HARD INTERACTIONS : EXPERIMENTAL SUMMARY

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Experimental results on heavy quark production, hadronic final states and searches, which were presented at the DIS2001 workshop, are summarized.

1 Introduction

During the three days of parallel sessions at DIS2001 there were 15 experimental talks presented in the 'Hard Interaction' working group. This paper summarizes these contributions and also some which were presented in the joint sessions of the 'Hard Interaction' and 'Structure Function' working groups. The theoretical talks are summarized in a separate contribution.

The subjects covered were heavy quark production at HERA and in photon-photon collisions at LEP, investigations of hadronic final state structures in DIS at HERA and LEP and searches for new physics.

2 Heavy quark production

2.1 Charm

S. Mohrdieck [1] presented H1 results on D^* production in DIS at HERA. The momentum transfer is restricted to $1 < Q^2 < 100\,\mathrm{GeV}^2$ and the inelasticity to $0.04 < y < 0.7$. The D^* is identified in the $D^* \to D\pi$ decay and selected in the range $p_T^{D^*} > 1.5\,\mathrm{GeV}$ and $|\eta^{D^*}| < 1.5$. Within this acceptance the visible cross section is found to be $\sigma(ep \to eD^*X) = 8.50 \pm 0.42^{+1.02}_{-0.76} \pm 0.65$ nb. A NLO DGLAP prediction calculated with HVQDIS [2] results in a cross section range between 5.2 and 7.0 nb. Within the CCFM approach the MC generator CASCADE [3] predicts cross sections in the range between 8.0 and 10.8 nb, in better agreement with the experimental cross section. Although both calculations describe the measured differential distributions (x, W, Q^2, $p_T^{D^*}$) quite well there is a preference for CASCADE in the η^{D^*} distribution.

S. Schagen [4] presented measurements of inclusive D^* production in DIS ($Q^2 > 10\,\mathrm{GeV}^2$) with the ZEUS detector compared to HVQDIS predictions. Fig. 1 shows very good agreement in the differential cross section with NLO-QCD predictions in shape and magnitude. Zeus also performed an independent analysis detecting charm by the semileptonic decay in the electron channel.

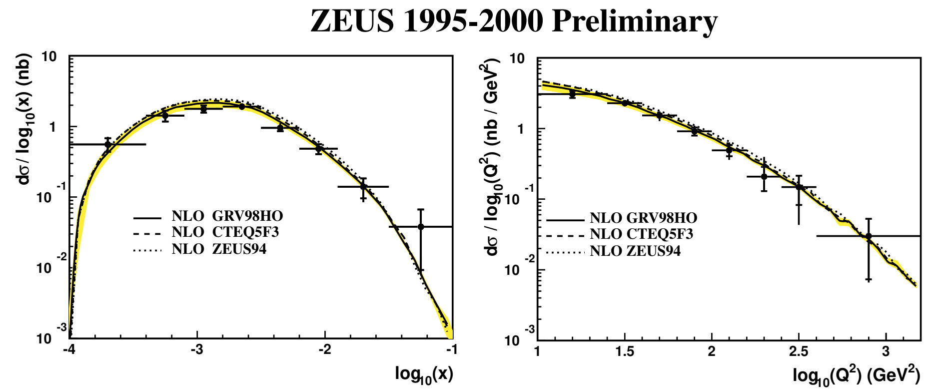

Figure 1: D^* differential cross sections in DIS at HERA compared to NLO-QCD.

Both analyses give consistent results. From the H1 and ZEUS data the structure function F_2^c is extracted (see report of the Structure Function WG).

S. Vlachos [5] presented results on charm production in photon - photon collisions at LEP by the four LEP collaborations. Charm was tagged by the D^* and the semileptonic decay methods. The $p_T^{D^*}$ dependence of the cross section is well described in shape and magnitude by a NLO QCD calculation [6]. The $\sqrt{s}$ dependence of the inclusive $c\overline{c}$ cross section is shown in Fig. 2, where also the decomposition into a direct and a resolved component is indicated, demonstrating the gluon component in the photon. Over the whole $\sqrt{s}$ range the data is well described by a NLO QCD prediction [7]. The L3 collaboration measured the charm cross section as a function of $W_{\gamma\gamma}$. The rise with $W_{\gamma\gamma}$ is found to be steeper than that for the total cross section and agrees well with a NLO-QCD prediction assuming a low value of the charm mass of 1.2 GeV.

