Heavy flavours: experimental summary

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Abstract. New measurements of charm and beauty production presented in the heavy flavour working group are summarized and discussed in comparison with QCD predictions.

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INTRODUCTION

The measurement of heavy flavours in lepton-hadron interactions provides a test of many aspects of QCD and a probe of the gluon content of the proton or, in charged currents, of its content of strange quarks. In the previous years, the charm measurements at HERA focused on the inclusive production of charmed mesons. At this workshop many new results have been presented that look beyond single heavy-meson production, by measuring fragmentation parameters, looking at di-jet correlations or at heavy-quark-jet characteristics and extending into unexplored kinematic regions. New measurements of $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$, based on an inclusive lifetime tagging technique, have been presented by H1. NuTeV has shown results on charm production in νA interactions from its full data sample. New data on heavy-quarkonium production in DIS and in hadronic interactions have also been presented. Various results on b production at HERA are now available, obtained from different experimental techniques and extended to a wide range of the b-production phase space.

CHARM FRAGMENTATION

The extremely large charm cross-section at HERA (up to 25% of the total cross-section for DIS) has allowed precise determinations of the of the probability that a charm quark will produce a specific charm hadron (fragmentation fraction) and also the relative momentum carried by that hadron (fragmentation function). These measurements may be compared with those from e^+e^- collisions in order to test the hypothesis of a universal charm fragmentation. Z. Rurikova and R. Walsh showed new measurements of the the fragmentation fraction from DIS at HERA for D^0, $D^\pm$, $D_s^\pm$, $D^{*\pm}$ mesons and the $\Lambda_c^\pm$ baryon. The measurements show in many cases comparable precision to e^+e^- measurements. A good agreement is observed between the two HERA experiments, with HERA photoproduction measurements and with e^+e^- measurements, supporting a universal charm fragmentation.

Measurements were also made of related quantities. The ratio of twice the cross section for mesons with a s quark to that for mesons with a u or d quark (strangeness suppression factor) is found to be about 0.25 in agreement with e^+e^-. The ratio of neutral to charged meson production is found to be consistent with 1 as expected. The ratio of vector c meson production to vector plus pseudoscalar meson production is found to be significantly less than the value of 0.75, which would be naively predicted from spin counting. Measurements of the fragmentation function, although not as precise as e^+e^- determinations, show a range of preferred values of fragmentation parameters for DIS.

These results on charm fragmentation are complemented by the huge amount of data on charm spectroscopy being produced at B factories, as was shown by C. Chen and B. Yabsley.

CHARMONIUM AND UPSILON PRODUCTION

Inelastic J/ψ production has long been described in pp collisions by non-relativistic quantum chromo-dynamics (NRQCD), which incorporates colour singlet (CS) and colour octet (CO) contributions. New measurements of J/ψ production from RHIC ($\sqrt{s} = 200$ GeV), presented by K. Read, have confirmed the good description of NRQCD in pp collisions. New measurements, presented by H. Wahl, of Tevatron ($\sqrt{s} = 2$ TeV) Υ data showed good agreement with NRQCD calculations.

In contrast to the good description in pp collisions NRQCD has not been able to describe ep collisions very well. New results, presented by A. Antonov, of inelastic J/ψ production at HERA show that, although there is good agreement between experiments, the data are substantially below predictions of NRQCD. Much better agreement is observed if only CS contributions are taken.

CHARM AND STRANGE MEASUREMENTS

New measurements of charm production at HERA, tagged using D^* were presented by G. Aghuzumtsyan, for the very low Q^2 region of $0.05 < Q^2 < 0.7$ GeV^2. Even at these low Q^2 values next-to-leading-order (NLO) QCD is found to describe the data well. New D^* measurements have also been made at higher Q^2. R. Hall-Wilton showed results for $Q^2 > 5$ GeV^2 using HERA II e^+p and e^-p data. The new e^+p and e^-p data are found to agree well as expected. There is no confirmation of the slight excess seen with the HERA I e^-p data.

R. Hall-Wilton also showed the huge improvement in signal to background possible when using the new ZEUS micro-vertex detector. As an example the background under $D^{\pm}$ peak can be reduced by a factor of 45, whilst the signal is reduced by only 2.7 if a cut on track significance is made. It is expected that much more precise charm and beauty results will be obtained from the HERA II data than existing measurements, due to the increased integrated luminosity and the new vertex detectors installed in H1 and ZEUS.

