, a light quark and the photon or Z boson are introduced. These lead to significant contributions to single top quark production at the Tevatron and HERA and to top pair production at the Tevatron. Higher-order QCD corrections stabilize the theoretical prediction for these processes and thus reduce the theoretical uncertainties so that more solid bounds can be set from the non-observation of these anomalous contributions. The approximate NNLO results exhibit only a very mild scale dependence and increase the NLO results by a moderate amount so that these processes are under proper control [40].

Charged Higgs bosons will dominantly be produced in association with top quarks at the Tevatron and LHC. In an approximation starting from bottom parton densities, the process of interest is $bg \to tH^-$ and its charge conjugate. The introduction of bottom densities is required, if one wants to resum potentially large logarithms originating from collinear bottom-quark configurations in the final state which originate from gluon splitting. The NLO results are known exactly and reduce the scale dependence significantly compared to the LO result [42]. The approximate NLO result based on the soft-gluon logarithms serves as an excellent approximation of the full calculation. In this talk it was demonstrated that the approximate NNLO corrections lead to a further moderate increase of the cross section and a drastic reduction of the scale dependence far below the expected experimental accuracy [41].

Higgs boson production in association with a $b\bar{b}$ pair is dominant for the minimal supersymmetric extension of the Standard Model at large values of $\tan\beta$, the ratio of the two vacuum expectation values of the scalar Higgs fields due to the strongly enhanced bottom Yukawa coupling. The full NLO QCD corrections have recently been obtained for the $q\bar{q}/gg \to b\bar{b}H$ subprocesses where the gluon-initiated subprocess is by far the dominant contribution [43,44]. The corrections increase the total cross sections by 60–130% at the Tevatron and by 10–80% at the LHC [43]. Due to the significant reduction of the scale dependence the processes are under better theoretical control after including the NLO corrections. If both (anti-)bottom quarks are required to develop large transverse momenta beyond about 20 GeV the radiative corrections are moderate and the reduction of the scale dependence is much stronger [43,44]. This is in fact the expected situation, if both bottom jets are tagged experimentally. The large QCD corrections to the total cross sections may potentially originate from the development of large logarithms due to collinear gluon splitting into bottom-antibottom quark pairs. The resummation of these logarithms requires the introduction of bottom parton densities in the (anti-)proton. Their DGLAP evolution provides the resummation. Comparisons between these two approaches, i.e. with and without bottom parton densities, have been performed and resulted in reasonable numerical agreement within their respective uncertainties [45]. The introduction of bottom densities, however, is based on a collinear approximation of the kinematics which is corrected only at higher orders by the proper matching of the partonic kernels. The quantitative effect of these kinematical approximations has not been analyzed in detail so the full uncertainties of both approaches are unknown.

4.3 Automatic tools

The construction of automatic tools is of increasing importance due to the growing complexity of theoretical calculations and experimental analyses. The latter are strongly based on proper Monte Carlo programs for optimizing cuts and methods in extracting the signal processes and their properties. The theoretical complexity is increasing either with the number of loops to be calculated or the number of external particles which is of particular relevance for future high-energy colliders.

ALPGEN is a Monte Carlo tool for multi-parton final states in hadronic collisions and includes only Standard Model processes at present [46]. There is a large list of available processes involving gauge bosons, heavy quarks and Higgs bosons accompanied by large numbers of jets. Several processes include full spin correlations which are of significant importance at the LHC. Up to eight final partons can be handled by this tool. In addition mass terms and the decay widths of unstable particles are included. The color structure of an event, however, is included in the leading $1/N_c$ approximation. An important feature is the interface to HERWIG [47] and PYTHIA [48] for the evolution of the partonic final state via parton showers. This requires a careful matching between matrix elements and parton showers. ALPGEN has already been used successfully in the analysis of Tevatron data involving W bosons and heavy flavours.

AMEGIC++ is a new tool suitable for the analytical calculation of complicated processes involving many particles in the final state [49]. The basic idea is the factorization of common helicity building blocks so that the factorial growth of the number of Feynman diagrams with the number of external particles is significantly reduced. In addition it uses the multi-channel method for phase space integration including a proper treatment of the peak structure of the matrix elements. This leads to an improved numerical stability. AMEGIC++ presently includes the Standard Model as well as the MSSM. In addition the ADD model has been included. All these models have been tested. A number of processes with a larger number of final-state particles has been tested against other existing tools and satisfactory agreement has been found. Soon the numerical treatment of larger numbers of final state jets will be improved so that it will become a useful tool for the LHC and LC.