2.2 Bottom

One motivation to study bottom quark production is the expectation that QCD predictions are more reliable due to the higher scale set by the mass of the b -quark. It has however been observed that in proton-antiproton interactions the b - cross section exceeds the NLO-QCD expectation by a sizeable factor. Here new results are presented on b - production in $\gamma\gamma$ collisions at LEP and in ep collisions at HERA.

A. Böhrer [8] presented measurements of the inclusive $b\overline{b}$ cross section from L3 and OPAL in $\gamma\gamma$ colllisions at LEP II. Both cross section measurements

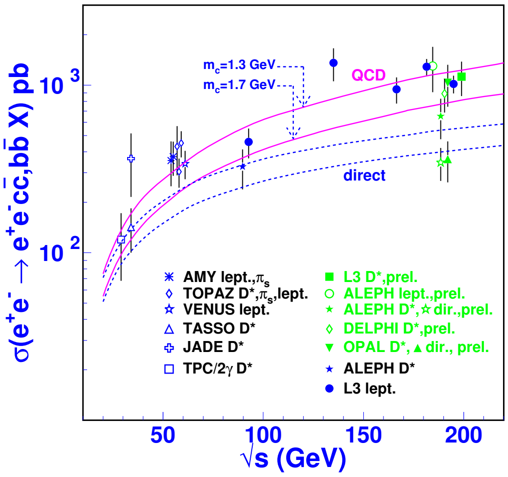

Figure 2: Inclusive charm cross section in photon-photon scattering.

$\sigma(ee \to b\bar{b}X)$ are in agreement (L3 $\sigma = 13.1 \pm 2.0 \pm 2.4$ pb and OPAL $\sigma = 14.2 \pm 2.5^{+5.3}_{-4.8}$ pb) but exceed the NLO-QCD prediction by a factor three corresponding to a 2 - 2.5 σ discrepancy for each experiment.

J. Kroseberg [9] reported on measurements of bottom quark production performed by H1 and ZEUS in photoproduction and DIS. The first observation [10] of open bottom production at HERA performed by H1 used the technique to identify bottom via the semileptonic decay. H1 now extended the analysis using also the lifetime technique making use of the silicon vertex detector. Fig. 3 shows a clear signature of bottom decays in the impact parameter distribution. Combining the consistent results of both analyses gives a visible cross section $\sigma(ep \to b\bar{b}X \to \mu X') = 170 \pm 25$ pb compared to a NLO-QCD prediction of 104 ± 17 pb. A ZEUS analysis in bottom photoproduction utilized the semileptonic b - decay into electrons. They established a fraction of resolved bottom production of 28 ± 5 % compatible with expectation. The measured bottom cross section is also here found to exceed the NLO-QCD prediction by a factor 1.5 to 2. H1 presented a first measurement of the bottom cross section in DIS in the range $1 < Q^2 < 100\,\mathrm{GeV}^2$ resulting in a visible cross section of $\sigma = 39 \pm 8 \pm 10$ pb compared to a NLO-QCD prediction (HVQDIS) of 11 ± 2 pb. The measured cross section exeeds also predictions based on LO-Monte Carlo programs like AROMA ($\sigma = 9$ pb) or CASCADE ($\sigma = 15$ pb). In summary it can be said that inclusive bottom production is found to

