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CHARM PHYSICS: Summary and Outlook

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ABSTRACT

Highlights of recent results in charm physics are reviewed and summarized.

1. Introduction – Charm

The era of high precision, high statistics studies in weak decays has finally arrived. As its twentieth birthday approaches, the charm quark has gracefully matured from the uncertain and trying times of its teenage years into solid adulthood. But despite its age, new physics is continually emerging in our studies of charm. Because the mass of the charm quark is not too much larger than Λ_{QCD}, (considering QCD scales logarithmically) it is not truly a 'heavy' quark, and therefore QCD effects and final state interactions play a much larger role in weak charm decays than, for example, in weak beauty decays.

A weak decay is depicted in Figure 1. The short-range weak interaction occurs in the small inner circle, while the confinement region is the large outer circle. Both electroweak and strong QCD effects play a role in weak decays. On the short distance scale, the weak interaction and QCD hard gluon radiation may both be exactly calculated. The long distance QCD effects, which include final state interactions, soft gluon radiation, confinement of quarks to form hadrons, and bound state effects, cannot be calculated perturbatively in QCD. Decoupling or factorization simplifies the weak decay problem into two distance scales and lets us calculate at least some of the QCD corrections, the short range dynamics part, along with the weak interaction:

• Weak Interaction – Small scale	Exactly Calculable
• Hard Gluon Radiation – Small scale	Exactly Calculable
• QCD Confinement – Larger scale	Non-Perturbative

Phenomenological models are however necessary to calculate the long-range, non-perturbative QCD effects.

Thanks to excellent emulsion and silicon detector vertex resolution, extremely high statistics in charm particle production, and the charm quark's long lifetime, huge, clean samples of charm have been collected, making precision studies of charm, and studies of the interplay of the strong and electroweak interactions possible.

We've come far beyond the naïve spectator model of weak decays shown in Figure 2a. In the case where the virtual W decays to leptons, the amplitude for such an external spectator semileptonic decay is factorizable into two parts: the leptonic part,

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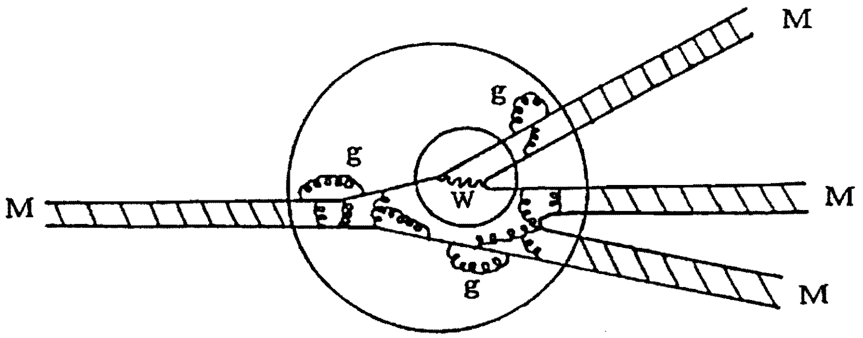


Fig. 1. The weak decay of a meson M involves both electroweak and strong QCD effects. The weak interaction occurs in the small inner circle, with the W intermediate vector boson, while the QCD confinement region is the larger outer circle. Initial and final state mesons are denoted M, and some soft gluons are denoted g.

