Electroweak and beyond the Standard Model physics

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Abstract. The status of the electroweak Standard Model and searches for physics beyond the Standard Model are reviewed. We focus on recent results from the HERA and Tevatron accelerators and also discuss measurements at the *B* factories and the future at the LHC.

Keywords: LEP, HERA, Tevatron, PEP II, KEK-b, LHC, CDF, DØ, H1, ZEUS, BaBar, Belle, Atlas, CMS, Standard Model, Electroweak, Higgs, SUSY, MSSM, GMSB, mSUGRA, Top, Leptoquark
PACS: 12.15.Ff, 12.15.Ji, 12.15.Lk, 12.15.Mm, 12.60.Cn, 12.60.Fr, 12.60.Jv, 13.60.Hb, 13.66.Fg, 13.66.Hk, 13.66.Jn, 13.88.+e, 14.65.Ha, 14.70.Fm, 14.80.Bn, 14.80.Cp, 14.80.Ly

INTRODUCTION

The Standard Model has been extraordinarily successful in describing all electroweak measurements to date. However, the pivotal particle in the explanation of electroweak symmetry breaking, the Higgs boson, has not yet been observed. Additionally there are theoretical problems with the Standard Model, the hierarchy problem, the lack of unification of the electroweak and strong forces and the lack of a candidate for the dark matter observed in the Universe.

In this report we summarise the latest results on electroweak precision measurements and outline the future prospects. We report the latest results on searches for the Higgs boson within and beyond the Standard Model. Finally we present a number of searches for physics beyond the Standard Model such as supersymmetry, leptoquarks and lepton-flavour violation, large extra dimensions and searches for new physics in the flavour sector.

The experimental measurements have been made at a variety of accelerators: the HERA $e^{\pm}p$ collider ($\sqrt{s} = 319$ GeV), the Tevatron $p\bar{p}$ collider ($\sqrt{s} = 1.96$ TeV) and the KEK-*b* and PEP-II e^+e^- colliders ($\sqrt{s} = 10.6$ GeV). Future prospects at the LHC ($\sqrt{s} = 14$ TeV) are also discussed.

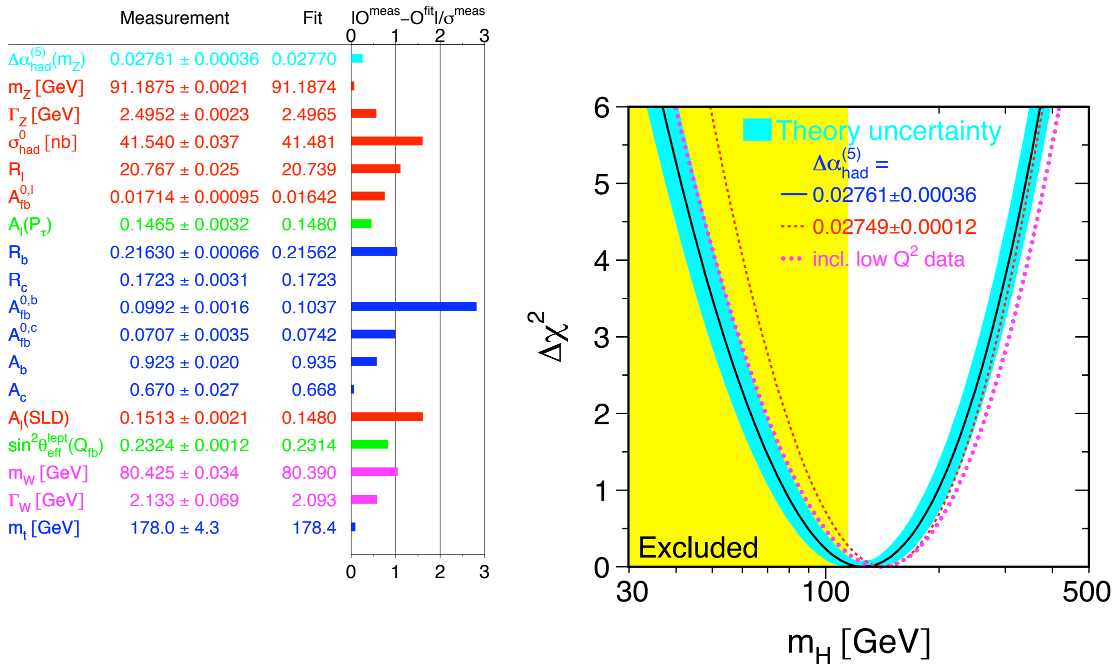

FIGURE 1. Left: The measurements used for the electroweak precision fit. The measurements and the pulls resulting from the fit are shown. Right: the χ^2 of the fit versus the Higgs boson mass. The yellow area is excluded by the direct Higgs boson searches at LEP.

ELECTROWEAK PHYSICS

Electroweak precision measurements

The electroweak sector of the Standard Model is examined to high precision by many direct measurements made at the LEP and SLC colliders in e^+e^- collisions and at the Tevatron in $p\bar{p}$ collisions [1]. A summary of these measurements is shown in Figure 1.

It is seen that all data agree to within 3σ with the fit result. The largest discrepancy arises from the measurement of the forward-backward asymmetry for b-quarks, $A_{FB}^{0,b}$.

Within the electroweak theory these measurements can be used to constrain the mass of the Higgs boson. The χ^2 of the fit is shown in Figure 1 versus the Higgs boson mass. The minimum is at 129 GeV with an uncertainty of $+74$ GeV and -49 GeV at 68% confidence level. The 95% upper limit on the Higgs boson mass is 285 GeV.

Most of these measurements are final and are not expected to be improved in the near future. The only measurements that are expected to change in the near future are the W-boson mass and the top-quark mass. The W-boson mass measurement at LEP is still being finalised and further improvements are expected from the Tevatron experiments. The top-quark mass measurement is also expected to improve substantially due to the new data at the Tevatron.

A new analysis of the W-boson mass using Run II data at the Tevatron of luminosity 200 pb^{-1} was performed and yielded a systematic uncertainty of 76 MeV [2]. However, the measurement is still ongoing and the central value is not yet known. The width of the W boson was measured by the DØ experiment to be $\Gamma_W = 2.011 \pm 0.09(\text{stat.}) \pm 0.107(\text{stat.})$ GeV. This is consistent with the theoretical prediction of $\Gamma_W = 2.099 \pm 0.003$ GeV.