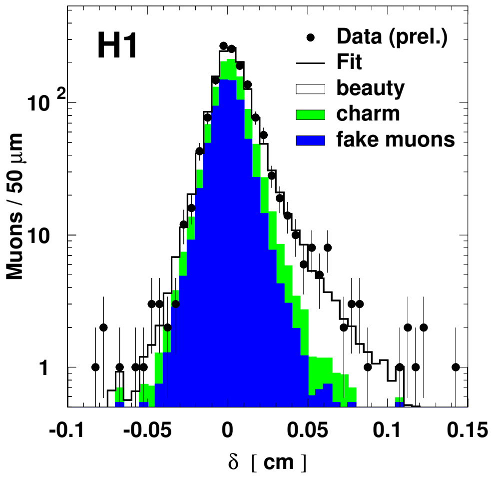

Figure 3: Bottom production in DIS at HERA : Impact parameter distribution.

be significantly higher than NLO-QCD predictions in $\gamma\gamma$, ep and $p\overline{p}$ scattering. The reason for this discrepancy is not understood at present.

A determination of the running b - quark mass was presented by M. J. Costa [11]. Data come from Z^0 running at LEP (ALEPH, DELPHI, OPAL) and SLD. Here one compares the relative rate of 3-jet events containing bottom to that in the total hadronic sample. ALEPH finds a result of $m_b(M_Z) = 3.27 \pm 0.22 \pm 0.22 \pm 0.38 \pm 0.16$ GeV in agreement with similar results from the other experiments demonstrating the running of m_b.

2.3 Charmonium

R. Brugnera [12] reported on studies of inelastic J/Ψ and $\Psi^{'}$ production at HERA performed by H1 and ZEUS. A motivation of the studies is to investigate whether the production can be described by color singlet (CS) contribution alone, or whether there is need for a color octet (CO) component. The J/Ψ cross section is measured as a function of the inelasticity $z = E_\Psi/E_{\gamma^*}$ (in the proton rest frame). The data are shown in Fig. 4 for a cut of the J/Ψ transverse momentum $p_T > 1$ GeV. A NLO - CS calculation describes the data well in shape and magnitude indicating no evidence for a large CO component. Unfortunately there is no NLO calculation available for the CO - contribution. Scaling a LO CS+CO calculation (with octet *ME* fixed using

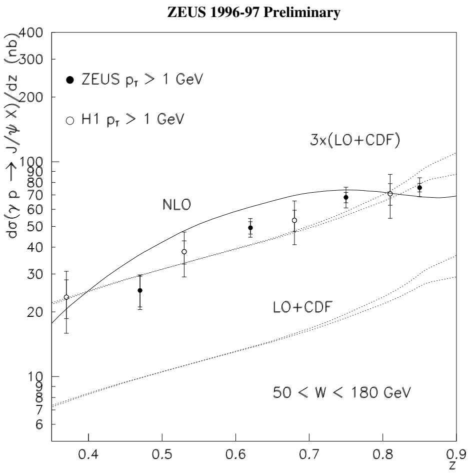

Figure 4: Inelasticity distribution in J/Ψ production at HERA.

CDF J/Ψ data) up by a k -faktor of 3 also describes the data well. ZEUS performed a first measurement of the J/Ψ decay angular distribution, which is expected to be more sensitive to a CO/CS discrimination. There is however no CO calculation available yet for comparison with the data. H1 showed first data in the low z region which are in principle sensitive to the resolved CS + CO components. However the experimental errors are still too large and a higher order CS+CO calculation is missing in order to reach a definitive conclusion on possible evidence for CO contributions. ZEUS presented data on inelastic $\Psi^{'}$ production indicating the same production mechanisms for both charmonium states.