D. Mason showed results on the forward di-muon cross section in νN charged current interactions from NuTeV. Since the sign of the beam can be determined at NuTeV it is possible to extract the strange and anti-strange sea quark distributions from the di-muon cross section. It is found that at leading order the data favour a slight positive strange asymmetry. It should be pointed out, however, this effect is not sufficient to wholely explain the observed difference of NuTeV's measurement of $\sin^2(\theta_W)$ with the world average.

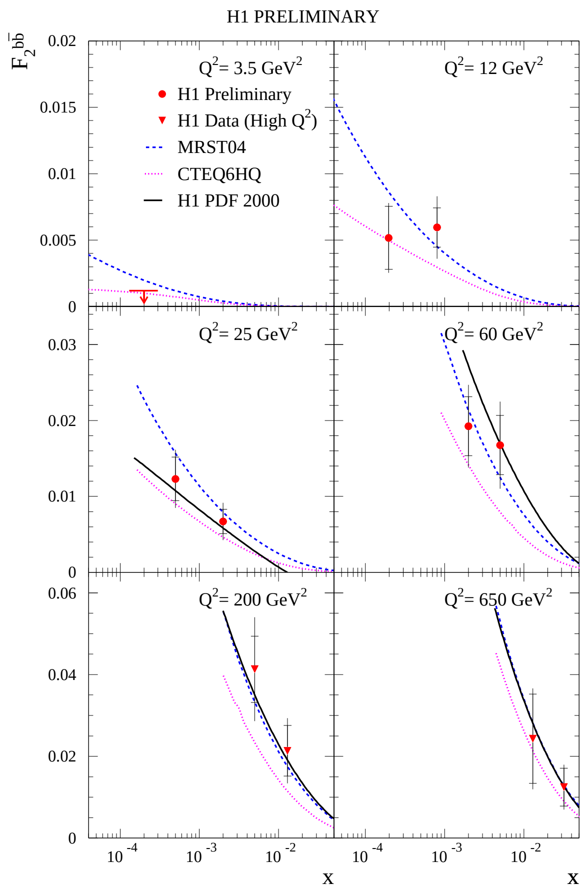

FIGURE 1. The measured $F_2^{b\bar{b}}$ shown as a function of Q^2 for various x values. The inner error bars show the statistical error, the outer error bars represent the statistical and systematic errors added in quadrature. The predictions of QCD are also shown.

INCLUSIVE CHARM AND BEAUTY MEASUREMENTS

New measurements, shown by T. Klimkovich, have been made at HERA using the vertex detector of the differential c and b cross sections ($d^2\sigma^{c\bar{c}}/dxdQ^2$ and $d^2\sigma^{b\bar{b}}/dxdQ^2$) for values of $Q^2 \geq 3.5$ GeV^2. The cross sections are converted into the structure functions $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$.

The measurements of $F_2^{c\bar{c}}$ are compared to determinations of $F_2^{c\bar{c}}$ obtained from D^* cross sections where QCD predictions are used to extrapolate over unmeasured phase space. Both determinations agree well. The measurements also agree well with the next