The most recent precise measurement of the top-quark mass is not yet included in the electroweak fit described above. The best precision is currently achieved in the $t\bar{t} \to WWbb \to l\nu jjbb$ decay channel, where one W boson decays leptonically and one decays hadronically. It has recently been made by the CDF collaboration with a luminosity of 319 pb^{-1} of Run II data and yields $m_{top} = 173.5\, ^{+3.7}_{-3.6}\, (\text{stat.+JES}) \pm 1.7(\text{syst.})$ GeV where JES denotes the uncertainty coming from the jet energy scale [3]. This measurement was made using a new technique to minimise the dominant systematic uncertainty coming from the jet energy scale uncertainty. Instead of making a one-dimensional fit for the top mass, the top mass and the jet energy scale are fitted simultaneously. It exploits the fact that within $t\bar{t}$ events the jets from the W decay can be used to gain additional knowledge of the jet energy scale. The major advantage of this method is that the jet energy scale uncertainty will improve directly with increasing statistics. The total uncertainty of $^{+4.1}_{-4.0}$ GeV is smaller than that of the Run I world average of ± 4.3 GeV.

The best result from the DØ collaboration in Run II with a luminosity of 230 pb^{-1} yields $170.0 \pm 4.2(\text{stat.}) \pm 6.0(\text{syst.})$ GeV and the uncertainty is dominated by the uncertainty of the jet energy scale. Additional measurements were made in events where both W-bosons decay leptonically and yield $m_{top} = 165.3 \pm 6.3(\text{stat.}) \pm 3.6(\text{syst.})$ GeV (CDF with $\mathscr{L}dt = 340\ \text{pb}^{-1}$) and $m_{top} = 155\, ^{+14}_{-13}\, (\text{stat.}) \pm 7(\text{syst.})$ GeV (DØ with $\mathscr{L}dt = 230\ \text{pb}^{-1}$).

By the end of 2006 the Tevatron experiments will have accumulated an integrated luminosity of about 2 fb^{-1} per experiment. With this luminosity a precision of $\approx$ 35 MeV is expected for the W-boson mass and $\approx$ 2 GeV for the top-quark mass. These measurements will further test the electroweak sector of the Standard Model and indirectly constrain the mass of the Higgs boson within the Standard Model.

At the LHC the precision is expected to be further improved due to the large statistics available: the goal is to measure the W-boson mass to 15 MeV and the top mass with a precision of $1-2$ GeV.

The Standard Model predicts that the cross sections for charged and neutral current ep deep inelastic scattering should exhibit dependence on the longitudinal polarisation of the incoming lepton beam. In the charged current case the dependence is predicted to be linear with the cross section becoming zero for right-handed (left-handed) electron (positron) beams, due to the chiral nature of the Standard Model. Figure 2 shows measurements of the cross section for charged current scattering as a function of the longitudinal polarisation of the lepton beam from the H1 collaboration [4]. The measurements are in agreement with the Standard Model. Similar measurements have also been made by the ZEUS collaboration [5].

The neutral current scattering process at HERA is sensitive to Z-boson exchange at large virtualities and can be used to constrain the couplings of the light quarks to the Z

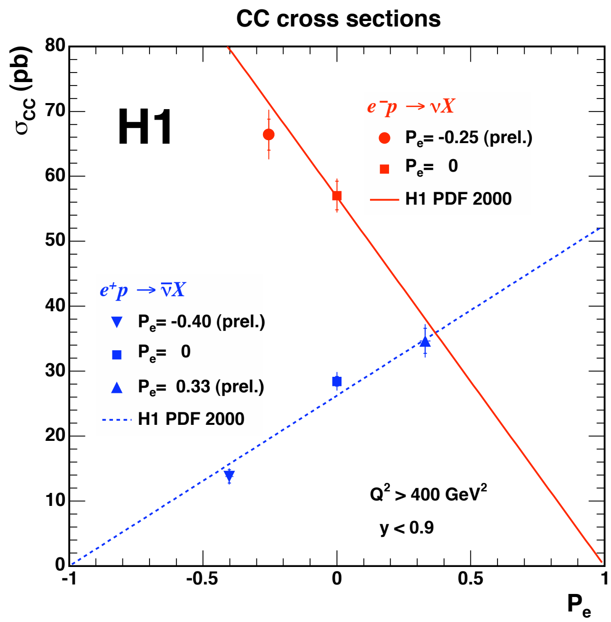

FIGURE 2. Measurements of the cross section for $e^{\pm}p$ charged current deep inelastic scattering as a function of the longitudinal polarisation of the lepton beam from the H1 collaboration.

boson. The results are shown in Figure 3 for the axial and vector couplings of u- and d-quarks using data from H1 corresponding to a luminosity of $\mathscr{L}dt = 100$ pb^{-1} [6].

It is seen that the precision is better for up-quarks as expected due to the larger u-quark density in the proton. It is also seen that the measurements resolve the ambiguity in the LEP data but are of inferior precision to the LEP data. It is expected that the precision will be improved substantially with the HERA II data and with the running with polarised lepton beams.

Top-quark and W-boson production

Due to the large mass of the top quark it can only be produced at the Tevatron $p\bar{p}$ collider (singly and in pairs) and at the HERA ep collider (singly). However, within the Standard Model the rate of top production at HERA is too small to be observed while at the Tevatron the cross section of 6.7 pb [7] for pair production and 3.9 pb for single top production is large enough, and the top quark was observed in pair production in 1995.

The Tevatron collaborations have measured the top quark pair production cross section in many different modes and using many different analysis techniques [8]. A summary of all these measurements is shown in Figure 4.