3 Hadronic final states

3.1 Results from fixed target DIS (HERMES)

V. Muccifora [13] reported on HERMES results on hadron formation in DIS in a nuclear environment. The HERA electron beam is scattered on ^{84}Kr, ^{14}N and D targets. Inclusive particle spectra are measured for all hadrons and compared to those for identified pions. The nuclear attenuation ratio ($R = A/D$), sensitive to the hadron formation time, has been measured as a function of energy transfer ν and fragmentation variable z. The data indicate a higher attenuation at high z. Fig. 5 shows $R(\nu)$ for charged hadrons and

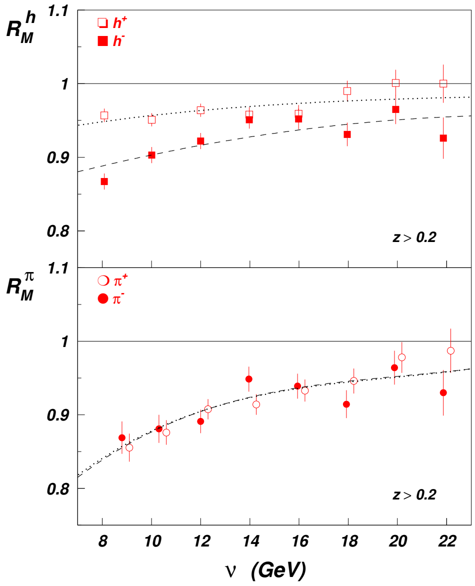

Figure 5: Nuclear attenuation as function of energy transfer ν in DIS measured by HERMES. For both charge states data for all hadrons and for identified pions are shown.

pions separately for both charge states. Since no significant difference is found for π^+ and π^-, the formation time seems to be charge independent. However the figure shows, that positive hadrons are less attenuated indicating a longer formation time for protons.

P. DiNezza [14] reported on studies of inclusive particle spectra performed in ep DIS interactions at HERMES. Comparing the $\pi^\pm$ and π^0 spectra as function of the fragmentation variable z, the data are found to be in good agreement with isospin invariance up to $z = 0.7$, but show a deviation above. At high z there may be possible contributions from exclusive processes and higher twist effects. The Q^2 dependences of the z - fragmentation spectra show clearly the scaling violations in the fragmentation process, in agreement with NLO-QCD predictions.

3.2 Hadronic Final states in $e - p$ scattering at HERA

P. Bussey [15] reported on the measurement of prompt photon production at HERA. The measurement was performed with ZEUS in the photoproduction regime. Prompt photons may be produced in a LO - direct process (Comp-

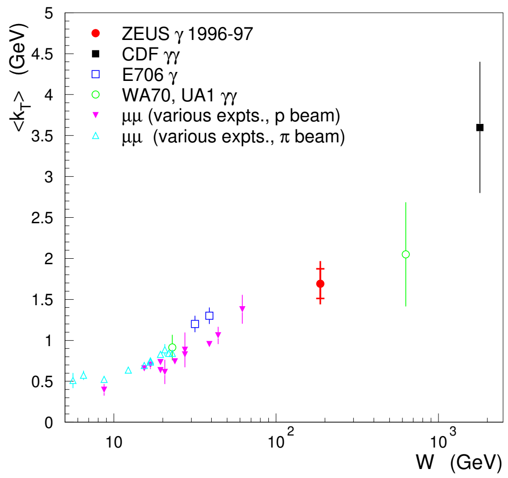

Figure 6: Average k_T of partons in the proton as function of the hadronic mass.

ton) or initiated from a resolved photon. The inclusive prompt photon spectra (E_T^γ, η^γ) are reasonably well described by the PYTHIA Monte Carlo and also by NLO-QCD calculations, although some discrepancies at small values of η^γ are visible. With the aim to investigate intrinsic transverse momenta of the partons in the proton, ZEUS analysed a subsample of prompt photon events exhibiting a prominent jet. Selecting only direct photoproduction ($x_\gamma \sim 1$) one assures that no k_T dependence is introduced from the photon side. Any non-balancing in azimuthal angle between jet and photon is then a measure of the intrinsic k_T of the parton in the proton. Fig. 6 shows that the new ZEUS measurement for the average k_T supports the increase of this quantity as a function of the mass of the hadronic system as observed in previous experiments.

