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HEAVY FLAVOR PRODUCTION IN HADRON COLLISIONS (WITH A FEW LEPTONS AND PHOTONS THROWN IN)

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ABSTRACT

Substantial advances in our understanding of several aspects of QCD have been achieved in the recent past using heavy quarks as a tool. However, many open questions still remain. These successes and puzzles are highlighted by the latest measurements of heavy quark production at the Tevatron, HERA and fixed target experiments, which will be reviewed here. Results in both open heavy flavor and heavy quarkonium production as well as evidence for new particles containing heavy quarks will be presented. The impact of these measurements on gaps in our understanding of QCD and how we hope to close these gaps in the future will be outlined.

1 Why Study Heavy Quark Production?

Quantum Chromodynamics is universally acknowledged to be *the* theory of the strong force. However, its study continues to be a compelling area of research because of the difficulty of performing calculations in regions where the theory becomes non-perturbative. This means that, although we understand the structure of the theory, we still cannot make accurate predictions for a wide range of important observables. Intellectually, this is frustrating (or an opportunity for the more optimistic). But it also has a more practical consequence. Our understanding of QCD processes is intimately entwined with our understanding of other aspects of the Standard Model because QCD is a part of all SM predictions, from estimates of backgrounds to corrections to electro-weak observables.

It turns out that the production of heavy quarks by the strong force is an excellent area to study some of the technical details of QCD that are so important in our tests of the Standard Model. To understand this, consider the production of a heavy quark-antiquark pair in the collision of two particles. Broadly speaking, this process consists of three components, which are all connected in real collisions: the structure of the incoming particles, the hard interaction producing the $Q\bar{Q}$ pair and the subsequent parton shower and fragmentation of the final state partons to produce observable hadrons.

It is in the second of these entwined processes, the hard scattering, where heavy quarks make their contribution to QCD. Particle structure and hadronization are clearly governed by non-perturbative physics. However, they are also largely universal functions, appearing in a variety of processes. The hard-scatter is process dependent. But since the masses of heavy quarks are much larger than the QCD scale, this hard-scatter should be calculable using perturbative QCD. Heavy quark production measurements can therefore be used to probe our ability to do perturbative calculations or can be used as a tool to understand parton densities and fragmentation.

Before embarking on a discussion of specific heavy quark production results, we should be clear as to exactly what a heavy quark is. In this paper, heavy quarks are taken to be b- and c-quarks. The obese t-quark is discussed in a separate contribution to these proceedings [1]. Using this definition, heavy quarks are produced at a variety of facilities. A comparison of those for which results are presented is given in Table 1.

Table 1: *Comparison of experimental facilities with results presented here.*

Exp. or Facility	**Colliding Particles**		$\sqrt{s}$ **/ nucl. [GeV]**	**Runs**	**Recorded Data**
FOCUS/E831	γ	BeO	18	96–97	
SELEX/E781	Σ^-, π^-	C,Cu	33	96–97	15B int's
NuSea/E866	p	Cu	38	96–97	9M J/ψ
Hera-B	p	C,Al,Ti,W	41	00,02–03	308K J/ψ
HERA Run I	$e^\pm$	p	300,318	93–00	130 pb^{-1}
HERA Run II	$e^\pm$	p	318	03–04	$\sim$70 pb^{-1}
Tevatron Run I	p	$\bar{p}$	1800	92–96	125 pb^{-1}
Tevatron Run II	p	$\bar{p}$	1960	02–04	$\sim$400 pb^{-1}
LEP (I and II)	e^+	e^-	90–210	89–00	3.6M bb

2 b- and c-Quark Production

2.1 History Lessons

The production of open b- and c-quarks has been one of the most troubling problems in QCD for more than a decade. For a recent review of this problem see [2]. Particularly in the b-quark sector, calculations, which are done at next-to-leading order (NLO) in α_s, were expected to provide a quite good description of the data. A quick look at the data taken prior to 2000 [2], however, indicates that while the shape of the b-quark production cross-section is reasonably well modeled by NLO theory for $p\bar{p}\to b\bar{b}$, $ep\to b\bar{b}$ and $\gamma\gamma\to b\bar{b}$ data, the predictions underestimate the magnitude of the cross-sections by factors approaching three. Surprisingly, data and predictions for c-quark production showed much better agreement, although with larger uncertainties.