All cross section measurements agree with the theoretical expectation. The highest precision measurements are the kinematic measurement using a neural network and the measurement using a secondary vertex tag in the lepton + jets channels. Similar measurements from the DØ collaboration are also in good agreement with the theoretical

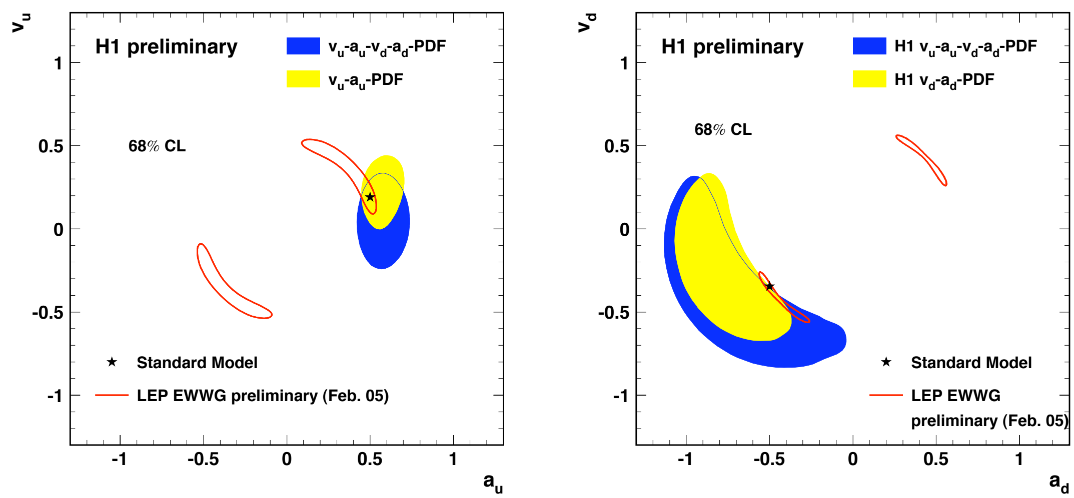

FIGURE 3. Vector versus axial coupling to the Z boson for up-quarks (left) and down-quarks (right). The open contours show the 68% C.L. contours for LEP data and the dark (blue) and light (yellow) contours show the regions allowed by H1. The dark contour shows the result of a fit for all couplings simultaneously and the light contour show the result fixing either the u- or the d-quark couplings.

prediction.

The production of single top quarks can go via two different processes. The s-channel process $q\bar{q} \to W^* \to tb$ where W is produced in the s-channel and decays into a t and b quark. In the t-channel process a W boson is exchanged in the t-channel between a b-quark and another quark, resulting in a final state of a t-, a b- and a 3rd quark. The cross section for the s-channel process is 0.88 ± 0.14 pb, and for the t-channel process it is 1.98 ± 0.30 pb [9].

CDF and DØ have searched for single top production but neither the s- or t-channel process has yet been observed. The best sensitivity is currently achieved by a neural network based analysis from the DØ collaboration with $\mathscr{L}dt = 230$ pb^{-1} [10]. Two separate neural networks are trained to discriminate against the main backgrounds: $t\bar{t}$ and $W + b\bar{b}$ production. An example of the output of neural network which discriminates between $t\bar{t}$ and single top is shown in Figure 4. The data are well described by the background predictions and no evidence for single top production is seen. Thus upper limits at 95% C.L. are set on the production cross sections, separately for the s-channel, $\sigma_s^{95} < 6.4$ pb, and t-channel, $\sigma_t^{95} < 5.0$ pb. CDF obtains upper limits of 13.6 pb in the s-channel and 10.1 pb in the t-channel with $\mathscr{L}dt = 162$ pb^{-1} [11].

With the expected integrated luminosity of Run II at the Tevatron, single-top production as predicted by the Standard Model will be discovered and the W-t-b coupling can be measured. A global analysis using measurements of W-boson polarisation from top-quark decays (in $t\bar{t}$ events) and the s- and t-channel single-top production cross sections can provide the most general determination of W-t-b couplings [12]. Furthermore, different models for the electroweak symmetry breaking mechanism could be distinguished by applying such a global analysis to the LHC data when it becomes available.

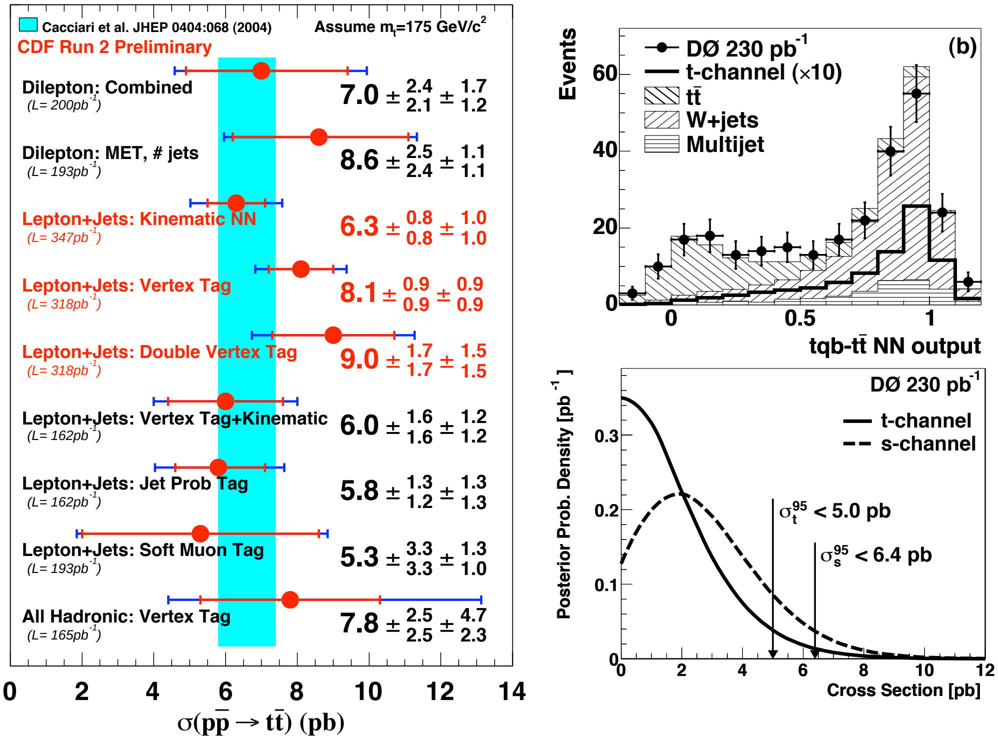

FIGURE 4. Left: top quark production cross section for several CDF measurements using different decay channels: the "Dilepton" channel ($t\bar{t} \to WWbb \to l\nu l\nu bb$), the "Lepton+jets" channel ($t\bar{t} \to WWbb \to l\nu jjbb$) and the "All Hadronic" channel ($t\bar{t} \to WWbb \to jjjjbb$). Right: Neural network output for single top production to discriminate against $t\bar{t}$ production (top) and probability density function for single top production cross section for the t- and s-channel production mechanisms (bottom). The 95% C.L. upper limits are indicated.