G. Grindhammer [16] presented recent measurements of jet cross sections in DIS from the H1 collaboration. The analysis for the inclusive jet cross section was restricted to $150 < Q^2 < 5000\,\mathrm{GeV}^2$ and performed in the Breit frame with a cut $7 < E_{T,jet}^{breit} < 50\,\mathrm{GeV}$. The data, shown in Fig. 7, are well described over the whole range in Q^2 and $E_{T,jet}^{breit}$ by a NLO-QCD calculation. The same holds for measurements of the double differential dijet cross sections performed by H1 in the same kinematic regions.

Very similar measurements were done by the ZEUS collaboration summarized in the contribution by E. Tassi [17]. The dijet cross section is measured

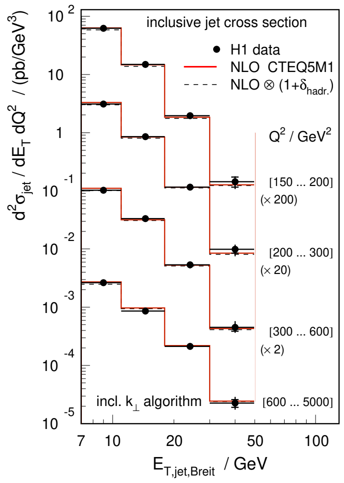

Figure 7: Inclusive double differential jet cross section in DIS compared to NLO-QCD.

in the region $470 < Q^2 < 20000\,\mathrm{GeV}^2$, requiring the jet transverse energies $E^{breit}_{T,jet1} > 8$ GeV and $E^{breit}_{T,jet2} > 5$ GeV. The distributions in $E^{breit}_{T,jet}$ and η^{breit}_{jet}, shown in Fig. 8 are well described by NLO-QCD calculations. ZEUS also measured the azimuthal asymmetry in the DIS inclusive jet sample. The observed asymmetry is well described by a DISENT NLO-QCD calculation. The inclusive jet and dijet measurements of H1 and ZEUS have been used to extract the gluon distribution in the proton and also α_s (see report of SF-WG).

A measurement of three jet production from H1 was presented by M. Wobisch [18]. This process is interesting since in lowest order it is already of order α_s^2 and recently a NLO-QCD calculation became available. H1 measured the process in the range $5 < Q^2 < 5000\,\mathrm{GeV}^2$, $0.2 < y < 0.6$ and required for the three jets, reconstructed in the Breit frame, $E^{breit}_{T,jets} > 5$ GeV and $M_{3-jet} > 25$ GeV. The data are well described by the NLO-QCD calculation in all kinematic variables as demonstrated in Fig. 9 for the Q^2 dependence of the cross section. Using the ratio of 3-jet to 2-jet cross sections offers the possiblity to reduce the sensitivity on the gluon distribution and scale uncertainties. This may turn out to be a sensitive method to determine α_s in future.

O. Gonzales [19] reported on an analysis performed by ZEUS to determine the strong coupling α_s from subjet multiplicities in DIS events. The subjet multiplicities have been measured in different regions of E_T^{jet} as a function of the cut on the jet resolution parameter y_{cut}. Fig. 10 shows the data compared

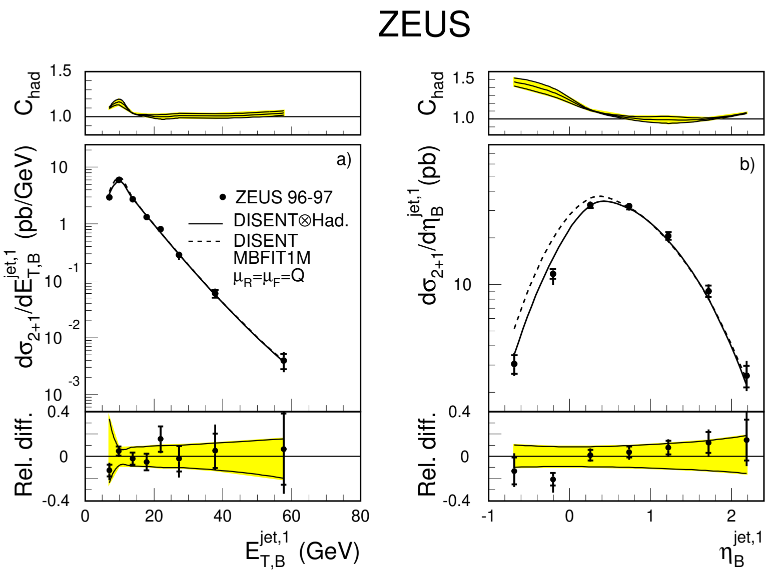

Figure 8: Differential dijet cross section in DIS compared to NLO-QCD.