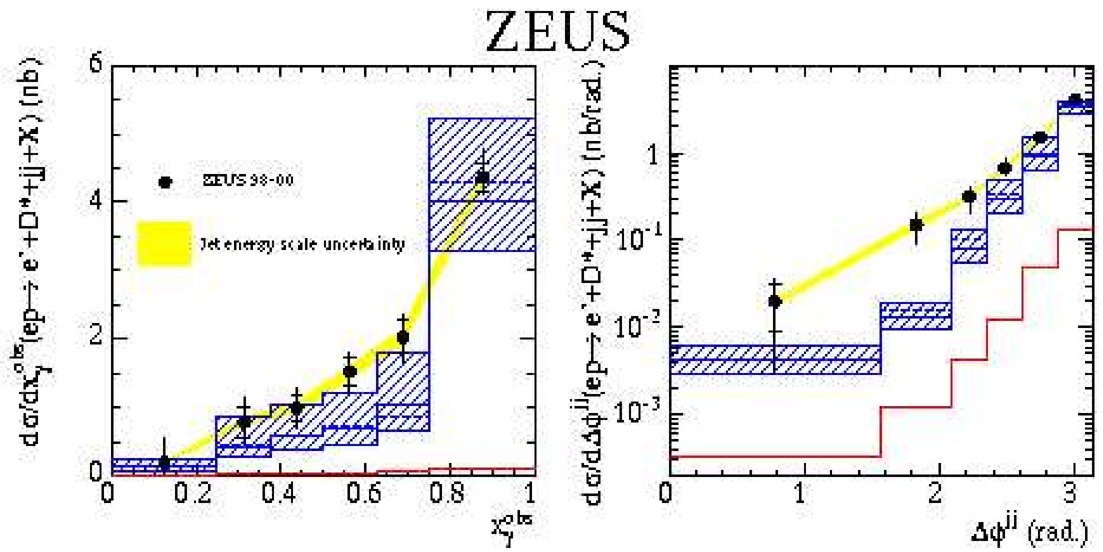

FIGURE 2. ZEUS results on jet-jet correlations in D^* photoproduction. The plots show the differential cross sections in $x_\gamma^{\rm obs}$, the fraction of the photon energy carried by the two-jet system, and $\Delta\phi^{\rm jj}$, the azimuthal angle between the two jets. An excess over the NLO QCD predictions is observed at low $\Delta\phi^{\rm jj}$.

to leading order QCD calculations of MRST and CTEQ, which use a variable flavour number scheme (VFNS). These measurements of $F_2^{b\bar{b}}$ (shown in figure 1)are the first to have been made. The measurements agree well with the VFNS calculations of MRST and CTEQ, although the difference between MRST and CTEQ is large at low Q^2 and x, where it can reach a factor of 2.

HEAVY-QUARK JETS

Jet cross sections are a powerful tool to study the parton dynamics in heavy quark production since jets are less influenced by fragmentation details and can be measured in a wider angular range than heavy hadrons.

T. Kohno and G.Fluke presented new results on jet photoproduction at HERA in events with a D^*. The differential cross sections in the jet transverse momentum and rapidity were found to agree well with NLO-QCD predictions based on the FMNR program, similarly to what was found in previous analyses of inclusive D^* photoproduction.

Further constraints on the theory can be obtained from dijet variables. The fraction of the photon's longitudinal momentum taken by the two-jet system, $x_\gamma^{\rm obs}$, can be used to distinguish the contributions of the leading-order direct-photon process ($\gamma g \to c\bar{c}$) that peaks at $x_\gamma^{\rm obs} \sim 1$ from resolved-photon processes in which the photons behaves as a source of partons and from higher-order radiative processes that dominate the low-$x_\gamma^{\rm obs}$ region. The azimuthal angle between the two jets, $\Delta\phi^{\rm jj}$, and the transverse momentum of the dijet system, $p_T^{\rm jj}$, are direct probes of high-order QCD effects since the leading order diagrams contribute only at $\Delta\phi^{\rm jj} = \pi$ and $p_T^{\rm jj} = 0$.

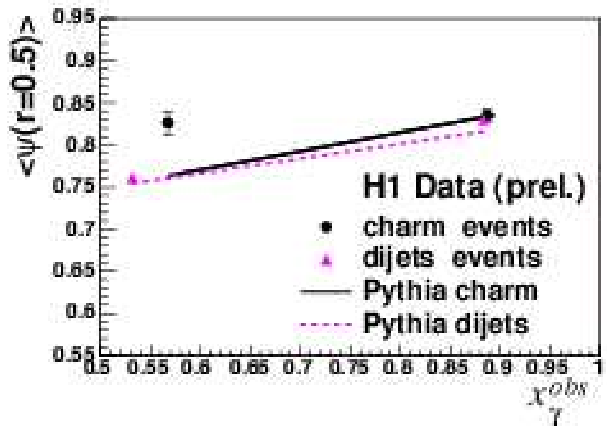

FIGURE 3. H1 results on the mean integrated jet shape as a function of $x_\gamma^{\rm obs}$ for an inclusive dijet sample (triangles) and for a charm-enriched dijet sample (points), compared to predictions from the PYTHIA MC.

Differential cross sections as a function of x_γ, $\Delta\phi^{\rm jj}$ and $p_T^{\rm jj}$ were measured by ZEUS in events with two jets and a D^*. The NLO QCD is able to describe the cross section in $x_\gamma^{\rm obs}$ but fails to reproduce the tails at small $\Delta\phi^{\rm jj}$ (Fig. 2) and large $p_T^{\rm jj}$. Parton-shower MC models can instead reproduce reasonably well the shape of these distributions, though with an incorrect overall normalisation. The H1 collaboration studied D^*-jet pairs in which the jet was explicitly required not to contain the reconstructed D^*. Also in this case the NLO-QCD agrees in general with the data but fails to reproduce the region of small azimuthal separation between the D^* and the jet.