At HERA the H1 and ZEUS experiments have searched for direct W production. H1 searches for events with an isolated high momentum lepton and large missing transverse momentum. In the HERA I e^+p data ($\mathscr{L}dt = 104.7$ pb^{-1}) an excess of these events was observed [13]: 18 events were observed compared to a Standard Model prediction of 12.4 ± 1.7. The excess was more pronounced at large p_T of the hadronic recoil, $p_T^X > 25$ GeV: 10 events were observed and 2.9 ± 0.5 expected. No such excess is observed by the ZEUS collaboration [14]: 36 events were observed and $32.5\,^{+1.8}_{-4.7}$ were expected. At high p_T^X ZEUS observe 7 events and expect $5.7\,^{+0.7}_{-0.4}$. The purity of the samples for W production are about 80% for H1 and 45% for ZEUS.

H1 have analysed $\mathscr{L}dt = 53$ pb^{-1} of HERA II data and repeated the analysis using identical cuts [15]: 10 events are observed and 6.1 ± 0.9 events are expected. At high $p_T^X > 25$ GeV there are 5 events observed and 1.7 ± 0.3 events expected. ZEUS have not yet analysed the data from HERA II. It remains to be seen whether this excess continues in H1 and whether the two experiments agree with the increased luminosity expected during the next few years.

At Run II of the Tevatron, a more precise theory calculation that includes the effects from not only the initial state multiple QCD gluon emission but also final state NLO QED corrections to the production and decay of the W boson is needed in order to determine the mass (M_W) of the W boson to an accuracy of about 40 MeV. Such a calculation has recently been done [16]. Since the modeling of the transverse momentum (q_T) distribution of the W boson is also important for the determination of M_W, a possible broadening in the q_T distribution, as suggested by semi-inclusive DIS energy flow data, would yield a different M_W value. Hence, it requires the measurement of the q_T distribution of the Z boson produced in the large rapidity region at the Tevatron to calibrate the q_T distribution of the W boson [17].

Searches for the Higgs boson

The Higgs boson is the only particle predicted by the Standard Model which has not yet been observed. In addition, many extensions of the Standard Model predict additional Higgs bosons that are searched for at colliders.

The most stringent limit on the Standard Model Higgs boson comes from the LEP collaborations which excluded a Higgs boson with $m_H < 114.4$ GeV at 95% C.L.[18]. After the end of LEP the Tevatron is now the only collider where the Standard Model Higgs boson could be observed.

At the Tevatron the main discovery modes are $WH \to l\nu b\bar{b}$, $ZH \to \nu\bar{n}ub\bar{b}$ and $ZH \to l^+l^-b\bar{b}$ if the mass of the Higgs boson is below about 135 GeV since at low mass the Higgs boson decays primarily to b-quarks. At higher masses the higgs boson decays mostly to W^+W^- and this decay is used to search for this Higgs boson.

The search results for $WH \to l\nu b\bar{b}$ (CDF) and $ZH \to \nu\bar{\nu}bb$ (DØ) are shown in Figure 5 where the invariant mass distribution of the b-jets is shown. For Higgs production a resonance is expected while for the backgrounds a continuous spectrum is expected. For the WH analysis only one of the two jets is required to be b-tagged with a secondary vertex algorithm while for the ZH analysis two b-tagged jets are required. In both channels the data agree well with the Standard Model prediction and an upper limit on the cross section times branching ratio is set. The cross section limits of all Standard Model Higgs searches are shown in Figure 5 and compared to the theoretical prediction.

Currently the cross section limits are about a factor of 20 higher than the Standard Model predictions. With increasing luminosity and improved analysis techniques the Tevatron expects to be able to set 95% C.L. limits up to $m_H = 135$ GeV and make a 3σ observation if $m_H < 120$ GeV with a luminosity of 8 fb^{-1}.

The LHC will give the definitive answer to the Standard Model Higgs boson after three years of low luminosity running: the 5σ discovery reach is shown in Figure 6 for $\mathscr{L}dt = 30$ fb^{-1} for ATLAS and CMS. A discovery will be possible for Higgs masses between 100 and 800 GeV. In a wide mass range a discovery can already be made after one year of LHC data taking with $\mathscr{L}dt = 10$ fb^{-1}.

The success of the Higgs boson search in the di-photon channel depends on how well we know about its background rates, i.e. di-photon rates produced via the $q\bar{q}$, qg and gg fusion processes. A theory calculation that includes the effects of multiple QCD gluon emission in the initial state has been performed to compare with Tevatron Run II data