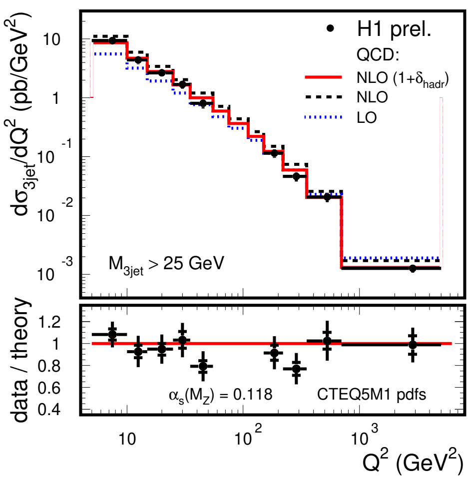

Figure 9: Q^2 dependence of the three-jet cross section in DIS compared to NLO-QCD.

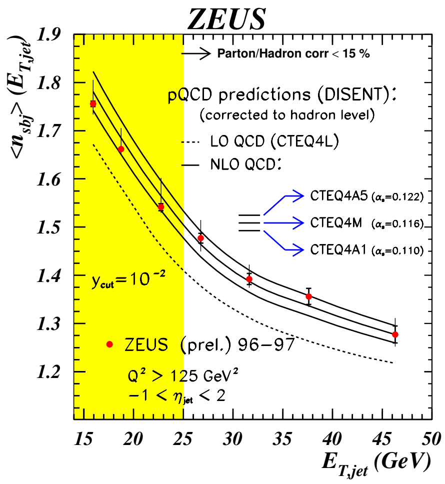

Figure 10: Average subjet multiplicity in DIS as function of E_T^{jet} compared to NLO-QCD for three values of α_s.

to an NLO-QCD calculation with different assumptions for α_s. The final value obtained is $\alpha_s = 0.1185 \pm 0.0016^{+0.0067+0.0089}_{-0.0048-0.0071}$, compatible and competitive with other determinations of α_s.

L. Zawiejski [20] presented a study of the multiplicity fluctuations in DIS for hadrons produced with $p_T < p_{Tcut}$ in the current hemisphere of the Breit frame. Using factorial moments, he compares ZEUS data and DLLA QCD predictions and notes a disagreement for low values of (< 1GeV) of p_{Tcut}. However one must keep in mind that perturbative QCD is not necessarily valid for p_{Tcut} smaller than 1 GeV. Several problems related to multiplicity fluctuations are addressed in ref. [21].

3.3 Hadronic Final states at LEP

P. Hodgson [22] presented recent results on dijet studies in gamma-gamma (untagged and single tagged) collisions from ALEPH and OPAL. Both collaborations found the dijet cross sections well described by NLO-QCD calculations. It was possible to separate direct and resolved photon contributions. Studies by OPAL on jetprofiles were also shown.

D. Bonacorsi [23] gave a broad review on recent QCD studies using LEP II data. Hadronic event shapes have been investigated by all LEP collaborations. The measurements at LEP II energies are well described by the QCD-model