Over the past few years, the picture of b-quark production at the Tevatron, where the discrepancy was originally uncovered, has become much clearer. One important aspect of this understanding was the realization that experimentalists should report what they observe: B-hadron production cross-sections, rather than cross-sections corrected to the b-quark level. When the DØ collaboration published a measurement of the p_T distribution of jets containing b-quarks [3], significantly better agreement with NLO predictions was found. Another piece of the puzzle was the correct incorporation of next-to-leading-log resummation of $\log(p_T/m)$ terms with the NLO hard scatter calculation including massive quarks (FONLL) [4]. Finally, the heavy quark fragmentation function was revisited by several groups [5, 6] yielding a calculation in the FONLL framework consistent with the hard scattering calculation and a reevaluation of parameters of the fragmentation function.

2.2 Open Beauty and Charm Production at the Tevatron

These new calculations [7] have been compared to a preliminary measurement of the B-hadron cross-section by CDF, using $H_B \to J/\psi X$ decays. CDF selects $H_B \to J/\psi$ decays in the $J/\psi \to \mu^+\mu^-$ mode from 37 pb^{-1} of their Run II data using the position of the J/ψ vertex with respect to the primary $p\bar{p}$ interaction point to distinguish long-lived H_B decays from prompt J/ψ production. The resulting H_B cross-section times branching ratio is shown on the left side of Figure 1 while a comparison of this new result to older CDF measurements and to the FONLL prediction [7] is shown on the right side. As can be seen, the agreement between data and prediction is excellent, both in shape and normalization. The total cross-sections, corrected to the quark level for the CDF data is $\sigma(p\bar{p} \to \bar{b}X, |y_b| < 1.0) = 29.4 \pm 0.6 \pm 6.2\ \mu$b in remarkable agreement with the FONLL prediction of $25.0^{+12.6}_{-8.1}\ \mu$b.

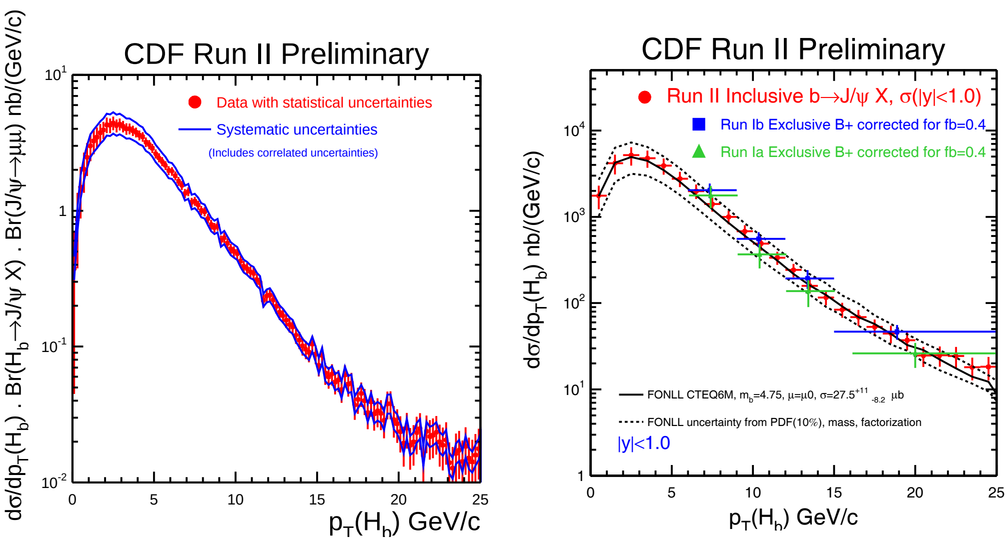

Figure 1: *The preliminary, CDF H_B differential cross-section times branching ratio (left) and that result, corrected to the b-quark level compared with older CDF measurements and the FONLL prediction (right).*

