hep-ex/0211009, Fermilab-Conf-02/275-E

Summary and Highlights of the 14th Topical Conference on Hadron Collider Physics (HCP2002)

Karlsruhe, Germany, September 29 – October 4, 2002

John Womersley
Fermi National Accelerator Laboratory, Batavia, IL 60510, U.S.A.

November 4, 2002

1 Introduction

First of all, I would like to thank the scientific committee, the conference organizers, the University of Karlsruhe and the Institute for Experimental Nuclear Physics, all of the speakers, and the conference secretariat, for making this an extremely well-organized and uniformly high-quality meeting. I would also like to thank all of the speakers who provided me with material for my talk before and during the conference.

There is obviously no point in these proceedings in attempting to repeat all of the material from the individual contributions; by definition, these are all available earlier in this volume. In the written version, therefore, I will try to give a high level overview of the current state of hadron collider physics and to highlight the connections between the many presentations at this conference.

2 Our Tools

The tools of hadron collider physics consist of accelerators, detectors, and computing infrastructure; theoretical predictions and simulation programs; our knowledge of the structure of the proton; and analysis techniques.

2.1 Accelerators and Detectors

At the Tevatron[1], we are not yet out of the woods, but gratifying progress in Run II was reported. Record peak ($3.6 \times 10^{31}\text{cm}^{-2}\text{s}^{-1}$) and weekly ($6.7\text{pb}^{-1}$) luminosities have been recorded in the last few weeks. The complex is now exceeding its performance in Run I. These improvements have come from specific modifications to the complex, and from much hard work. The injectors are providing the necessary beam for higher luminosities, and there is a fully resource-loaded plan for the next year. The major issues are Tevatron transfer and acceleration efficiencies, emittance dilution, beam lifetimes at 150 GeV (before acceleration), and the role of long range beam-beam effects. There is no silver bullet; rather, there are a large number of ten to fifteen percent improvements to be made.

The CDF and DØ detectors are both working well and recording physics quality data. DØ[2] showed results from tracking, calorimeter and muon detectors. Improvements are still in store in the trigger, including a silicon vertex detector currently under construction. CDF[3] reported on detector and trigger capabilities. Track triggering uses the drift chamber at level 1 and displaced tracks from silicon at level 2; this is a major success and has already yielded some very impressive heavy flavor samples. A tau trigger[4] is running and a clear $W \to \tau\nu$ signal is seen.

The HERA accelerator[5] has been substantially upgraded since its last physics run in 2000. There are new interaction regions with ~ 500 m of new accelerator, 58 new magnets, and spin rotators. The goal is to increase luminosity by a factor of roughly four and to deliver about 1fb^{-1} to the experiments by 2006. Commissioning has been a painful process, thanks to synchrotron radiation problems (better shielding is needed) and beam-gas interactions (requiring improved vacuum). The detectors have also been upgraded, in pursuit of physics goals in QCD, proton structure and searches.

At the LHC [6], the challenges are those of complexity and scale. For the detectors, these take the form of occupancy and radiation in the tracking detector, the need to build huge detectors to measure high-p_T muons, the need for excellent electromagnetic energy resolution in the calorimeters (for $H \to \gamma\gamma$), and the challenges of triggering and subsequent data processing. The management, logistical and assembly issues are also on a new scale. The scheduled accelerator start-up remains in 2007. Dipole magnet production is the critical path and it is still very early in the process (40 of roughly 2000 dipoles are expected by the end of 2002).

2.2 Luminosity Measurement

Knowledge of the luminosity in a hadron collider requires counting the rate of a reference process with a known cross section. Traditionally, the total inelastic cross section has been used. This allows instantaneous, real-time, bunch by bunch measurements. The CDF and DØ detectors have installed new detectors to measure the inelastic rate in Run II[7]: scintillators in DØ, and a novel Čerenkov detector in CDF. The inelastic cross section can determine luminosity at the $\Delta\mathcal{L} \sim 3-5\%$ level, but there are problems in knowing what cross section to use (in the past, DØ used the World Average and CDF used their own measurement) and what uncertainty to assign (these two cross sections were not really compatible within their errors). These will be resolved for Run II.

It has been proposed [8,9] that greater precision could be obtained by using inclusive W or Z production as the reference process. This is a better known, calculable cross section, but the acceptance needs to be modelled and the calculated cross section depends on parton distributions (hence it is important to understand the uncertainties on the latter). The feasibility of this idea has been demonstrated using DØ Run I data, but it has not yet been used by the experiments; CDF and DØ will do this "for real" in Run II. Initially we expect $\Delta\mathcal{L} \sim 3 - 5\%$ here, with the hope of reducing the error to $\sim 1\%$ over time.