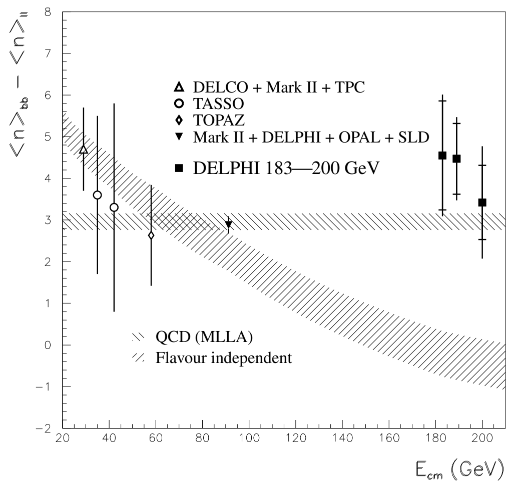

Figure 11: Difference in average charged particle multiplicity in e^+e^- scattering between a sample with bottom events and all hadronic events .

extrapolations tuned to LEP I data. Values of α_s derived from the eventshape variables are in good agreement with the expected running of α_s. New measurements on jet production rates, charged particle spectra and charged particle multiplicities were also presented. The impact of the LEP II data is demonstrated in Fig.11, that shows the difference of the charged particle multiplicity between $b\bar{b}$ events and all hadronic events. Whereas the data at lower energies could not distinguish between the prediction of flavor independent fragmentation and energy independence as predicted by QCD, the inclusion of LEP II data settles this issue.

4 Searches

P. Padley [24] reported on a quasi model independent search strategy (SLEUTH) for physics beyond the SM developed by D0. The experimental data are partitioned into exlusive final states characterized by isolated objects (leptons, photons, jets, W, Z, missing momentum) described by a set of variables (mainly transverse momenta). Compared to SM-MC expectations the SLEUTH method identifies within the spanned space of variables regions of excess and quantifies the degree to which this excess is interesting. The method allows an a posteriori analysis of interesting events. SLEUTH is sensitive to new physics (proven for the top signal), but does not give evidence for new physics in the present D0 data from run I.

I. Iashvili [25] presented the prospects for Higgs at the Tevatron Run II. The associated productions WH and ZH with a decay of the Higgs boson in $b\bar{b}$ are the most interesting channels to search for light Higgs ($M_H < 135$ GeV) at Tevatron. For heavier Higgs, the decay modes $H \rightarrow WW$ and $H \rightarrow ZZ$ can be exploited. It is clear that good b-tagging and di-b-jet mass resolution are essential to isolate the Higgs signals. The results of a detailed study of the signals and of the backgrounds is summarized on a discovery/exclusion plot, from which one can read, for instance, that a 5σ discovery up to 125 GeV is possible with an integrated luminosity of 30 fb^{-1}.

A. F. Zarnecki [26] reported on searches beyond the standard model performed by H1 and ZEUS within the framework of contact interaction studies. Here one looks for phenomena at energy scales beyond the HERA center of mass energy. One searches in the data sample of neutral current DIS events for deviations from the standard model Q^2 dependence. Both experiments do not observe any significant deviation. Within the contact interaction approximation limits are derived on physics beyond the SM in the areas of compositeness, large extra dimensions, quark radius, high mass leptoquarks and lepton flavor violation. The limits obtained are in general competitive and comparable to those of LEP or TEVATRON.

Z. Zhang [27] presented searches beyond the standard model performed by H1 and ZEUS looking for direct production of new particles within the HERA center of mass energy range. Leptoquarks and squarks in R_P violating SUSY can be produced at HERA in s-channel fusion of the electron and a quark from the proton. Leptoquarks decay in eq or νq resulting in event topologies identical to those of NC and CC DIS events. One utilizes the different angular distributions in the eq cms system by imposing a mass dependent y-cut to enhance the separation power between NC-DIS and leptoquark production. Fig. 12 shows the distribution in the invariant mass of the eq system. The data are well compatible with the SM NC expectation. Limits are derived on the Yukawa couplings λ of different species of leptoquarks as a function of their mass. For a coupling strength of 0.03 (that is 100 times smaller than the electromagnetic coupling) leptoquark masses up to 275 GeV can be excluded. Searches for squarks were performed looking also for gauge decays which result in a variety of possible final state topologies. Coupling limits were determined in MSSM and mSUGRA, excluding squark masses up to 270 GeV for electromagnetic coupling strength. A search for excited fermions resulted in limits on couplings for e^*, ν^* and q^* which significantly extend the range covered by LEP up to the kinematic limit of HERA.