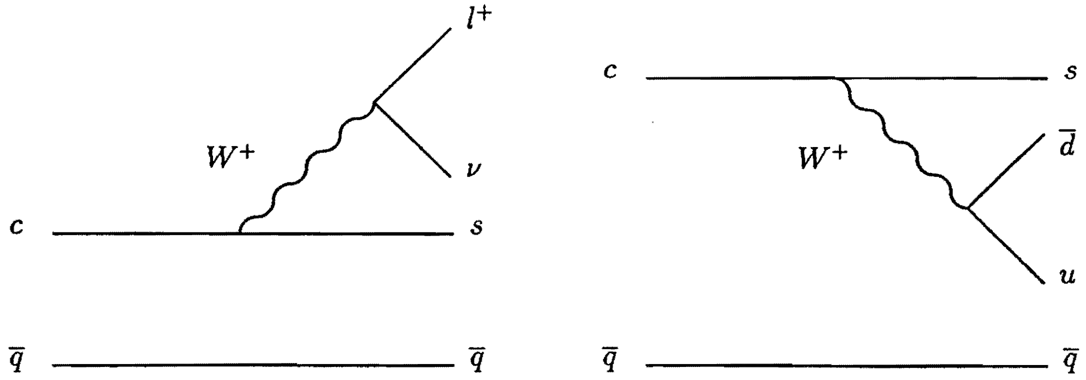
which is exactly calculable, and the hadronic part, which describes how the quarks form hadrons. The hadronic part of the amplitude may be specified in terms of form factors, which unfortunately are not exactly known, so we rely on phenomenologically-inspired q^2 dependent functions for the form factors.

In Figure 2b, an internal spectator decay is depicted. Note that gluon radiation and final state interactions may occur between the spectator quark and the quarks resulting from the decay of the virtual W. (Semileptonic decays cannot occur via this diagram, so they have no strong interaction complications from the W decay products.) This diagram is sometimes referred to as colour-suppressed, as the colour of the quarks resulting from the virtual W^+ decay must match the colour of the spectator quark to form a hadron. Figures 2c and 2d depict non-spectator W-exchange and annihilation diagrams. These amplitudes are in principle helicity-suppressed, although in the case of W-exchange, soft gluonic radiation may greatly reduce any any helicity-suppression. In the case of charmed baryon decays, it is expected that there is very little helicity suppression. There are many detailed reviews of weak decays in the charm quark system.[1,2]

2. New Experiments in Charm Physics: BES and HERA

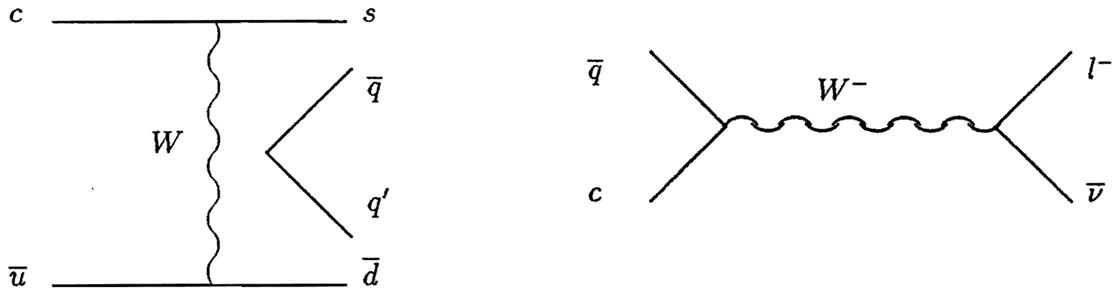
The measurement of absolute branching fractions of charmed hadrons is essential for both the understanding of details of non-perturbative QCD contributions to weak decay rates, and in order to do B physics, which usually requires complete reconstruction of charmed hadrons, and knowledge of their branching fractions to specific decay modes.

For some time now, all D_S branching fractions have been measured relative to the $D_S \rightarrow \phi\pi$ decay mode. Theory, models, and many assumptions are then used to deduce and extract absolute branching fractions for D_S decays. BES has recently completed a run just above threshold for $e^+e^- \rightarrow D_S^+ D_S^-$ production (below D_S^*



a) External Spectator

b) Internal Spectator



c) Exchange

d) Annihilation

Fig. 2. Charm quark decay diagrams.