New CDF measurements of open charm production [8] have also been compared to FONLL predictions [9]. The measurement uses 5.8 pb^{-1} of hadronic charm decay triggers collected with the CDF Silicon Vertex Trigger. Prompt contributions to the sample of reconstructed D^0, D^{*+}, D^+ and D_s^+ mesons are obtained using the impact parameter of the charm meson candidate. The measured differential cross-sections in the rapidity region $|y| \leq 1$ agree fairly well with FONLL predictions, as shown in Figure 2, although the data lie systematically on the high side of the theory.

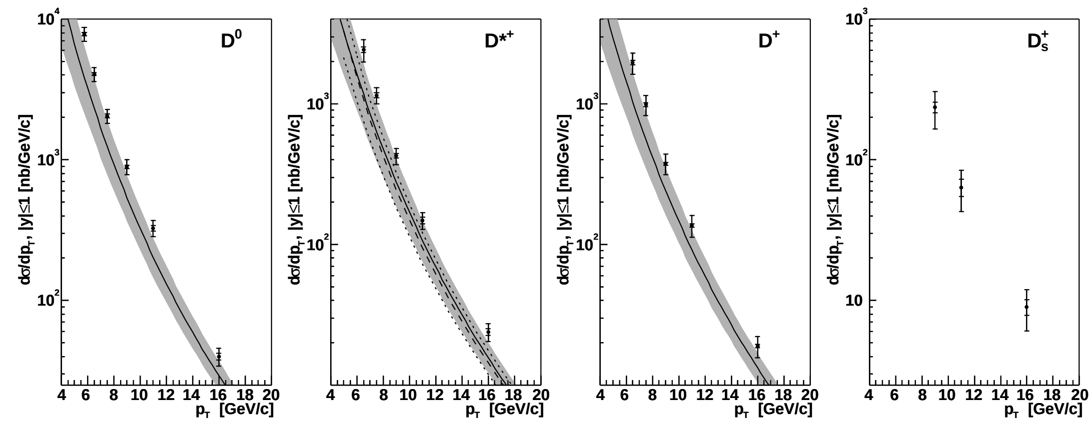

Figure 2: *The CDF differential charm meson cross-section measurements compared to the FONLL prediction.*

2.3 Open Beauty and Charm at Fixed Target

The Hera-B experiment has made new measurements of open b- and c-quark production in a fixed target environment. Their preliminary measurement of the $b\bar{b}$ cross-section uses $J/\psi \rightarrow e^+e^-$, $\mu^+\mu^-$ decays with displaced vertices from a total of 320K J/ψ candidates in ~35% of their 02-03 data sample. The new Hera-B measurement, $\sigma(b\bar{b}) = 12.3^{+3.5}_{-3.2}$ (stat) nb/nucleon, is lower than their previous result, $32^{+14}_{-12}\,^{+6}_{-7}$ nb/nucleon [10], which used the 40-times smaller 2000 data sample. It agrees well with the prediction of Kidonakis, *et al.* [11], 30±13 nb/nucleon, although the errors on the prediction are still rather large.

Hera-B has also made a preliminary measurement of the open charm cross-section using 98±12 D^0, 189±20 D^+ and 43±8 D^{*+} fully reconstructed mesons. The resulting $D\bar{D}$ cross-sections, in μb/nucleon, extrapolated to the full x_F range, are $\sigma(D^+)$ = 30.2±4.5±5.8 and $\sigma(D^0)$ = 56.3±8.5±9.5, which are consistent with previous measurements but significantly more accurate.