At the LHC[10], ATLAS and CMS have set the goal of $\Delta\mathcal{L} = 2\%$. They appear to be "covering all the bases," with dedicated small angle detectors (TOTEM in CMS, Roman Pots in ATLAS) and plans for special running with a detuned β^* to measure the reference process at 14 TeV; wider-angle forward detectors for real-time monitoring of luminosity; and the potential to use physics processes like W and Z-production offline.

2.3 Computing and Analysis

Computing for data processing and analysis is a challenge for modern experiments both because of the quantity of data and the size and geography of the collaborations [11]. There is a natural synergy between the need to address these challenges and current ideas about "Grid" computing. Developments at the Tevatron are making something like a Grid a reality (distributing data analysis using the SAM system for both CDF and DØ), and the LHC will rely much more on the full realization of distributed resources and the tools to make them useful.

Given the low signal cross sections for many interesting processes at hadron colliders, analysis of our data clearly benefits from the use of advanced techniques to separate signal from background. Multivariate tools[12] are now quite widely employed.

2.4 Simulation

Event generators are essential tools for understanding hadronic processes. There is much effort towards improving the showering event generators, such as Herwig and Pythia, that are very widely used in hadron collider physics[13] The parton shower can be corrected using the matrix element to cover phase space better. There is work to connect parton showers with the leading order matrix elements for many-body final states without double-counting or dead regions of phase space – very useful with the new generation of automatic matrix element calculators (see below). There are also efforts to merge higher order matrix elements with parton-showering event generators without double-counting, perhaps the best known being the MC@NLO project.

The Herwig event generator is currently being rewritten in C++, and uses a common class library with Pythia7 (but not common physics functions). A beta version for e^+e^- is expected later in 2002, with the first release in 2003 and a full version for hadron colliders by 2004.

It would be very desirable to have a better modelling of the underlying event in hadron-hadron collisions; this is an important source of uncertainty on the jet energy scale (and thus on the top mass). To help, there are some very nice data from CDF [14] on particle flow around and between jets. Multiple parton scattering also needs to be understood: what fraction of the $Wb\bar{b}$ background at the LHC is due to a W and a $b\bar{b}$ pair from different parton-parton collisions?

2.5 Proton Structure

Our current knowledge of parton distributions is dominated by deep inelastic scattering (DIS) data from HERA [15]. Structure functions are measured at the few % level and cover six orders of magnitude in x and Q^2. Photon, Z and $W^\pm$ exchange are probed. With the HERA II upgrade, we can expect higher luminosity, more e^- data, and information from polarized beams. In addition to DIS, the latest CTEQ6 and MRST2001 fits use Tevatron jet data to constrain the gluon distribution.

One can fit all the current data with NLO theory and a reasonably consistent set of parton distributions[16]; the resulting χ^2 is about 1.1 per degree of freedom. Most recent work has been directed at understanding the uncertainties on these distributions (inspired by, among other things, the controversy over whether parton distributions were consistent with the Tevatron high-E_T jet cross section). A variety of approaches is used by the different groups, mainly differing in their treatment of systematic errors. The uncertianties in the distributions are at the $1-5\%$ level except in odd regions (such as the gluon and d-quark distributions at high-x). Unfortunately, it appears that the uncertainties due to varying the theoretical assumptions, α_s, cuts on the data and so on can be much greater than the experimental errors. As an example, if the parton distributions are refitted after excluding DIS data below a cut of $x = 0.005$, the calculated Tevatron W and Higgs cross sections shift by about three times the nominal uncertainty from the original parton distributions. This probably points to inadequacies in the theoretical predictions that are used to extract parton distributions from measured DIS cross sections (such as incomplete treatment of higher order terms, low-x or high-x resummation, low-Q^2 or higher twist effects).

2.6 Theoretical Progress

There are various fronts on which theoretical progress at hadron colliders is taking place.

Next-to-next-to-leading order (NNLO) calculations are required to challenge the high statistics results from the Tevatron and HERA [17,18]. This has been known for a while, but the bottleneck was calculation of the two-loop box graph, a critical component of the NNLO jet cross section. This has now been solved and there has been great progress in the last couple of years; we can expect the first NNLO parton level Monte Carlo generators in the next two years, including $p\overline{p} \to \mathrm{jet} + X$.