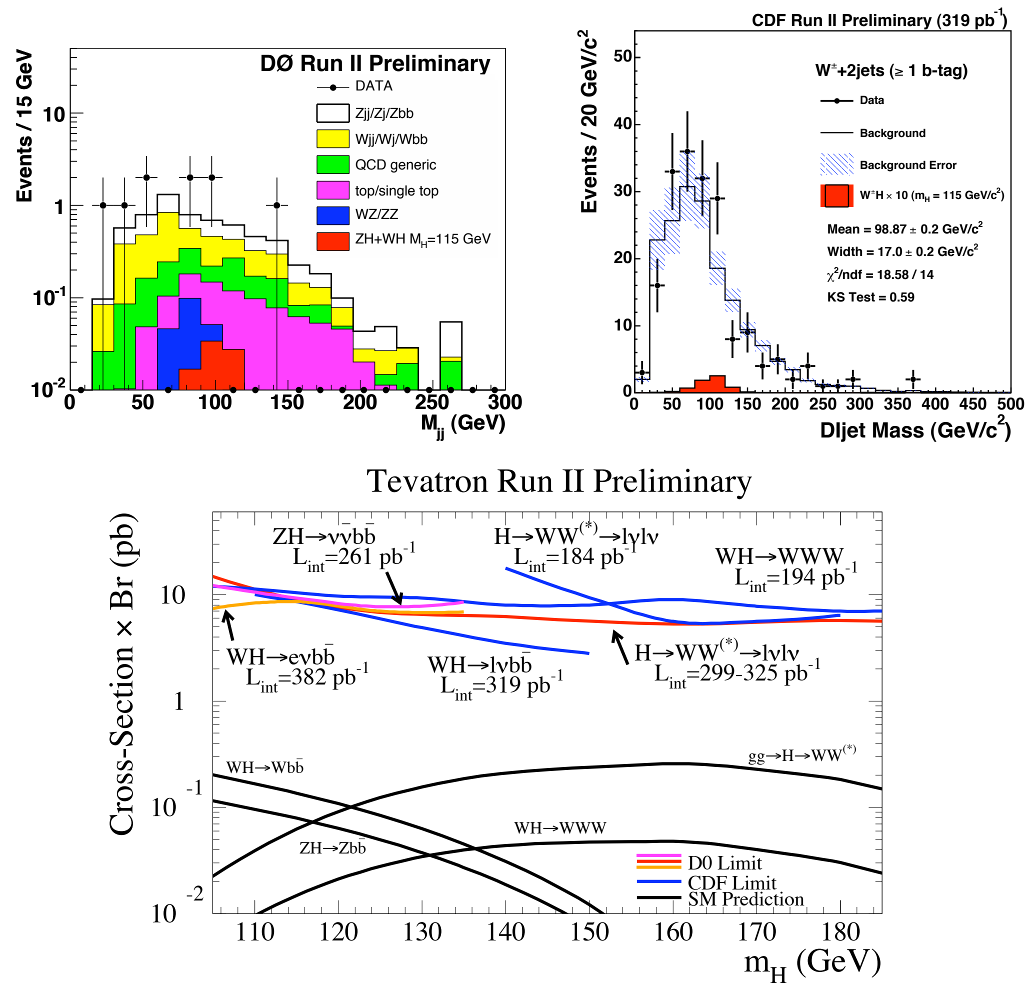

FIGURE 5. Top: $b\bar{b}$ invariant mass distribution for $ZH \to \nu\bar{\nu}b\bar{b}$ (left) and $WH \to l\nu b\bar{b}$ production (right). Bottom: Higgs Production cross section times the branching ratio: the experimental upper limits at 95% C.L. and the theoretical expectations for various production and decay modes are shown.

and the complete NLO calculation. It was found that the resummed calculation agrees well with the NLO calculation in the invariant mass distribution of the di-photon pair. The q_T distribution of the $\gamma\gamma$ pair agrees better with data than the NLO calculation in the low q_T region [19].

SEARCHES FOR PHYSICS BEYOND THE STANDARD MODEL

Higgs bosons beyond the Standard Model

In many extensions of the Standard Model additional Higgs bosons are predicted.

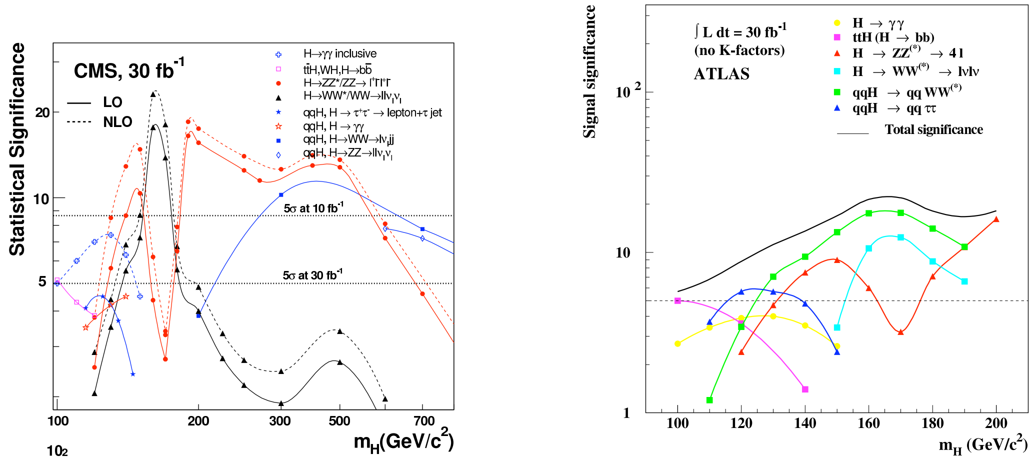

FIGURE 6. LHC Discovery reach for the Standard Model Higgs boson at CMS (left) and ATLAS (right) for $\mathscr{L}dt = 30\ \mathrm{fb}^{-1}$.

In supersymmetry (see section below) there are two Higgs doublets, leading to the existence of 5 Higgs bosons: the neutral scalars h and H, the neutral pseudo-scalar A and two charged Higgs bosons $H^{\pm}$. The main parameter that governs the Higgs sector is $\tan\beta$ which is the ratio of the vacuum expectation values of the two Higgs fields. At low $\tan\beta$ the h behaves very similarly to the Standard Model Higgs. However, at large $\tan\beta$ the couplings to down-type quarks are enhanced ($\propto \tan^2\beta$) and the A is degenerate in mass with either the h or the H.

DØ have made a dedicated search for Higgs bosons at high $\tan\beta$ in the associated production of a Higgs boson with a b-quark: $p\bar{p} \to \Phi b + X \to b\bar{b}b + X$ where $\Phi = h, A, H$. No evidence was found for Higgs production and the data are used to constrain the allowed parameter space [20]. The result is shown in Figure 7 where $\tan\beta$ is shown versus the mass of the Higgs boson. It is seen that a large region of the parameter space is excluded by these data.

In left-right symmetric models doubly-charged Higgs bosons appear naturally. These decay into two leptons and several searches have been made by the Tevatron and HERA collaborations in the channels $H^{\pm\pm} \to e^{\pm}e^{\pm}$, $H^{\pm\pm} \to e^{\pm}\mu^{\pm}$, $H^{\pm\pm} \to \mu^{\pm}\mu^{\pm}$ and $H^{\pm\pm} \to \tau^{\pm}\tau^{\pm}$.