Measurements of charm production have also been made by the FOCUS collaboration, which has produced new results on charm baryon/anti-baryon production asymmetries [12]. The asymmetry is predicted to be vanishingly small by perturbative QCD. However "leading particle effects", can enhance the production of baryons sharing valence quarks with the target or projectile particles. The measured integrated and differential asymmetries for Λ_c^+, $\Lambda_c^+(2625)$, $\Sigma_c^{++(*)}$ and $\Sigma_c^{0(*)}$ agree poorly with predictions from the PYTHIA Monte Carlo. For example, FOCUS measures the asymmetry in the production of Λ_c^+ baryons and anti-baryons to be $0.111 \pm 0.018 \pm 0.012$, 1.8σ away from the prediction of 0.073. A better description of older asymmetry measurements has been achieved using heavy quark recombination models [13]. But this has yet to be compared to the FOCUS data.

2.4 Open Beauty and Charm in *ep* Collisions

Experimentally, both H1 and ZEUS search for b-quark production in ep collisions using muon plus jet(s) events. ZEUS separates b-quark events from backgrounds using the component of the muon's momentum transverse the the closest jet axis, $P_t^{\rm rel}$, while H1 takes advantage of their silicon strip detectors to include the impact parameter of the muon track with respect to the primary interaction vertex, along with $P_t^{\rm rel}$, to their list of discriminating variables.

The experiments make measurements in two kinematic regions – the deep inelastic scattering (DIS) regime, where photon virtuality is high ($Q^2 > 1$ GeV^2) and the photo-production (PhP) regime, where there the photon is nearly real ($Q^2 < 1$ GeV^2). Each of these regimes is sensitive to different effects in heavy quark production and provide complementary input to the measurements from the Tevatron, where $\log(p_T/m)$ effects, for example, are expected to be much more important. The results of preliminary H1 measurements from 2003 and 2004 and of published ZEUS data [14] are shown in Figure 3.

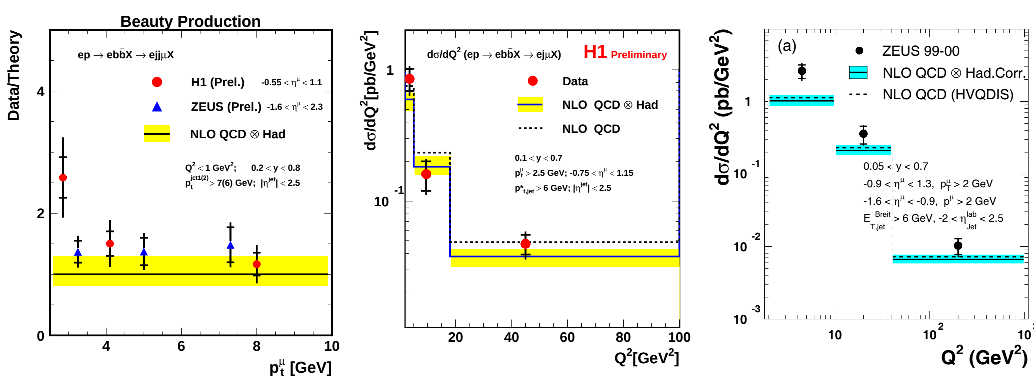

Figure 3: *Measurements of b-production by H1 and ZEUS in photo-production (left plot) and DIS (middle and right plots).*

Charm quark production is also measured by both experiments using $D^{*\pm}$

mesons. Preliminary results from H1 (2003) and from ZEUS (2002) in PhP events as well as recently published ZEUS data [15] are presented in Figure 4.