Leading order simulations for up to 8 partons in the final state are now available (e.g. QCD backgrounds to $t\bar{t}H$). These and other matrix elements can now be automatically generated by the non-expert user with programs such as Madgraph, Comphep, Alpgen, etc.

Vector bosons plus jets are a critical background at the Tevatron and LHC [9] and need to be well understood. At Leading Order, $W/Z+$ any number of jets is available. At NLO, W/Z + 2jets is handled by the `mcfm` program, but there is a real need for an NLO W/Z + 3jets parton level generator (this is the dominant backgound to top). The cross section calculations are reasonably stable at NLO and there is good agreement with the data for inclusive and one-jet final states; the data with up to four jets agrees with the LO calculation after some scale tuning. Vector boson transverse momentum in the low-p_T region is not modelled well by these programs: non-perturbative parameters are involved but can be extracted from the data (using the Z to model the W for example).

3 Our Physics

In the opening presentation[19], we heard five ways in which hadron colliders can confront the Standard Model:

- The strong interaction
- The CKM matrix
- Electroweak measurements
- The top quark
- The Higgs boson

To these we should add

- Direct searches for new phenomena not part of the Standard Model.

3.1 QCD

No one doubts that QCD *is* the theory of the strong interaction of quarks and gluons. QCD is so central to the calculation of signal and background processes at hadron colliders that we need to make sure that we can have confidence in our ability to make predictions in its framework. We need to resolve some outstanding puzzles in the data, and ensure we understand how to calculate the backgrounds to new physics.

Jet Production

Both CDF[14] and DØ[20] reported inclusive jet E_T distributions from Run II. While these are not yet fully corrected, already we see events out to $E_T \sim 400\,\mathrm{GeV}$. CDF are making use of their new forward calorimetry to cover the whole range $0.1 < |\eta| < 3.0$. With the full Run II dataset the inclusive distribution should extend out to $E_T > 600\,\mathrm{GeV}$, allowing us to pin down the high-E_T behaviour of the cross section and providing tighter constraints on the gluon PDF. (Recall that the gluon at high x is one of the least well-constrained PDF's).

Another issue provoking much discussion was the choice of jet algorithm [21]. The DØ Run I data have shown that cone and $k_\perp$ algorithms yield different cross sections for collider jet data; this is expected and qualitatively agrees with parton-level simulations. Quantitatively, though, it is not yet fully clear whether the difference is actually at the level expected and whether showering and hadronization (not modelled in a parton level Monte Carlo) can explain it.

At HERA, jet studies allow very precise tests of QCD predictions [22]. Studies are carried out in two regimes: photoproduction and deep inelastic scattering (DIS). There has been a big effort to reduce the experimental uncertainties in tests of perturbative QCD at HERA, and now the theoretical uncertainties limit the precision attainaible in many analyses: higher orders or resummed calculations are needed. Also, the present precision in the predictions is not sufficient to constrain the partonic content of the photon. Both H1 and ZEUS have new, precise determinations of α_s using DIS data; the uncertainties are comparable to that in the current World Average.

Heavy flavour production

At the Tevatron, Run I left a lot of unanswered questions[23]. The measured inclusive B production cross section lies significantly above the NLO QCD prediction, though the prediction can be made to agree better with resummation and retuned $b \to B$ fragmentation (from LEP). For charmonium, the observed cross section requires a large colour-octet component which matches the p_T distribution seen in data but then completely fails to describe the J/ψ polarization above p_T 10 GeV. The CDF secondary vertex trigger in Run II is working beautifully and the resulting large charm and bottom samples will allow these puzzles to be explored in much more detail. DØ[24] showed preliminary Run II J/ψ and muon+jet cross sections as first steps in measuring the charmonium polarization (and production process) and the b-jet cross section.

At HERA [25] there have been many new results on charm and bottom production in 2002. Almost all lie significantly above NLO theory, though a ZEUS DIS measurement at the largest Q^2 is in agreement (note that the same pattern is seen in the Tevatron b-jet cross section which comes closer to QCD at the highest p_T). There is no hard evidence for (or against) a colour-octet contribution to J/ψ production at HERA.

On the theoretical side[18,26], there were suggestions that an incomplete treatment of fragmentation may be part of the reason for the B-production "excess." Also, Tevatron data on fragmentation have not been published since the 1988-89 run and higher statistics would be useful. Given the uncertainty as to whether NLO theory is adequate for heavy flavour, we really need NNLO calculations both for charmonium and b production.