threshold), so that only $D_S^+ D_S^-$ pairs are produced, each with the beam energy. By reconstructing events in which either one or both D_S are reconstructed, the absolute branching fraction $D_S \to \phi\pi$ may be measured model-independently:

$$Br(D_S^\pm \to \phi\pi^\pm) = (4.2^{+9.0+1.7}_{-1.5-0.0} \pm 0.5)\%$$

The excellent particle identification capabilities of the dE/dx and Time-of-Flight systems, and the fact that the D_S energy is constrained to the beam energy, result in excellent signal/background enhancement. BES has also taken advantage of doubly-tagged D_S candidates to measure the D_S pseudoscalar decay constant via the decay $D_S \to \ell\overline{\nu}_l$. Measurement of this decay constant gives the coupling of the weak hadronic current to the vacuum, a measure of the c and $\overline{s}$ quark wave function overlap, which provides critical tests of QCD calculations involving sum rules, lattice gauge calculations, and potential models. Measurements of f_{D_S} from CLEO, WA75, and BES are listed in Figure 3, alongside theoretical predictions. Additionally, the BES group has obtained a sample of doubly-tagged $D^*\overline{D}$ and $D^*\overline{D^*}$ events, which has been used to confirm CLEO's relatively new D^* branching fraction results.[3]

Charmed D^* mesons and J/ψ mesons have been reconstructed at the ZEUS

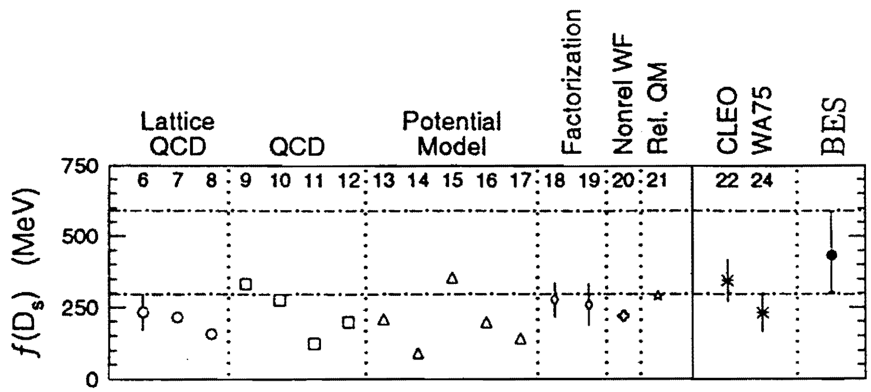


Fig. 3. Calculations and measurements of the D_S pseudoscalar coupling constant.

and H1 experiments at the HERA $e-p$ collider, and provide a probe of QCD. The charm cross section and its Q^2 dependence provides a test of our understanding of QCD charm production mechanisms such as photoproduction via low $p_\perp$ γ−proton diffractive scattering or high $p_\perp$ γ−gluon fusion. Elastic and quasi-elastic electroproduction via γ−gluon fusion probes the gluon density of the proton or pomeron and tests vector meson dominance models. Prompt μ from charm and beauty decays have been observed and the charm photoproduction cross-section $\sigma(\gamma p \to c\bar{c}X)$ measured. The data compare well with theory and with extrapolations from lower energy experiments. It is clear that critical tests of QCD in the charm sector have only just begun at HERA, but preliminary charm results to date are well described by QCD.

3. High Precision Studies in Charm

Detailed high precision understanding of charm decays continues at fixed target experiments, e^+e^- colliders and hadron colliders.