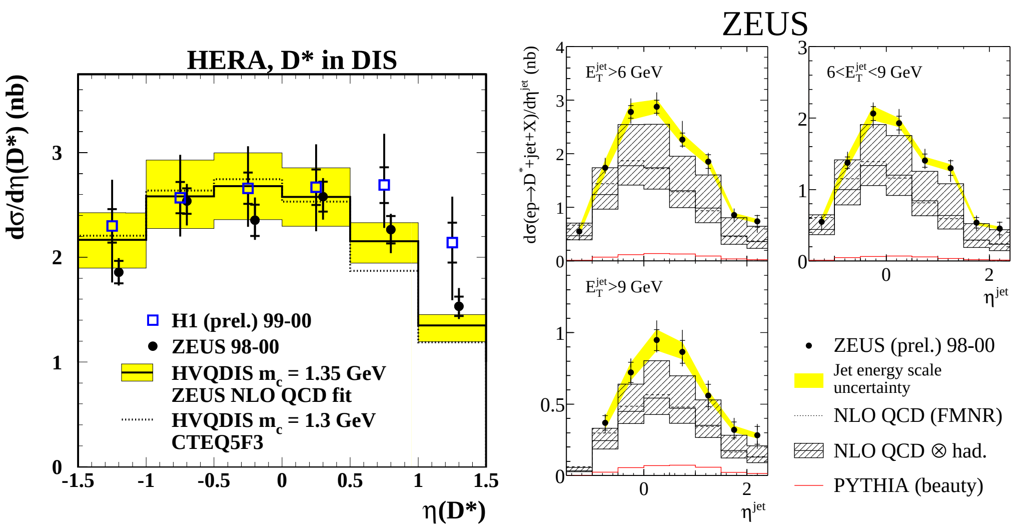

Figure 4: *Measurements of D^* production by H1 and ZEUS in DIS (left) and by ZEUS in photo-production (right)*

Agreement between both beauty and charm data and NLO predictions is generally good within the relatively large experimental and theoretical errors. Some problems may arise in b-quark production at low p_T and low Q^2 (see Figure 3). However, H1 and ZEUS do not see the same discrepancies. In the charm PhP data, mild deviations between data and theory are observed in the medium p_T and high η regions. ZEUS has studied these further in a preliminary measurement of the cross-section of jets containing $D^{*\pm}$ mesons, designed to reduce sensitivity to hadronization effects. As can be seen in Figure 4 some disagreement between data and predictions remains indicating that hadronization is unlikely to be the main cause of the problem.

2.5 b- and c-Quark Summary

The general picture emerging from new measurements of beauty and charm production and from recent theoretical advances is of remarkably better agreement between data and theory. Comparisons between measurement and prediction for the results discussed above show agreement to within about two sigma (taking into account both experimental and theoretical errors) for all recent measurements. This is obviously a big improvement over the situation a few years ago. However, optimism should not be allowed to run rampant over caution. Uncertainties on nearly all measurements are dominated by systematic errors indicating that higher statistics alone will be unlikely to produce major improvements in accuracy. On the theoretical side, uncertainties on the predictions are nearly always substantially larger than those on the measurements further adding to the difficulty of making quantitative comparisons.

3 Heavy Quarkonium Production

3.1 More History

As was the case with open beauty and charm, our understanding of the production of bound heavy quark-antiquark states has had a checkered past. (For a discussion of the decays of quarkonia see [16]). Until the late 90's the direct production of J/ψ and Υ states was expected to proceed via a color singlet mechanism (CSM) where the $Q\bar{Q}$ meson retains the quantum numbers of the $Q\bar{Q}$ pair produced in the hard scatter. CDF measurements of prompt J/ψ and ψ(2S) production in Run I [17] were higher than CSM predictions by a factor of 50 though. This discrepancy was largely resolved by the introduction of the color octet model (COM) of quarkonium production [18]. This model allows contributions from the production of $Q\bar{Q}$ pairs in a color octet state, which evolve into color singlet states by the emission of a soft gluon. The COM also improved the agreement between the rate of J/ψ production observed in *ep* collisions and predictions [19, 20, 21].

However, the introduction of the COM has a price: unlike the CSM, the COM predicts large values for the polarization of quarkonia states at high p_T. These large polarizations have not been observed experimentally in J/ψ or ψ(2S) production at the Tevatron [22] or fixed target experiments. Measurements of Υ polarization tend to suffer from limited statistics and are generally not yet able to discriminate significantly between CSM and COM predictions for polarization. However, the NuSea collaboration finds large polarization for Υ(2S,3S) states [23], in agreement with COM predictions.