There is also the suggestion [27] that one could test the charmonium production mechanism using vector boson plus charmonium associated production.

Direct Photons

Isolated photon results from hadron collisions[28] are quite consistent with NLO QCD at high p_T, but CDF, DØ and E706 data show an excess at the low p_T end of the spectrum. One explanation proposed is that there is additional transverse momentum ("k_T") from soft gluon radiation. One can model this using a few GeV of Gaussian transverse smearing, resulting in a much improved match to the measured cross sections. The amount of smearing needed increases smoothly from about 1 GeV at fixed target energies to 1.5 GeV at HERA and 3.5 GeV at the Tevatron. Resummation offers the hope of a more predictive calculation. The fragmentation contribution to photon production cannot be neglected; again, LEP results are used. Also, at HERA, photon production may indicate a need to review the present modelling of the partonic structure of the photon.

QCD at the 1 GeV scale

In low-x DIS at HERA [29], DGLAP evolution of the structure function F_2 works all the way down to about $2\,\mathrm{GeV}^2$. Leading order DGLAP plus a resolved photon describe the data well. Below this, a variety of models are invoked: Regge, color dipoles, etc. There is no sign in the data of BFKL evolution or of saturation effects. One place where the data seem to prefer BFKL – in fact the only place I can think of where this is the case – is high-t vector meson production at ZEUS[30]. A resolved photon interacting with a BFKL gluon ladder describes the data well, and straightforward two-gluon exchange fails to do so.

At the Tevatron, experiment E735 measured particle production at $p_T \sim 1\,\mathrm{GeV}$ in Run I [31]. The data can be interpreted as showing some of the features expected with the onset of quark-gluon deconfinement.

Such deconfinement is of course the domain of RHIC. Recent results from STAR[32] on gold-gold collisions show large anisotropies in particle flow; this is expected in a hydrodynamical picture of the collision where there is an elliptical source region (coming from the overlap between two nuclei in a non-head-on collsion). The behaviour of the velocity moments as p_T increases is consistent with jet quenching. More strikingly, the clear back-to-back dijet topology that is seen in pp collisions at RHIC is absent in $Au\,Au$ collisions; the trigger jet remains, but with "nothing" recoiling against it. Qualitatively, this is just what is expected if a parton-parton pair is produced near the edge of "blob" of quark-gluon matter; a jet travelling outward will emerge unimpeded, while its back-to-back companion has to travel through the deconfined matter and is rescattered and quenched.

Diffraction

Presentations on diffraction at HERA [33], CDF [34] and DØ [35] together with a theoretical view [30] showed that there is still much to understand in this area.

A rapidity gap is a region of phase space with no particles flowing into it; a gap is expected if the hard scattering involves exchange of a colourless object like a pomeron. In $p\overline{p}$ collisions, such a gap would often be spoiled by particles from spectator parton interactions and so the gap survival probability is expected to be small. Even though factorization (the apparent partonic structure of an exchanged pomeron) is not guaranteed to work in $p\overline{p}$ collisions, if one simply takes pomeron parton densities inferred from HERA together with the guess that there is a 10% rapidity gap survival probability, then one can describe CDF and DØ data quite well. In this picture the pomeron is about 80% gluonic.

DØ showed a new result on diffractive W production tagged with rapidity gaps (complementing CDF's earlier result). W production with a rapidity gap is observed at perhaps 1% of the inclusive W rate. If true, this is certainly surprising: how can one kick a parton out of a proton with $Q^2 = m_W^2$ and not destroy the proton in the process? Moreover, how can one do this fully 10% of the time that one makes a W? (assuming a 10% gap survival probability and a 1% measured rate). Does this tell us something about the makeup of the proton – or about the underlying event in $p\overline{p}$ collisions?

In Run II, both CDF and DØ are improving their diffractive instrumentation. CDF have added shower counters and calorimeters to cover $3.5 < |\eta| < 7.5$; DØ have new Roman Pots in the $\pm z$ direction and veto counters covering $2.5 < |\eta| < 6$. Some Run II physics goals that even the "pomeron skeptical" could support include making a direct measurement of the rapidity gap survival probability, indeed testing the assumption that rapidity gaps correlate with diffracted (anti-)protons seen in the Roman Pots. It will also be good to measure the cross section for the process $p\overline{p} \to p\,(gap)\,jj\,(gap)\,\overline{p}$. This will provide a sanity check for ideas of Higgs production through $pp \to p\,(gap)\,H\,(gap)\,p$ at the LHC. Published cross sections for the latter process cover three orders of magnitude with prospects ranging from "promising" to "impossible".