H1 observe a slight excess in high mass, $m_{ee} > 100$ GeV, dielectron production: 6 events are observed compared to a Standard Model background of 0.75 ± 0.13 events. However, these events are not consistent with doubly-charged Higgs production. Furthermore, that interpretation is also ruled out by the CDF and OPAL experiments as can be seen from Figure 7 where the coupling is shown versus the mass of the $H^{\pm\pm}$. Limits are also available for the other decay modes [21].

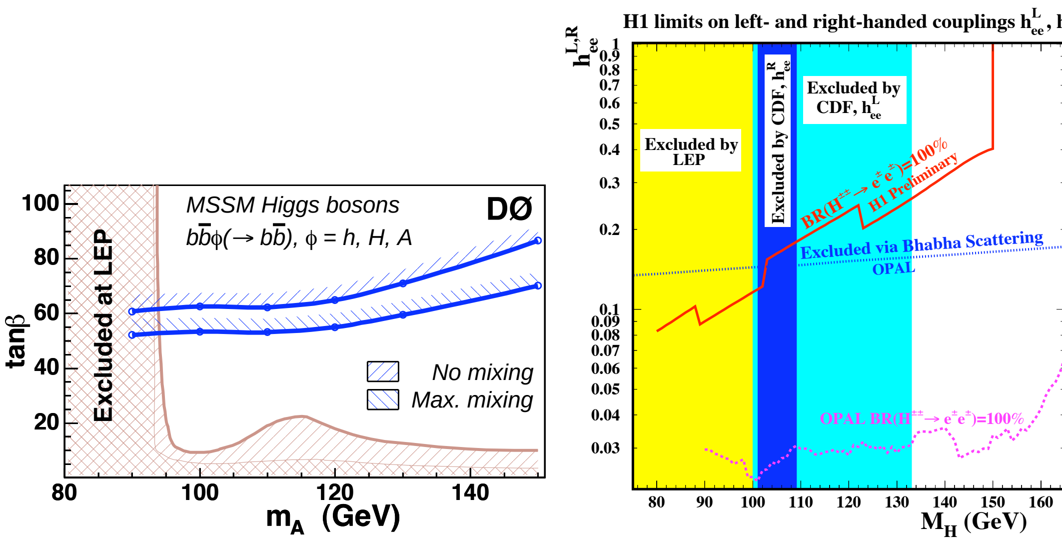

FIGURE 7. Left: Excluded regions of $\tan\beta$ versus m_A for the DØ and the LEP experiments. Shown are two scenarios (“no mixing” and “max. mixing”) which result in different sensitivities due to different radiative corrections. Right: excluded region in coupling versus $m(H^{\pm\pm})$ plane. The H1, CDF, OPAL and LEP regions are shown.

Supersymmetry

Supersymmetry (SUSY) is one of the most promising candidates for a theory beyond the Standard Model. (A comprehensive introduction to SUSY models can be found in the talk given by H. Baer in these proceedings [22].) Through the introduction of superpartners, differing in spin by half a unit, for each of the Standard Model particles it provides solutions to many of the problems associated with the Standard Model and may provide a dark matter candidate particle. None of the superpartners of the Standard Model particles have been observed indicating that supersymmetry is a broken symmetry which predicts additional particles in the Higgs sector.

R-parity is a multiplicative quantum number defined as $R_p = (-1)^{3B+L+2S}$ where B is baryon number, L is lepton number and S is spin. It follows that Standard Model particles have $R_p = 1$ and SUSY particles $R_p = -1$. If R_p is a conserved quantity then SUSY particles may only be pair-produced and the lightest SUSY particle is stable and may be a dark matter candidate. Conversely in R-parity violating scenarios SUSY particles may decay to Standard Model particles. Searches for SUSY at HERA generally consider scenarios in which R-parity is violated, which yield the most competitive limits, while at the Tevatron both R-parity violating and conserving scenarios are explored.

The R_p violating Yukawa coupling λ'_{131} (where the indices refer to generation) allows the resonant production of the stop squark in eq fusion at HERA. The stop squark is of particular interest since due to the large top-quark mass, large mixing can occur in the third generation of squarks, which can lead to low stop masses for high $\tan\beta$ SUSY scenarios. Stop quark decays have been searched for by the ZEUS collaboration [23]. No evidence for Stop production was observed and Fig. 8 shows the upper limits on

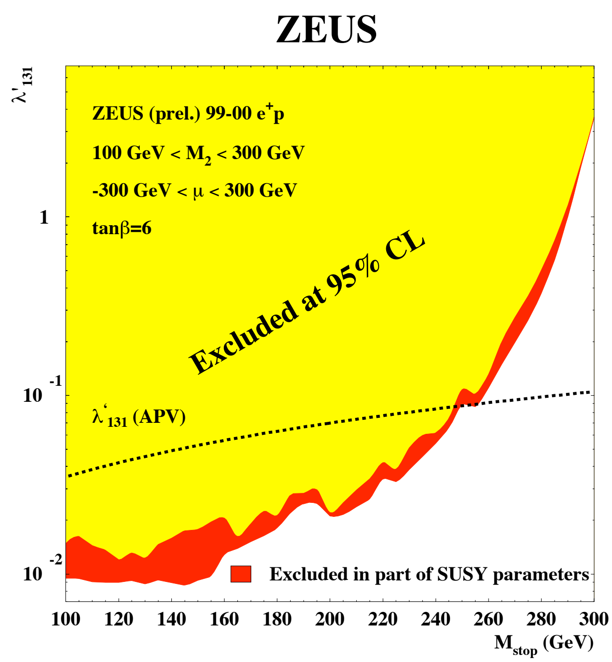

FIGURE 8. Limits on λ'_{131} and the stop mass from the ZEUS collaboration.

the coupling and mass of the Stop that were derived in the framework of the Minimal Supersymmetric Standard Model (MSSM). For a coupling of electromagnetic strength stop masses up to 265 GeV are excluded by this search. Comparable limits are obtained by the H1 collaboration in a similar scenario [24].