3.1. Semileptonic Decays of Charmed Hadrons

Semileptonic decays may proceed only through the external spectator diagram, depicted in Figure 2a. Since the virtual W decays to leptons, there is only one diagram which contributes to the amplitude, and any QCD effects are confined to the hadronic part of the decay. While the leptonic part of the weak decay is exactly calculable, the hadronic part is typically described by form-factors which are q^2 dependent functions which are deduced from phenomenological models. (q^2 is the invariant mass of the lepton and neutrino.) For a decay of a pseudoscalar meson into leptons plus a pseudoscalar meson, (for example, the decay $D^0 \to K^-\ell^+\nu_\ell$) only one form factor is necessary to describe the decay (in the limit the leptons have zero mass). For the semileptonic decay of a vector meson to a pseudoscalar meson plus leptons, three form factors are needed to describe the decay. Models differ in the form of the form factors: of two current popular models, the ISGW model uses exponential form factors,[5] while WBS model has single-pole type form factors.[6]

CLEO has recently constructed decays of the charmed baryons $\Xi_c^+ \to \Xi^0 e^+\nu$ and $\Xi_c^0 \to \Xi^- e^+\nu$. These decays are particularly interesting: if one assumes that the production rates of Ξ_c^+ and Ξ_c^0 are identical, and that their semileptonic widths are identical, then the ratio of their semileptonic branching ratios is the ratio of their lifetimes. Recall that this is the case in D^0 and D^+ decays, where differences in lifetimes originate from the hadronic sector, in which non-spectator decays are responsible for lifetime differences. CLEO measures $\tau(\Xi_c^+)/\tau(\Xi_c^0) = 2.46 \pm 0.70^{+0.33}_{-0.23}$, which suggests that the W-exchange amplitude is significant in decays of charmed baryons. Using theoretical predictions that the interference in the case of the Ξ_C^+ has both destructive and constructive components, while the Ξ_c^0 has components from W-exchange and constructive interference, each of these components can be deduced if all charmed baryon amplitudes/lifetimes are fit simultaneously. This result agrees well with direct measurements at fixed target experiments.

CLEO has also presented results from semileptonic decays of charmed hadrons, and has deduced form factors at $q^2 = 0$. In the case of the decay $D_S^+ \to \phi \ell^+ \nu$, the three form factors may be denoted $A_1(q^2)$, $A_2(q^2)$ and $V(q^2)$, and from the angular distributions of the decay the ratios $\frac{V(q^2)}{A_1(q^2)}$ and $\frac{A_2(q^2)}{A_1(q^2)}$ may be deduced. These ratios should be the same as the ratios measured in the decay $D^+ \to \overline{K^{*}}^0 \ell^+ \nu$, if SU(3) flavour symmetry holds. CLEO has measured these ratios for the decay $D_S^+ \to \phi \ell^+ \nu$ and results are consistent with world average results for the decay $D^+ \to \overline{K^{*}}^0 \ell^+ \nu$: $\frac{A_2(q^2)}{A_1(q^2)} = 1.4 \pm 0.5 \pm 0.3$ and $\frac{V(q^2)}{A_1(q^2)} = 0.9 \pm 0.6 \pm 0.3$, which agree with predictions from the theory of ISGW.[5]

There are however problems in understanding semileptonic D_S decays. CLEO has measured the ratio of pseudoscalar to vector rates in D_S semileptonic decays, a quantity which many otherwise successful theories fail to predict correctly in analogous D decays. Not only do the branching ratios $Br(D_S^+ \to \eta' \ell^+ \nu)/Br(D_S^+ \to \phi \ell^+ \nu) = 0.71 \pm {}^{+0.19}_{-0.18}{}^{+0.08}_{-0.10}$ and $Br(D_S^+ \to \eta \ell^+ \nu)/Br(D_S^+ \to \phi \ell^+ \nu) = 1.74 \pm 0.34 \pm 0.24$ disagree with theory, but the ratio of these branching ratios does not agree with expectations from the factorization hypothesis. Clearly there is a need for further work in understanding semileptonic decays.

Finally, CLEO has studied the decay $\Lambda_c^+ \to \Lambda \ell^+ \nu$ in order to study the form factors in Heavy Quark Effective Theory.[7] Decays of charmed baryons are characterized by form factors, two axial, two vector. But in the limit of the charmed quark being infinitely heavy, the spin and flavour symmetries reduce the number of independent form factors to one, which may be measured via studying the angular distribution of the Λ_c^+ semileptonic decays.