3.2 CKM Physics

Our goal here is to confront the unitarity triangle in ways that are complementary to the e^+e^- B-factories[36]. CP violation is now established in the B system through $B_d \to J/\psi\, K_S^0$. We find $\sin\phi_d = 0.734 \pm 0.054$; either $\phi_d = 47°$ ($= \sin 2\beta$ in the SM) or 133° (new physics). BaBar and BELLE can and will do much more with their data, for example, is $B \to \pi K$ consistent with $\gamma < 90°$ (SM)? Is the mixing asymmetry the same in $B_d \to J/\psi\, K_S^0$ and $B_d \to \phi K_S^0$? $B \to \pi\pi$ will be an important piece of the puzzle, and right now the two experiments' measurements of this asymmetry are not really consistent.

The "El Dorado" for hadron collider experiments (first at the Tevatron, then at the LHC[37]) is the B_s system. They will measure the mixing parameter $x_s = \Delta m_s/\Gamma_s$ and thus determine the length of the unitarity-triangle side opposite the angle γ. CDF expect to have sensitivity to SM values of x_s with a few hundred pb^{-1}, and to reach up to $x_s = 70$ with $2\,\mathrm{fb}^{-1}$. The width difference $\Delta\Gamma_s/\Gamma_s$ may also be significant in the B_s system. The angle γ can be extracted using the decay $B_s \to D_s K$. It will be interesting to see if there is sizeable CP violation in $B_s \to J/\psi\,\phi$ (it should be small in the SM); also, $B_s \to KK$ complements $B_d \to \pi\pi$ and together they can pin down γ. There are many other interesting topics such as rare decays (e.g. $B \to K^*\mu^+\mu^-$, $B_{s,d} \to \mu^+\mu^-$) and relating CP violation in the B system with $K \to \pi\nu\overline{\nu}$.

CDF reported[38] most impressive results from Run II, building on their Run I experience together with the new detector capabilities (silicon vertex trigger, time of flight detector). With a leptonic trigger, signals for $B^+ \to J/\psi\,K^+$, $B^0 \to J/\psi\,K^{*0}$, and $B_s \to J/\psi\,\phi$ are seen; using the SVT, the purely hadronic modes $B^\pm \to D^0\pi \to K\pi\pi$ and $B \to$ hadron hadron are being recorded. We can also look forward to the world's largest sample of charm mesons.

In DØ the tools are being put in place for a B-physics program[39]. The inclusive B lifetime has been measured and DØ's first B mesons are being reconstructed ($B^\pm \to J/\psi K^\pm$). DØ can not make use of purely hadronic triggers but benefits from its large muon acceptance, forward tracking coverage, and ability to exploit $J/\psi \to e^+e^-$.

3.3 Electroweak Physics

Here we wish to indirectly probe new physics through its virtual effects on precision electroweak observables. At hadron colliders, the most powerful constraints come from our measurements of the masses of the W boson and the top quark.

DØ[40] and CDF[41] both reported first results from Run II samples of W and Z candidates. The experiments have measured the cross section times branching ratio to leptons $\sigma \cdot B$ the new centre of mass energy of 1.96 TeV (Fig. 1) and also the ratio of $\sigma_W \cdot B(W \to \ell\nu)/\sigma_Z \cdot B(Z \to \ell\ell)$ which allows an indirect extraction of the W width. CDF also have taken a first look at the forward-backward asymmetry in e^+e^- production in Run II.

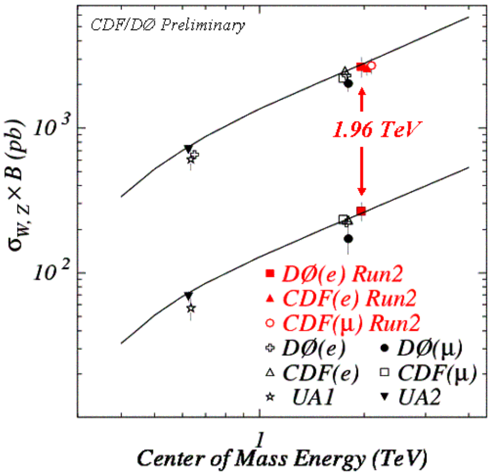

Fig. 1. Cross section times leptonic branching ratio for $p\overline{p} \to W/Z \to \ell$. The data points at 1.96 TeV are new, preliminary Run II measurements