To describe jet-jet correlations in heavy-quark photoproduction the theory should probably merge ingredients from NLO-QCD and parton shower MC as in the case of the MC@NLO program that is currently available only for hadron-hadron collisions. Results on correlations between b-tagged jets in $p\bar{p}$ collisions at the Tevatron were presented by R. Lefevre. All the distributions, including $\Delta\phi^{\rm jj}$ are well described by MC@NLO.

N. Parua presented the first measurement of Z^0 production associated to a b-tagged jet at Tevatron. The rate for this process, which is directly sensitive to the b PDF, was found in agreement with the NLO prediction.

The study of jet shapes is another tool to understand the production of heavy flavours in ep collisions at HERA. M. Martisikova reported about the measurement of jet shapes in the photoproduction of two jets, one of which tagged as charm. The integrated jet shape $\psi(r)$, defined as the fraction of the jet transverse energy contained in a cone of radius r, was measured for the untagged jet and compared to the PYTHIA MC as a function of different kinematic variables. The PYTHIA MC comprises flavour-creation (FC) processes ($\gamma g \to c\bar{c}$, $gg \to c\bar{c}$, ...), in which the two hard jets come from charm quarks and flavour-excitation (FE) processes ($cg \to cg$, $cq \to cq$), in which a charm quark from the photon interacts with a parton from the proton to produce a charm-jet plus a gluon or light-quark jet. Since gluon jets are broader than quark jets (including charm jets), the shape of the untagged jet is sensitive to the relative amount of FC and FE events. For $x_\gamma^{\rm obs} > 0.75$, were FC processes are expected be dominate, the untagged-

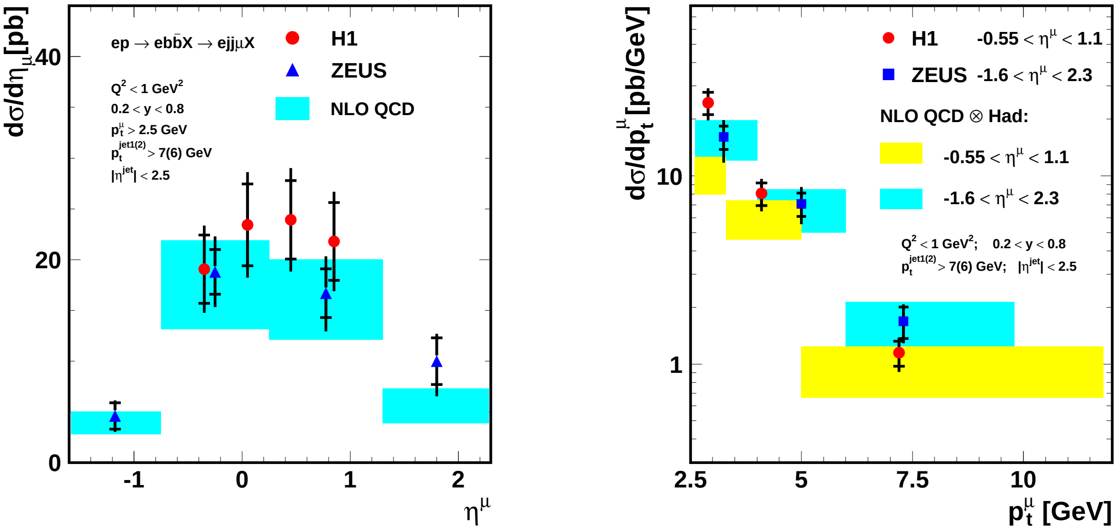

FIGURE 4. Beauty production cross section at HERA in events with two muons and a jet as a function of the muon pseudorapidity (η^{μ}) and of transverse momentum (p_T^{μ}). H1 and ZEUS results are compared to NLO-QCD theory (FMNR). In the left plot the ZEUS and H1 data are given for two different η^{μ} ranges and should be therefore compared to the the theoretical prediction for the corresponding range.

jet shape was found to be well described by PYTHIA. Conversely, for $x_{\gamma}^{\rm obs} < 0.75$, were most of the contribution from FE is expected, PYTHIA predicts significantly broader jets than those found in the data as show in figure 3. The charm sample is indeed compatible with being composed of two charm jets even at low $x_{\gamma}^{\rm obs}$.