3.2. Spectroscopy

There are four $\ell = 1$ p-wave mesons with spin-parity $J^P = 0^+, 1^+, 1^+,$ and 2^+ for each the D^0, D_S^+, and D^+. The approximate spin-flavour symmetry for heavy quarks[7] results in the charmed p-wave mesons being arranged in two doublets:

- 0^+ 1^+ : very broad resonance ($j = S_q + \ell = \frac{1}{2}$)
- 1^+ 2^+ : narrow resonance ($j = S_q + \ell = \frac{3}{2}$)

where S_q is the spin of the light quark in the charmed meson. CLEO has observed both narrow p-wave states for each the D^0, D_S and D^+ mesons, verifying their spin-parity assignments through helicity analyses. The masses and branching fractions agree well with predictions of potential models.[8]

CLEO has reported new measurements of branching ratios of the Λ_c^+. While only slightly more than 25% of all Λ_c^+ decay modes are known, some decay modes which can only occur via $W-$exchange have been observed (along with decays which can occur via both spectator and exchange diagrams). These contributions to the total Λ_c^+ width leads one to conclude that the lifetimes of charmed baryons could be much smaller than for charmed mesons–a fact which has been observed. Additionally, when Pauli interference and final state interactions have been considered, the complete picture of hierarchy in charmed hadron lifetimes may be deduced.

From Fermilab, there is possible evidence (preliminary, pending full helicity analysis) from E-771 for the $^1P_1$ and $^3D_2$ charmonium states. The observed masses agree well with potential model predictions of these charmonium states.

3.3. Charm at LEP

At LEP, separated primary charm quark and primary beauty data samples are used to test electroweak theory such as the coupling of the Z^0 to $b\bar{b}$ and $c\bar{c}$ quarks, and to test QCD, in studying, for example, fragmentation processes of each the b and c quarks. In contributions to this conference, OPAL has performed detailed studies of D^* mesons and Λ_c baryons including measurement of total production rates from the Z^0, and in particular, separating out contributions from primary b quarks from primary c quarks, either based on momentum distributions, or if momentum distributions themselves are to be studied to gain insight into QCD hadronization. This separation may be achieved by several techniques:

- the presence of a high p, high p_T lepton, characteristic in semileptonic B decay
- global event topology and jet shape variables input to a neural network
- the displacement of tracks from the Z^0 vertex in the opposite thrust hemisphere to a D^* candidate is used to tag $Z^0 \to b\bar{b}$ events.
- the reconstruction of the decay vertex of the D^0 candidate produced in D^* decay, taking advantage of the fact that the B_d^0 lifetime is about four times that of the D^0, so that D^0s produced from D^*s from B decay have significantly larger displacements from the primary Z^0 decay vertex than those produced from primary charm quarks.

Fragmentation studies are approaching the precision necessary to rule out some fragmentation function models. The Peterson fragmentation function is only slightly favoured over several other popular models. Characteristics of charm fragmentation near 90 GeV may be compared to previous studies at lower energies to study scaling violations as an interesting test of QCD.