A search for light gravitinos in the Gauge Mediated Supersymmetry Breaking (GMSB) model has been performed by the H1 collaboration [24]. In this model the lightest SUSY particle is the gravitino, and decays of a neutralino to a photon and a gravitino were considered. In this way the search is independent of the squark sector. Events with an isolated photon, jet and missing E_T were selected and since no signal was observed limits were set on the neutralino masses and Yukawa couplings. For Yukawa couplings equal to one, neutralino masses up to 112 GeV can be excluded

R-parity conserving decays are characterised by large missing E_T from the lightest SUSY particle which remains undetected. The CDF and DØ collaborations have both searched for events in which a chargino and neutralino are produced and decay through channels with three leptons and missing E_T [25]. No signal is observed but the search yields lower limits on the mass of the chargino of 113-128 GeV depending on the parameters of the minimal supergravity (mSUGRA) model chosen. The DØ collaboration set a limit on the cross section times branching ratio to three leptons, for production of neutralino and chargino of around 0.2 pb. This extends the limit set by LEP, but unlike the LEP limit is model dependent. Similarly the Tevatron experiments have searched for chargino and neutralino production in the GMSB framework through the decay to two photons and missing E_T. The results from the two experiments have been combined to yield a lower limit on the chargino mass of 209 GeV. A large variety of other SUSY searches are also being explored by the Tevatron experiments and their discovery potential will benefit from increased accumulated luminosity in the future.

With a 14 TeV centre-of-mass energy and an expected integrated luminosity of 10 fb^{-1} per year in the first three years the LHC has vast potential to discover supersymmetry at the TeV scale. Detailed studies to develop reconstruction methods and algorithms to best measure various SUSY parameters are well advanced [26]. Full simulation studies show it will be possible to accurately determine the masses of the SUSY particles using a variety of complementary techniques and also to determine the spins of the new particles in order to demonstrate that they are indeed the predicted superpartners of the Standard Model particles.

To fully explore the discovery reach of the Tevatron and the LHC for supersymmetric Higgs bosons produced via bottom quark fusion, the parton distribution function (PDF) uncertainty in its production rate needs to be studied [27]. It was found that at the Tevatron the PDF uncertainty dominates the higher order uncertainty.

Recently, the production cross section for $gb \to H^- t$ at the LHC was calculated to higher orders with less scale dependence than the exact NLO calculation [28].

Leptoquarks and lepton-flavour violation

The symmetry between quarks and leptons in the Standard Model suggests some more fundamental theory may exist allowing direct interactions between quarks and leptons. Leptoquarks are hypothetical bosons which couple to a lepton and a quark and are suggested in many theories that extend the standard model to mediate such interactions. It is usually assumed that leptoquarks couple to fermions of the same generation. Models in which this is not the case introduce flavour changing neutral currents and lepton flavour violation.

Searches by the HERA experiments for leptoquarks produced in eq fusion yield limits on the masses of first generation leptoquarks that depend on the Yukawa coupling of the leptoquark to the lepton and quark. In contrast in searches by the Tevatron experiments for pair-production of leptoquarks the production mechanism is via the strong interaction through $q\bar{q}$ annihilation and gg fusion and is therefore independent of the leptoquark coupling.

Searches at HERA have been made for s-channel resonant leptoquark production through the electron-quark and neutrino-quark decay channels [29, 30]. For a coupling of electromagnetic strength, first generation leptoquark masses below 275-325 GeV can be excluded depending on the leptoquark type. In addition searches for lepton-flavour violation through the interactions $ep \to \mu(\tau)X$ have been performed. Such interactions could be mediated by leptoquarks and also by squarks in R_p violating supersymmetry models. No evidence for lepton-flavour violation was found and the results were interpreted in terms of limits on leptoquark and squark masses. For couplings of electromagnetic strength masses up to around 300 GeV can be excluded. Despite stringent limits on lepton-flavour violation from low energy experiments HERA improves on some of these limits, particularly in the $e-\tau$ transition when second or third generation quarks are involved.

Searches for pair-produced leptoquarks at the Tevatron have been made in both the charged lepton and neutrino decay channels [31]. Results from Run II include only the first and second generations so far and depend on the branching ratio to the charged lepton and quark final state, β. First generation leptoquarks with masses below 256 GeV and 234 GeV can be excluded for values of β of 1 and 0.5, respectively. The corresponding limits for second generation leptoquarks are around 225 GeV and 210 GeV.

Future leptoquark searches should benefit from increased luminosity at HERA and the Tevatron and in the case of HERA also longitudinal lepton-beam polarisation, should lead to more stringent limits.

Searches for new physics in the flavour sector

A complementary method to direct searches for new particles is the high precision study of complex low energy decays in which new physics can manifest itself through virtual loops and corrections to Standard Model processes. The SLAC and KEK *B* factories are ideal for this purpose since very high luminosities, clean signal topologies and low backgrounds make the BaBar and Belle experiments sensitive to rare processes at a level never before achieved. The large number of *B* mesons produced at the Tevatron and high precision tracking detectors also make the CDF and DØ experiments sensitive to such decays.

Searches for new physics through gluonic penguin decays of *B* mesons have been performed by the BaBar and Belle collaborations [32]. In these processes the *b*-quark decays to an *s*-quark and a gluon via an internal loop. By comparing these decays with those to charmonium which proceed without an internal loop, there is sensitivity to new particles contributing virtually. Figure 9 compares the values of $\sin 2\beta$ obtained from gluonic penguin processes to that measured in charmonium decays. A discrepancy of 3.7σ significance is observed between the penguin and charmonium decays, however improved statistics and a better theoretical understanding are necessary before a signature for new physics can be established. Similar measurements have been made by the CDF collaboration [33], however higher statistics are necessary to make the measurements competitive with the *B* factories.

Similarly, radiative penguin decays in which a *b*-quark decays to an *s*-quark and a photon are sensitive to new physics. The branching fractions for the fully inclusive process $B \to X_s\gamma$ and a semi-inclusive sum over many final states have been measured at the *B* factories and found to be in agreement with the Standard Model predictions. In addition the direct *CP* asymmetry has also been measured in these channels and found to be compatible with the Standard Model prediction of zero.