An interesting QCD prediction is that, in heavy-quark jets, the gluon radiation is suppressed in a dead cone of size $\alpha_0 = M_Q/E_Q$ around the quark direction. A. Peireanu presented a study of jet shapes and subjet multiplicities in H1 DIS data containing a D^* meson, with a first attempt to measure α_0 in DIS. At the present stage the value of α_0 found for the charm jets is statistically compatible with that for non-charm jets. Further studies and more statistics are needed to obtain conclusive results on the dead cone effect.

BEAUTY PRODUCTION AT HERA

QCD predictions are expected to be more reliable for beauty than for charm since the b-quark mass is large enough to assure a reliable perturbative approach. In past years the comparison between NLO-QCD and HERA data gave some problem, while more recent results have found substantial agreement. O. Behnke presented the final H1 measurement of beauty production in events with jets and muons from HERA-I data. This analysis exploited a combination of the muon impact parameter and of the muon transverse momentum with respect to the associated jet, to distinguish the beauty signal from the background from charm and fake muons. The the cross sections for the photoproduction

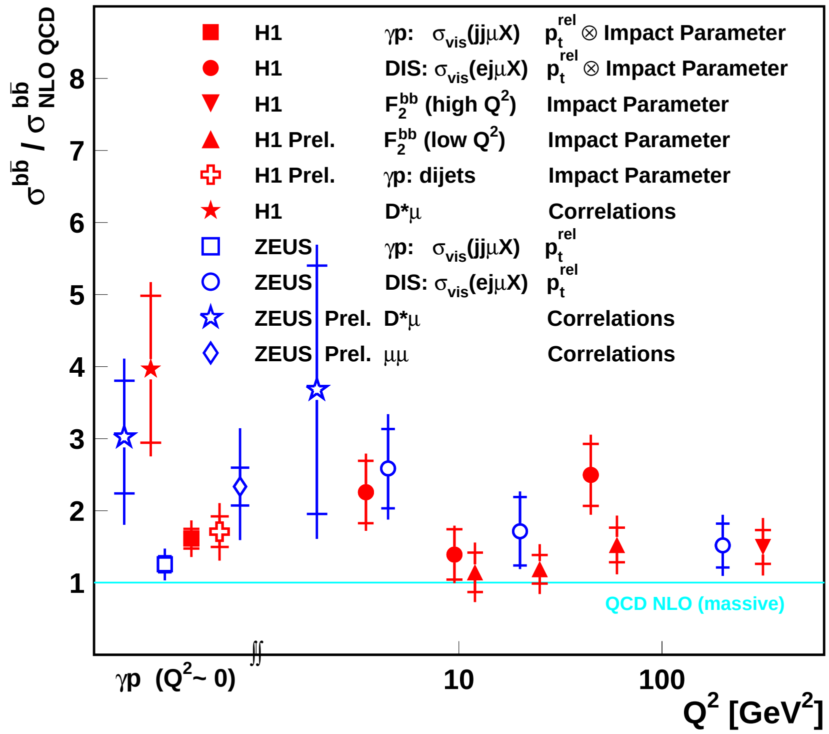

FIGURE 5. Ratio of different beauty cross-section measurements at HERA to the corresponding NLO QCD predictions. The theoretical uncertainty on the NLO Theory ranges from 40% for the total cross-section to 15% at large Q^2.

of two jets and a muon $ep \to e'b\bar{b}X \to e'jj\mu X'$ are found in agreement with previous ZEUS data and are close to the upper limit of the uncertainty band of the NLO-QCD prediction, as shown in Figure 4. Some discrepancy with the theory was found at low muon transverse momentum, were the data are ~ 3 standard deviations above the theory. In the same p_T^μ range the ZEUS data are in agreement with the theory. A similar excess at low muon p_T, though less statistically compelling, was found in DIS ($Q^2 > 2$ GeV^2).

Beauty photoproduction in dijet events $ep \to e'bbX \to e'jjX'$ was also measured by H1 with a multi-track impact parameter technique, similar to that used for charm and beauty in DIS, which provided a measurement of the b and c components of an inclusive dijet sample without any muon selection. As explained by L. Finke, the b cross section was found somewhat larger but still compatible with the NLO-QCD theory.

Measurements of beauty productions in events with jets at HERA have reached good precision but are sensitive only to a relatively small region of the $b-$quark production phase space, namely large p_T and central rapidities. Measurements based on a double b tags give the opportunity to cover a larger phase space, including sensitivity for b-quarks produced with zero transverse momentum and a larger rapidity range. As shown by A.