Currently, the hadron collider determination of m_W is $80\,454 \pm 59\,\mathrm{MeV}$, while the world average (which is dominated by LEP) is $m_W = 80\,451 \pm 33\,\mathrm{MeV}$. The high precision achieved at LEP means that it will take a hadron collider dataset of order $1\,\mathrm{fb}^{-1}$ in Run II before we can significantly tighten our knowledge of m_W – this is not a short term prospect. Given $15\,\mathrm{fb}^{-1}$, however, we will eventually be able to drive the uncertainty down to the 15 MeV level. Even greater precision will be possible thanks to the huge statistics at the LHC[42] should it be needed.

3.4 The Top Quark

We wish to measure the top quark's properties with greatly increased statistics, and also use it as a possible window to new physics. Both DØ[43] and CDF[44] showed "steps on the road to rediscovering top" and both experiments have candidate events. In contrast to the case with the W mass, we can look forward to significant improvements in the short to medium term because the Run I dataset was so statistically limited. We expect of order 500 b-tagged $t\overline{t}$ events in the lepton + jets final state, per fb^{-1} recorded. We plan to improve the cross section and mass measurements, look for $t\overline{t}$ spin correlations, and observe single top production (which yields a model-independent measurement of the CKM matrix element $|V_{tb}|$).

DØ also reported[45] a significant improvement in the extraction of the top mass using existing Run I lepton + jets data. The new technique makes use of more information per event: it involves calculating a likelihood as a function of m_t, for both signal and background hypotheses, event by event. All possible jet assignments and neutrino momenta are considered. The event likelihoods are then combined to give an overall likelihood curve from which m_t is extracted. This technique gives better discrimination between signal and background than the published 1998 analysis[46] and improves the statistical error equivalently to a factor 2.4 increase in the number of events. The new result is

$$m_t = 179.9 \pm 3.6(\text{stat.}) \pm 6.0(\text{sys.})\,\text{GeV} \quad \textit{Preliminary} \tag{1}$$

Use of the hadronic W decay offers hope to reduce the current systematic error, which is dominated by jet energy scale.

Some beyond-the-standard-model theories predict unusual top properties and/or states decaying into top that would be visible in Run II or at the LHC[47]. Examples include $X \to t\bar{t}$ (searched for by CDF and DØ, who reported a new Run I limit at this meeting), a top-Higgs with flavour-changing decays visible as a $t +$ jet resonance, and anomalously enhanced single top production.

3.5 The Higgs Boson

Our goal is to discover (or exclude) the SM Higgs and/or the multiple Higgs bosons of supersymmetry. We want to observe as many production modes and decay channels as possible so that we can combine measurements to extract the Higgs couplings.

At the Tevatron[48,49], the emphasis now is on developing the foundations needed for Higgs physics: good jet resolutions, b-tagging and trigger efficiencies, and a good understanding of all the backgrounds. One area that can be attacked with relatively modest luminosities in Run II is associated production of a neutral SUSY Higgs with a $b\bar{b}$ pair; at high $\tan\beta$ the cross section is enhanced and Run I data have already allowed limits to be set.

To explore the full range of SM Higgs masses will require $10 - 15\,\text{fb}^{-1}$ and that, in turn, dictates upgrades to the CDF and DØ detectors and trigger systems. These upgrades are now moving towards approval with installation planned for 2005.

On the theoretical front [50] there are improved predictions both for signals and backgrounds. Backgrounds are available at NLO level using `mcfm` and DIPHOX programs. The $t\bar{t}$ process, from which the top quark Yukawa coupling can be extracted, is now calculated at NLO: the Tevatron cross section is 20% lower than earlier (LO) estimates, while the LHC is 20% higher. The $gg \to H$ process is even available at NNLO (resulting in much reduced scale-dependence) and the p_T and y distributions at NLO. At the LHC[51], there has been a lot of interest in the Weak-boson fusion process for Higgs production as a way of accessing $H \to \tau\tau$ and $b\overline{b}$ decays – both as a low mass Higgs discovery mode and in order to make coupling measurements.

3.6 Searches for Physics beyond the Standard Model

In Run I [52], CDF and DØ carried out extensive searches for supersymmetry: squarks and gluinos through E_T^{miss}+jets(+ lepton(s)); charginos and neutralinos through multileptons; gauge mediated SUSY through E_T^{miss} + photon(s); stop and sbottom; and R-parity violating variants. Searches for other new phenomena included leptoquarks, dijet resonances, W' and Z', massive stable particles, monopoles, and extra dimensions. In all cases, no new physics was found. (At this meeting, CDF did report a possible disagreement between the observed and predicted number of lepton+photon+E_T^{miss} events. This may be something to watch at HCP 2004?)