A topic of high interest are the events observed at HERA which comprise

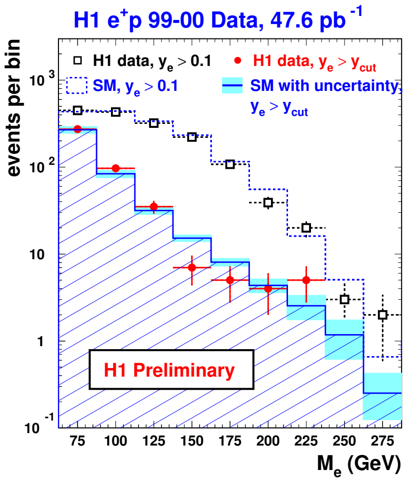

Figure 12: Invariant eq mass for NC-DIS like events for two cuts on the inelasticity y compared to SM expectation.

a charged lepton (e and μ) of high p_T combined with a high missing p_T. Fig. 13 shows one of these events. H1 found in previous data an excess of events over the SM expectations, which is dominated by on-shell W production. T. Matsushita [28] (ZEUS) and C. Diaconu [29] (H1) reported on latest results on this topic using all luminosity taken at HERA. ZEUS found in their inclusive analysis in the electron channel 10 events compared to 11.0 ± 1.6 expected, and in the muon channel 7 events with 5.4 ± 0.7 expected. In this analysis the SM background is not dominated by W production. H1 selects in their analysis for the e and μ channel combined 18 events with 10.5 ± 2.5 expected, where 8.2 events are from W production. The excess events are predominantly observed at high values of the hadronic transverse momentum p_T^X (see Fig.14). When H1 and ZEUS make similar selections on the phase space and suppression of non-W background they agree on the SM expectations but differ in the number of observed events (9 for H1 within 82 pb^{-1} compared to 2 for ZEUS in 130 pb^{-1}). It is evident that only higher luminosity will allow to settle the puzzle of these outstanding events observed at HERA. Both collaborations derived from these analyses limits on anomalous FCNC couplings.

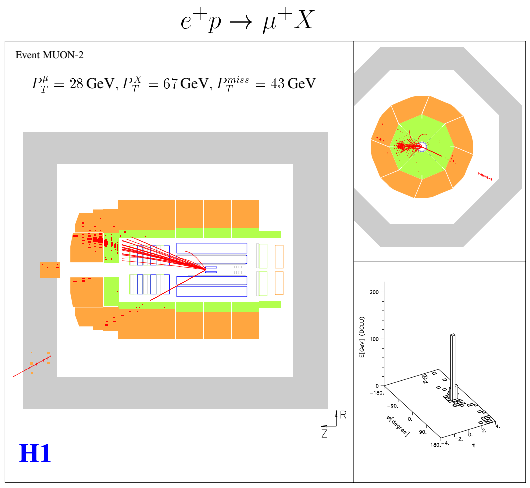

Figure 13: HERA event with isolated lepton and missing transverse momentum.

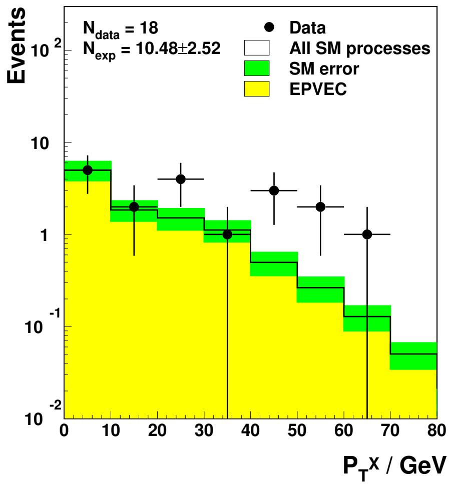

Figure 14: Hadronic transverse momentum observed by H1 in the HERA events with an isolated lepton and missing transverse momentum compared to SM expectation.

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