Longhin, the recent ZEUS double-tag analysis based on dimuon events has a sizeable acceptance for about 90% of produced $b\bar{b}$ pairs, allowing for a measurement of the total $b\bar{b}$ cross section at HERA with small extrapolation uncertainties. The result,

$$\sigma_{\rm tot}(ep \to e'b\bar{b}X) = 16.1 \pm 1.8({\rm stat.})^{+5.3}_{-4.8}({\rm syst.})\,{\rm nb}$$

is about two standard deviations larger than the NLO QCD predicted value $\sigma^{NLO}_{\rm tot}(ep \to e'b\bar{b}X) = 6.8^{+3.8}_{-1.7}$ nb. A similar result was found in the recently published H1 analysis of $D^*\mu$ correlations presented by N. Malden. The visible beauty cross-section was found again about 2 standard deviations larger than expected by NLO-QCD. A new measurement of the total $b\bar{b}$ cross section in pA collision was presented by U. Husemann. In this case the NLO theory has been found in good agreement with the data.

Figure 5 summarizes in one plot the status of the agreement between data and theory for beauty production at HERA by showing the data/NLO ratio for all recent measurements. The theory predictions are obtained with FMNR for $Q^2 < 1$ GeV^2 and with HVQDIS for $Q^2 > 1$ GeV^2. The uncertainties on the theory, that ranges from $\sim$40% for the total cross section to $\sim$15% at large Q^2, are not shown. At large Q^2 the inclusive $F_2^{b\bar{b}}$ results from H1 are in agreement with the NLO and with ZEUS and H1 data from jet-plus-muon ($ej\mu X$) analyses. For Q^2 around few GeV^2, the points from the $ej\mu X$ analyses are somewhat above the theory but still compatible. In photoproduction ($Q^2 < 1$ GeV^2) the most precise measurements are those based on jets and muons (H1 and ZEUS $jj\mu X$) and the H1 dijet analysis with inclusive impact parameter tag. They are substantially in agreement with the theory. The double-tag analyses (ZEUS and H1 $D^*\mu$ correlations and ZEUS $\mu\mu$ correlations) that are sensitive to lower b-quark momenta, but are in general less precise than the dijet ones, are about a factor two above the predictions, with a 2-3 sigma significance. It will be therefore very interesting to see if these hints for an inaccuracy of the theory at low transverse momentum will be confirmed from high statistics analyses at HERA-II. It is also interesting to note the large difference between VFNS calculations of CTEQ and MRST for the inclusive DIS b measurements (see figure 1) in certain regions of phase space. This may indicate that the theory errors that have been assumed so far are under estimated. It should also be noted that the final state observables are compared with theory based on the fixed flavour number scheme, which is expected to be valid only for p_T and Q^2 of not much larger than the quark mass. Unfortunately at the present time there are no VFNS calculations of final state heavy quark observables. The participants in the heavy flavour session expressed a strong wish to theorists to provide a VFNS that could be used to compare with final state observables.

CONCLUSIONS

The huge heavy flavour datasets, provided by HERA, have been used to make measurements of charm fragmentation that are comparible in precision with the world's best. Good agreements is observed between ep and e^+e^- supporting a universal charm fragmentation.

Despite several new precision measurements of inelastic charmonium and upsilon producion and good agreement between independent measurements there is still no good description of *ep* data with non-relativistic QCD calculations. This contrats with *pp* data where similar calculations give a good description of the data.

One of the few methods to constrain the strange quark density of the nucleon is from the di-muon cross section of neutrino-nucleon scattering. New measurements of the strange-antistrange asymmetry were demonstated to be insufficient to wholely explain the deviation of NuTeV's measurement of $\sin^2(\theta_W)$ compared to the world average.

There have been many new measurments of charm production, inclusive or in conjunction with a muon and or jets. All such measurements are broadly in agreement with next to leading order QCD predictions in both *pp* and *ep* scattering. The situation is less clear in beauty cross sections. Measurements made in *pp* collsions show good agreement with calculations. In *ep* collisions many measurements lie above the QCD predictions. It is interesting that predictions of MRST and CTEQ for the inclusive DIS cross section differ by as much as a factor of 2 in some regions of phase space. Perhaps if the reasons for these differences could be understood a better description of beauty production in *ep* scattering might be had.

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