DØ[53] has embarked on a number of searches using Run II data. Work has started on understanding the E_T^{miss} distribution in multijet events as a prelude to squark and gluino searches; trilepton candidates are also being accumulated. A gauge mediated SUSY search has been carried through to set a limit of 0.9 pb on the cross section for $p\overline{p} \to \gamma\gamma + E_T^{\text{miss}}$. Virtual effects of extra dimensions are being sought in $p\overline{p} \to e^+e^-$, $\mu^+\mu^-$, and $\gamma\gamma$. Limits of $M_S(GRW) > 0.92(0.50)$ TeV are set in the electron/photon (and muon) final states. Also, a search for leptoquarks decaying to electron+jet excludes masses less than 113 GeV (for $B(\text{LQ} \to ej) = 1$). None of these cross sections or mass limits is better, yet, than published Run I limits, but serves as a demonstration that the pieces are all in place.

There is also a niche for searches at HERA. The existing data no longer indicate any high-Q^2 excess but there are some deviations in leptonic final states[54] (H1 see an excess of $e/\mu + E_T^{\text{miss}}$, ee and eee events; ZEUS do not, but have an excess of taus). These are not compatible with any obvious "new physics" explanation and we will have to wait for HERA II data[55]. HERA II benefits from significantly increased luminosity; its polarization could be an important tool to disentangle any eventual signal. HERA complements the searches that will be carried out at the Tevatron on the same timescale, looking for R-parity violating stop production, FCNC in the stop sector, doubly charged Higgs particles, extra dimensions, leptoquarks, and lepton flavour violation.

The combination of 14 TeV and 100 fb^{-1} makes the LHC an extremely potent discovery machine. It is impossible to prove a theorem that any new physics associated with the TeV scale will be detectable at LHC, but "proof by enumeration" has been carried a long way. It will be hard for SUSY to escape detection[56]. The mass reach is up to 2.5 TeV for squarks and gluinos in minimal SUGRA, and exclusive mass reconstruction has been demonstrated at several benchmark points. Other new physics detectable[57] includes extra dimensions and TeV-scale gravity (the gamut from indirect effects to black hole production); compositeness (up to scales 20–40 TeV); excited quarks, technicolor, strong WW scattering, leptoquarks, new gauge bosons, and heavy right handed neutrinos.

4 Our future

It is impossible to avoid the feeling that hadron collider physics has been wandering in the wilderness for the past year. Whichever side of the Atlantic we have been on, we seem to have been beset with problems: technical, financial, management, schedule, and politics. We need to keep the faith – we must remember that the physics remains the best in the world. We also have a vibrant, enthusiastic community of young physicists. There are clear indications that point to the existence of physics beyond the Standard Model: neutrino mixing requires a new mass scale; astrophysics and cosmology require dark matter and maybe stranger things yet; the overall rather poor χ^2 of global electroweak fits may be telling us something; the questions of masses and mixing angles remain unanswered; the equal electric charges of the electron and proton surely require some kind of grand unification; and the origin of the 246 GeV weak scale is still unknown. Electroweak symmetry breaking and the Higgs is central to all of these. It is the key question for the Standard Model and a window to beyond-the-Standard-Model physics.

In the short term, we can look forward to physics results from Run II with few hundred inverse picobarns. This is a significantly increased sample over Run I with improved detectors and a higher centre of mass energy. We can expect results on

- a first look at B_s^0 mixing,
- top quark measurements with increased statistics and purity,
- jet cross sections at high E_T (constraining the gluon PDF),
- new limits on physics beyond the SM (e.g. MSSM (A/H) at large $\tan\beta$).
- ...

In the longer term, it will be a disappointment if Run II does not tell us something about electroweak symmetry breaking. The goal should be to transform both our indirect and direct knowledge of the Higgs as shown in Fig. 2[58], or better yet to make this plot irrelevant. This way we can lay the foundations for a successful LHC physics program – and hopefully a linear collider to follow.