3.2 J/ψ Polarization at Fixed Target

The NuSea collaboration has recently turned to the J/ψ, with a new polarization measurement of those mesons in proton–copper collisions [24]. Approximately nine million $J/\psi \rightarrow \mu^+\mu^-$ candidates are selected allowing measurements of the polarization to be made in several bins of x_F. An average polarization of 0.069±0.004±0.080

is found, which agrees with previous fixed target findings of very small polarization, but with substantially better accuracy. The measurement is lower than predictions based on the COM, which range from 0.35 to 0.65. But J/ψ mesons produced in decays of other particles (predicted to have small polarizations) have not been excluded from this analysis, or from most of the other fixed target results. So direct comparisons with COM predictions are difficult.

3.3 J/ψ Production in ep Collisions

The ZEUS collaboration has released recent, preliminary results on the production of J/ψ mesons in DIS events and their polarization in a PhP sample. While the polarization measurement has too low statistics to allow a distinction to be made between CSM and COM predictions, the DIS production measurement does have sensitivity to differences between the models. This measurement selects 203$\pm$19 $J/\psi \rightarrow \mu^+\mu^-$ decays out of 73 pb^{-1} of data and can be compared to a previously published H1 result [20] where 458$\pm$30 $J/\psi \rightarrow \mu^+\mu^-$, e^+e^- decays were observed in 77 pb^{-1} of data. Measurements of the differential cross-section are shown in Figure 5 for both the ZEUS and H1 data. These data imply that the shape of the cross-section is better modeled by the CSM than by the COM, although errors on the predictions are still quite large.

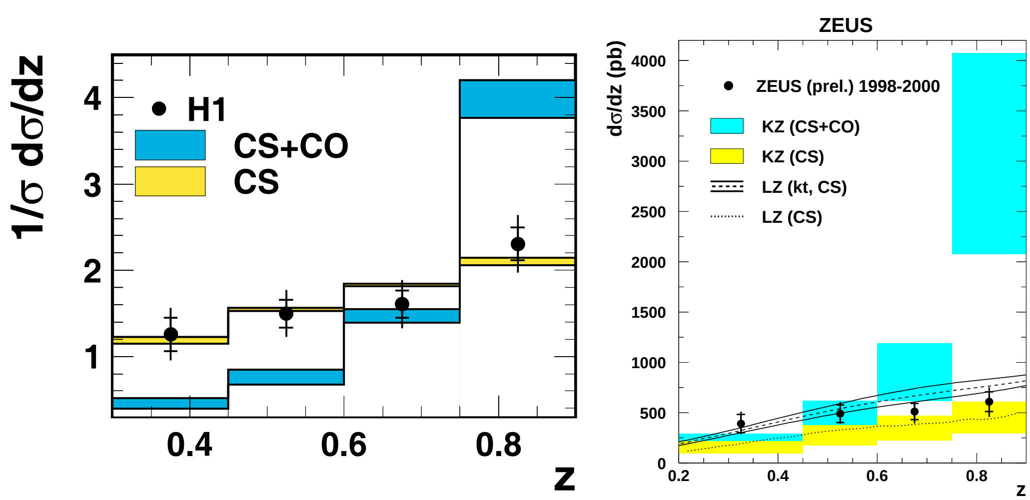

Figure 5: *A comparison of H1 and ZEUS J/ψ differential cross-sections in DIS with CSM and COM predictions.*

3.4 Heavy Quarkonium Summary

Despite recent measurements, our view of the production of heavy quarkonia states remains obscured. A COM description of the data is strongly preferred by measurements of J/ψ production at the Tevatron and, to a lesser extent by Υ polarization measurements at fixed target. On the other hand, the color singlet model provides a better description of J/ψ polarization at the Tevatron and fixed target experiments as well as matching the shape of the J/ψ differential production cross-section in DIS events at HERA. Finally, the absolute normalization of the J/ψ cross-section in DIS and PhP events is described well be neither model. As is the case with open beauty and charm production though, quarkonium measurements tend to be systematics limited and uncertainties on theoretical predictions are quite large.