Decays of *B* mesons to di-leptons have very small branching fractions in the Standard Model since they are suppressed by CKM, GIM and helicity effects. However, many models for physics beyond the Standard Model predict large enhancements in these branching fractions, in some cases up to three orders of magnitude, for example in SUSY scenarios with high $\tan\beta$. Such decays have been searched for by the *B*-factory and Tevatron experiments and stringent limits set on the branching ratios. For example

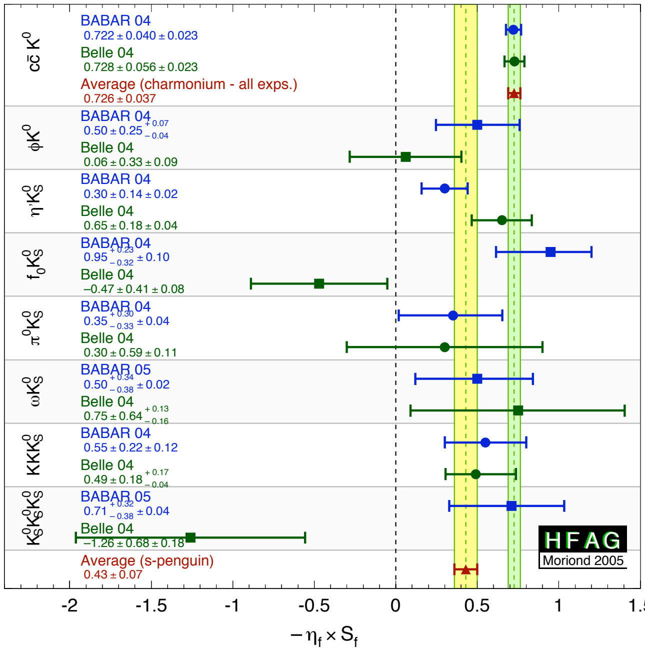

FIGURE 9. Measurements of $sin2\beta$ from gluonic penguin and charmonium decays by the Babar and Belle collaborations.

the CDF collaboration sets a limit of $Br(B_d \rightarrow \mu^+\mu^-) < 3.8 \cdot 10^{-8}$ at 90% CL.

Continued high luminosity running at the B factories and Tevatron offers the prospect of higher precision tests of the Standard Model in the flavour sector in the future.

Many new physics models could be compatible with current data and yield interesting new phenomena in future data. One such example is the MSSM with U(2) flavour symmetry in the quark sector [34]. For example, the apparent deviation in the decay branching ratio of $B_d \rightarrow \phi K_s$ could be explained together with all known flavour physics data.

Other searches

Many other searches for physics beyond the Standard Model have been performed, most notably at the Tevatron [31]. Direct searches for new particles in the di-lepton invariant mass spectra allow limits to be set on Randall-Sundrum gravitons, additional vector bosons such as the Z', technicolour mesons, little Higgs scenarios etc. Indirect searches yield limits on large extra dimension scales in excess of 1 TeV and quark-lepton compositeness scales from 4.2-9.8 TeV depending on the model. A direct search for magnetic monopoles was performed by the CDF collaboration using a novel time-of-flight trigger and dedicated track reconstruction algorithm, which resulted in a lower mass limit of 350 GeV for Drell-Yan pair production.

For a more extensive discussion on new physics models with extra bosons and fermions, see the talks given by L. Wang [35] and T. Tait [36], respectively, in these proceedings. It was argued that extra bosons with electroweak gauge quantum numbers are well motivated by the "little hierarchy problem" [35]. Similarly, vector-like quarks are motivated by the precision electroweak measurement of A_{FB}^{b} [36].

SUMMARY

The electroweak Standard Model continues to give an extraordinarily good description of the wide range of measurements made at LEP, HERA, the Tevatron and the *B* factories. The expected increases in luminosity at HERA, the Tevatron and the B factories in the next few years will test the accuracy of the Standard Model to further precision. The LHC will extend the potential for precision measurements and searches for physics beyond the Standard Model into new territory.

ACKNOWLEDGMENTS

It's a pleasure to be able to thank all the participants for their interesting talks and lively discussion, and the organisers for an exciting and perfectly organised workshop.

REFERENCES

1. P. Renton, in these proceedings.
2. C. Hays, in these proceedings.
3. J.-F. Arguin, in these proceedings.
4. A. Nikiforov, in these proceedings.
5. A. Tapper, in these proceedings.
6. B. Portheault, in these proceedings.
7. R. Bonciani *et al.*, Nucl. Phys. **B529**, 424 (1998); N. Kidonakis and R. Vogt, Phys. Rev. D **68**, 114014 (2003); M. Cacciari *et al.*, JHEP **404**, 68 (2004).
8. K. Ranjan, in these proceedings.
9. B. W. Harris *et al.* Phys. Rev. D **66**, 054024 (2002), Z. Sullivan, Phys. Rev. D **70**, 114012 (2004).
10. V. Abazov *et al.*, DØ Collaboration, preprint hep-ex/0505063, submitted to Phys. Lett. B.
11. D. Acosta *et al.*, CDF Collaboration, Phys. Rev. D**71** 012005 (2005).
12. F. Larios, in these proceedings.
13. V. Andreev *et al.*, H1 Collaboration, Phys. Lett. B**561** (2003) 241.
14. K. Piotrzkowski, in these proceedings.
15. C. Veelken, in these proceedings.
16. Q.-H. Cao, in these proceedings.
17. P. Nadolsky, in these proceedings.
18. R. Barate *et al.*, ALEPH, DELPHI, L3 and OPAL Collaborations and LEP Working Group for Higgs boson searches, Phys. Lett. B**565**:61-75, 2003.
19. C. Balazs, in these proceedings.
20. C. Hensel, in these proceedings.
21. A. Schoening, in these proceedings.
22. H. Baer, in these proceedings.
23. C. Horn, in these proceedings.
24. D. South, in these proceedings.
25. J. Zhou, in these proceedings.
26. N. Ozturk, in these proceedings.
27. A. Belyaev, in these proceedings.

28. N. Kidonakis, in these proceedings.
29. L. Lindfeld, in these proceedings.
30. G. Barbagli, in these proceedings.
31. R. Illingworth, in these proceedings.
32. T. Meyer, in these proceedings.
33. M. Herndon, in these proceedings.
34. S. Gopalakrishna, in these proceedings.
35. L.T. Wang, in these proceedings.
36. T. Tait, in these proceedings.