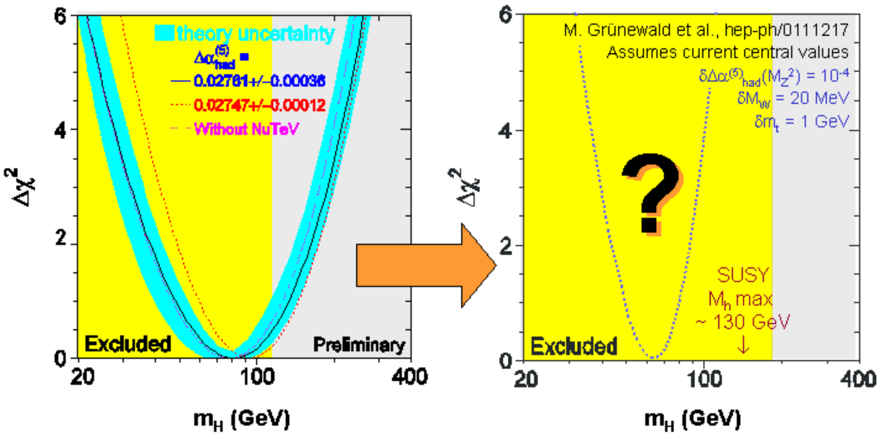

Fig. 2. Current (left) and anticipated post-Run II (right)[58] status of indirect and direct constraints on the standard model Higgs. Indirect constraints are shown by the parabolic curve and direct exclusion by the yellow shaded region. The current plot is from the LEP electroweak working group.

References

1. Elvin Harms, to appear in the proceedings of the 14th Topical Conference on Hadron Collider Physics (HCP2002), Karlsruhe, Germany, September 29 – October 4, 2002.
2. Volker Büscher, *ibid.*
3. Frank Chlebana, *ibid.*
4. John Smith, *ibid.*
5. Carsten Niebuhr, *ibid.*
6. Gigi Rolandi, *ibid.*
7. Sergei Klimenko, *ibid.*
8. Michael Dittmar, *ibid.*
9. Walter Giele, *ibid.*
10. Michael Rijssenbeek, *ibid.*
11. Matthias Kasemann, *ibid.*
12. Birger Koblitz, *ibid.*
13. Stefan Gieseke, *ibid.*
14. Mario Martinez, *ibid.*
15. Henning Schnurbusch, *ibid.*
16. Robert Thorne, *ibid.*
17. Nigel Glover, *ibid.*
18. Thomas Gehrmann, *ibid.*
19. Scott Willenbrock, *ibid.*
20. Elizabeth Gallas, *ibid.*
21. Sergei Chekanov, *ibid.*
22. Oscar Gonzalez, *ibid.*

23. Mary Bishai, *ibid.*
24. Daniela Bauer, *ibid.*
25. Andreas Meyer, *ibid.*
26. Bernd Kniehl, *ibid.*
27. Cesar Palisok, *ibid.*
28. Sung-Won Lee, *ibid.*
29. Olaf Behnke, *ibid.*
30. Jeff Forshaw, *ibid.*
31. Laszlo Gutay, *ibid.*
32. Markus Oldenburg, *ibid.*
33. Aharon Levy, *ibid.*
34. Dino Goulianos, *ibid.*
35. Silvia Tentindo-Repond, *ibid.*
36. Robert Fleischer, *ibid.*
37. Marcel Merk, *ibid.*
38. Sandro de Cecco, *ibid.*
39. Wendy Taylor, *ibid.*
40. Andrew Alton, *ibid.*
41. Eric James, *ibid.*
42. Dominique Pallin, *ibid.*
43. Ken Johns, *ibid.*
44. Wolfgang Wagner, *ibid.*
45. Juan Estrada, *ibid.*
46. DØ Collaboration (B. Abbott *et al.,*), Phys. Rev. D58 052001 (1998).
47. Elizabeth Simmons, to appear in the proceedings of the 14th Topical Conference on Hadron Collider Physics (HCP2002), Karlsruhe, Germany, September 29 – October 4, 2002.
48. Pasha Murat, *ibid.*
49. Suyong Choi, *ibid.*
50. Robert Harlander, *ibid.*
51. Bruce Mellado, *ibid.*
52. Hyunsoo Kim, *ibid.*
53. Andrei Nomerotski, *ibid.*
54. Elisabetta Gallo, *ibid.*
55. Yves Sirois, *ibid.*
56. Darin Acosta, *ibid.*
57. Pamela Chumney, *ibid.*
58. M. Grünewald *et al.,* contribution to the Proceedings of the 2001 DPF/DPB Snowmass Summer Study, `hep-ph/0111217`.