4 New Particles

4.1 The $X(3872)$ at the Tevatron

In the summer of 2003, the Belle collaboration announced the observation of a new particle with a mass of around 3872 MeV in $B^+ \to K^+X(3872)$ decays [25]. This particle, which like the ψ(2S), decays to $J/\psi\pi^+\pi^-$ has now been observed by several other experiments [16] including CDF [26] and DØ [27]. Both Tevatron experiments observe large signals, with CDF finding 730±90 (11.6σ) events with a fitted mass of 3871.3±0.7±0.3 MeV and DØ seeing 522±100 (5.2σ) with a fitted mass of 3871.8±3.1±3.0 MeV (referenced to the ψ(2S) mass). The large signal samples available to the Tevatron experiments (the original observation by Belle consisted of ∼35 signal events) will allow detailed studies of the $X(3872)$ to be made. DØ has started this process by studying several kinematic properties, in production and decay, of their $X(3872)$ sample, finding that the $X(3872)$ behaves very much like the ψ(2S) within the statistics of their test.

4.2 Charmed Pentaquarks?

Controversy continues to boil over the evidence for a pentaquark particle, Θ^+, with a valence quark content of ($uudd\bar{s}$) [28]. Undeterred by this uncertainty, several groups have looked for a charmed pentaquark, Θ_c^0, with quark content ($uudd\bar{c}$). The H1 collaboration sees evidence for this particle in the decay $\Theta_c^0 \to D^{*-}p$ [29]. As shown in Figure 6, significant signals are seen by H1 in both DIS and PhP. They find 51±11 (5.4σ) Θ_c^0 candidates at a mass of 3099±3±5 MeV from a sample of ∼8500 D^* mesons in 75 pb^{-1} of data.

The primary experimental difficulty in the H1 analysis is to avoid reflections from $D^{**}\rightarrow D^{*}\pi$ decays, which peak in the 3100 MeV region if the pion is misidentified as a proton. H1 avoids these reflections by separating pions from protons using dE/dx. They have performed many cross-checks to verify the reliability of this selection.

Motivated by H1's result, ZEUS, CDF and FOCUS have conducted preliminary searches for the Θ_c^0. Despite having similar sensitivity to H1 and larger samples of D^* mesons – 43K, 200K and 36K for ZEUS, CDF and FOCUS, respectively – none of these experiments observe any evidence for the H1 signal.

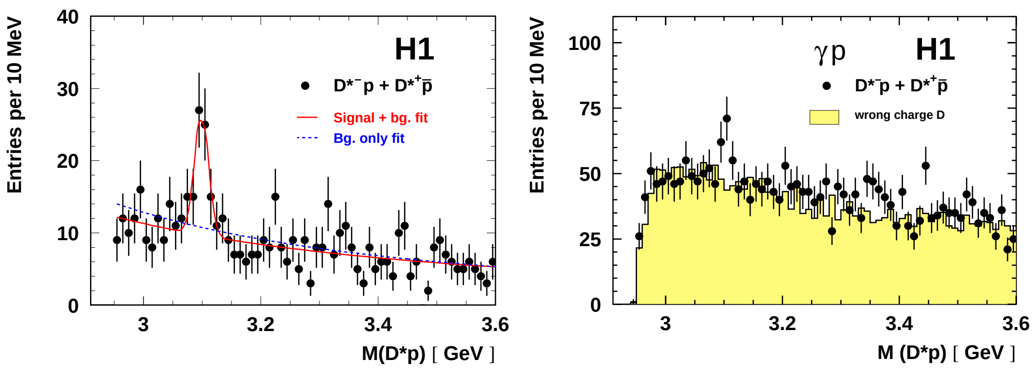

Figure 6: *Evidence for the* Θ_c^0 *by H1 in DIS (left) and photo-production (right).*

4.3 New Particles at SELEX

Two new particles have recently been sighted by the SELEX collaboration. Significant mass peaks for a doubly charmed baryon, $\Xi_{cc}^+(3520)$, decaying to $\Lambda_c^+K^-\pi^+$ and pD^+K^- [30] and a charm-strange meson, $D_{sJ}^+(2632)$, decaying to $D_s^+\eta$ and D^0K^+ [31] are shown in Figure 7. The new measurement of the $\Xi_{cc}^+(3520)$ supports a previous SELEX observation of this particle, but has not been confirmed by the FOCUS or E791 collaborations.