4.4 The anomalous magnetic moment of the muon

The theoretical status of the anomalous magnetic moment $(g-2)_\mu$ of the muon has been reviewed with particular emphasis on open problems [50]. The QED part of the calculation is known up to the 5-loop order with an uncertainty far below the experimental error, so this part is under excellent control. Due to the enormous experimental accuracy, electroweak corrections have to be included at the 2-loop level, since they are significantly larger than the experimental error. The major source of uncertainties is the (non-perturbative) hadronic contribution from low-energy scales. The leading part can be obtained from experimental e^+e^- data thanks to a dispersion relation connecting them to the hadronic contribution to $(g-2)_\mu$. Recent low-energy e^+e^- data shifted this contribution slightly and significantly reduced the uncertainty. Due to the approximate isospin symmetry the same hadronic contributions can alternatively be extracted from τ decay data. However, there is a sizeable discrepancy between the values obtained from e^+e^- and τ data which is unresolved. Possible explanations may be provided by a better treatment of isospin-symmetry violating effects or a more conservative estimate of the uncertainties. The last contribution to $(g-2)_\mu$ is due to light-by-light effects where quite recently a sign error in old calculations was pointed out [51]. The correction of this error reduced the discrepancy between theory and experiment by about one standard deviation.

The E821 experiment at BNL has published a new value for $(g-2)_\mu$ in this year and reached satisfactory agreement for μ^- and μ^+ [52]. The experimental and theoretical errors are of similar magnitude. Future improvements are expected on the theoretical side from more precise e^+e^- data at low energies. The deviation between the theoretical and experimental values amounts to 2.7 standard deviations and may indicate physics beyond the Standard Model.

4.5 Strong electroweak symmetry breaking

If the Higgs fields do not exist, the electroweak interactions become strong at higher energy scales. In these scenarios electroweak symmetry breaking is generated by non-perturbative effects analogous to chiral symmetry breaking in QCD. These effects can be treated in terms of a chiral Lagrangian involving the heavy Standard Model particles and the longitudinal modes of the W and Z bosons. In analogy to QCD, heavy vector resonances as the ρ meson are expected to exist which couple to the intermediate vector bosons as well as to the top quark. In the past longitudinal $W_L W_L \to W_L W_L$ scattering processes have been investigated at future hadron and linear e^+e^- colliders [53]. However, this framework also allows $t\bar{t}$ production via $W_L W_L \to t\bar{t}$, which involves the new coupling between the ρ resonance and top quarks [54]. The sensitivity of a linear collider to this process has been analyzed by taking into account unitarity and low-energy constraints. A careful signal and background analysis shows that a linear e^+e^- collider with a c.m. energy of 1.5 TeV will allow to probe the couplings of the ρ resonance to vector bosons and top quarks down to values of 0.1–0.2. In the future, progress will be achieved by optimizing the cuts and finalizing the analysis for all models considered.

5 Conclusions and outlook

The Standard Model continues to be confirmed by the recent results obtained at colliders and b-factories. A wide spectrum of measurements at LEP, HERA and the Tevatron, involving leptons and bosons in the final state finds good agreement with Standard Model predictions. Impressive luminosity increases have allowed the measurement of CP violation in B mesons decays and pushed the branching ratio limits for rare decays down to the level of 10^{-6}.

The final data samples provided by the complementary colliders LEP, HERA, and the Tevatron towards 2007 should be 1000 pb^{-1} of ep collisions at $\sqrt{s}$ of 319 GeV, 2.8 fb^{-1} of e^+e^- collisions at $\sqrt{s}$ up to 209 GeV, and 8-16 fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. While LEP analyses are close to final, at HERA and the Tevatron exploration of new territories will continue. The LHC will greatly extend our capabilities in both direct searches and precision measurements. Given a discovery at LHC, the last 'touche' of precision will be given by the next linear collider.

These present and future prospects, however, can only be fulfilled, if significant theoretical progress will be achieved for the relevant signal and background processes. These tasks will be made doable by the development of automatic tools for theoretical calculations and their interface to the experimental requirements. Many recent improvements in these directions have been obtained and presented.

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