Should the evidence for these particles hold up to further scrutiny, they promise to provide some interesting physics. Both have rather strange properties. The decay length distribution of the $\Xi_{cc}^+(3520)$ candidates indicates a lifetime significantly shorter than expected and the relative branching ratios of the two observed decay modes are inconsistent with phase space expectations. The two $D_{sJ}^+(2632)$ decay modes observed also show a large difference from phase space predictions and, even more mysteriously, the width of the particle is much narrower than expected, $<$17 MeV at 90% C.L.

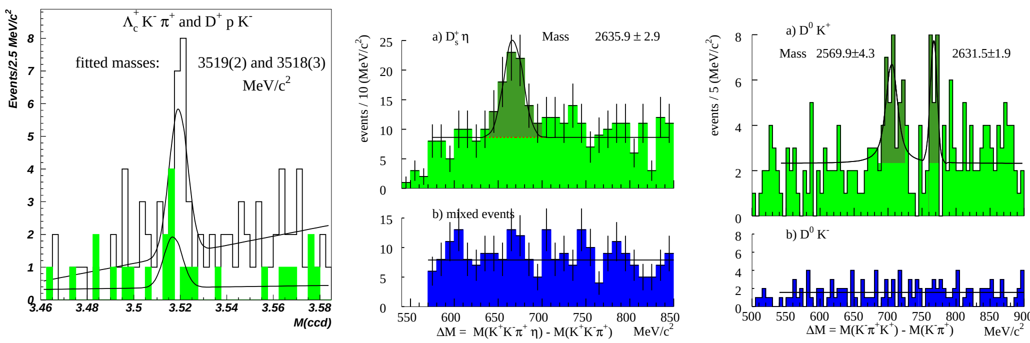

Figure 7: *SELEX mass plots for the* Ξ_{cc}^{+}*(3520) (left), the* D_{sJ}^{+}*(2632)*$\rightarrow D_s^+\eta$ *(middle) and the* D_{sJ}^{+}*(2632)*$\rightarrow D^0K^+$ *(left).*

5 Where to Now?

After several years of particularly intense activity in the area of heavy quark production, our understanding of the topic has increased substantially. Problems that have plagued the comparison of b-quark data and predictions seem to have been largely resolved thanks to the efforts of both experimentalists and theorists.

The field should, by no means, slide into complacency though. Both experimental systematic errors and theoretical uncertainties in beauty and charm production must be reduced before modeling of these processes can approach the level needed for understanding the next round of results from the LHC. Confusion also continues to reign in the area of heavy quarkonium production. Seemingly inconsistent experimental results across production and polarization measurements need to be resolved. And, as we have seen, surprising new particles, possibly pointing the way to interesting new phenomena, are waiting in the wings.

Fortunately, the future of heavy flavor production physics looks bright. Both the Tevatron and HERA accelerators have started new runs, which promise orders of magnitude more data than currently available, with upgraded detectors. Further down the road the LHC experiments, Atlas, CMS and LHCb, as well as BTeV at Fermilab should be able to collect heavy flavor data sets that dwarf those foreseen from Run II at the Tevatron and HERA, allowing production studies using exclusive final states. The optimism engendered by this possibility must be tempered by the knowledge that the physics goals of the upcoming experiments are not aimed primarily at heavy flavor production. In particular, the ability to do this type of physics will be limited by the performance of trigger systems, which rely primarily on muon triggers to collect heavy flavor data. BTeV, with its displaced vertex trigger, is an exception, which deserves special attention here. Despite the challenges a heavy flavor production program presents, though, active efforts have been started to study its possibilities [32]. I believe that we can look forward to exciting reviews of heavy flavor production for many *Physics in Collision* conferences to come.

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