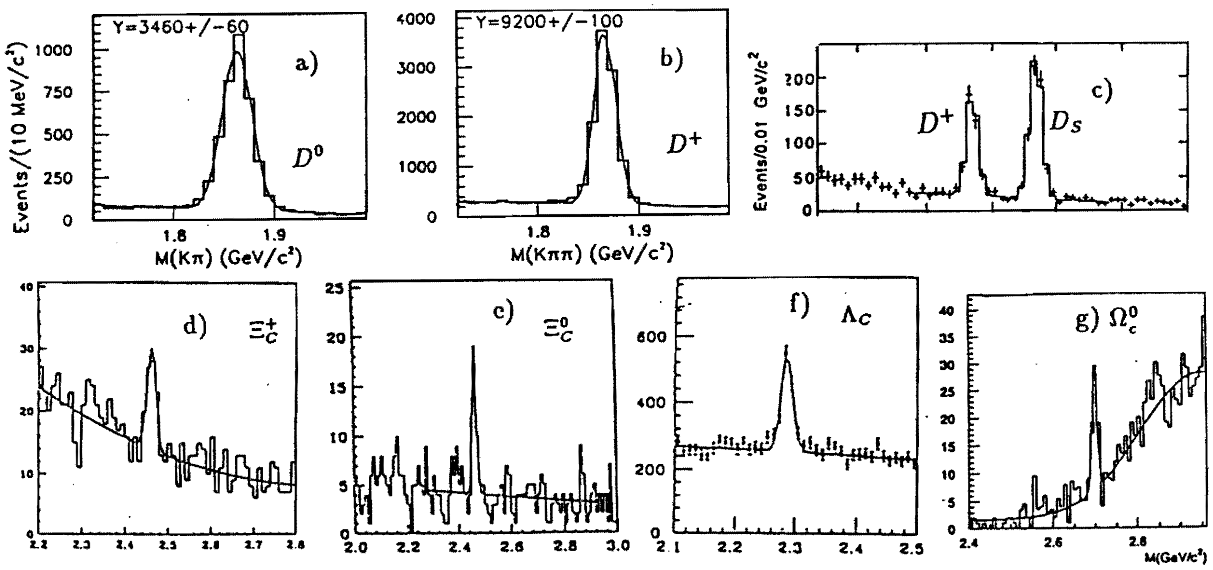


Fig. 4. Charmed hadron invariant mass plots from E-687. a) D^0, b) D^+, c) D_S, d) Ξ_C^+, e) Ξ_C^0, f) Λ_C, g) Ω_c^0

Additionally, completely reconstructed charmed hadrons are crucial building blocks in the reconstruction of B hadrons. Semileptonic B decays to D, D^* and D^{**} mesons accompanied by a lepton have been reconstructed using kinematic and vertex information. OPAL has made the first observation of semileptonic B meson decays to charged p-wave D mesons, and has determined that p-wave D mesons account for (34±7)% of charmed semileptonic B meson decays, in agreement with earlier results from the CLEO[9] and ARGUS[10] collaborations.

3.4. Charm at Fixed Target Experiments

Fixed target experiments have contributed immensely to our knowledge of charm production, lifetimes, and spectroscopy, noted the large number of contributed talks from Fermilab experiments E-672, E-687, E-706, E-771, E-789 and E-791.

Powerful vertexing techniques have been used to tag very clean charmed hadron samples, from which high precision, high statistics charmed hadron lifetimes have been measured. Detailed studies involving Dalitz analysis of multi-body charm meson decays been performed, including 5-body decay modes and D_S decay modes involving the f_0 and f_2, and the observation of $\Omega_c^0 \to \Sigma^+ K^- K^+ \pi^+$, a new decay mode, (shown in Figure 4g), with statistics sufficient (over 40 events) to soon measure its lifetime.

Measurements of 1% to a few % on charm hadron lifetimes have been been performed with the E-687 spectrometer at Fermilab. The clean charmed hadron signals from which lifetimes are extracted are shown in Figure 4. In the naïve spectator model, a free charm quark would have lifetime given by analogy to muon decay, approximately of 1-2$\times 10^{-12}$s, and so the spectator model predicts all charmed hadrons to have the same lifetime. Experimentally, a lifetime hierarchy is observed, with lifetimes varying over an order of magnitude:[11]

	$\tau(D^+)$	$>$	$\tau(D_S^+)$	$>$	$\tau(D^0)$	$\approx$	$\tau(\Xi_C^+)$	$>$	$\tau(\Lambda_C^+)$	$>$	$\tau(\Xi_C^0)$
$\tau(ps)$	1.057		0.467		0.414		0.35		0.202		0.098
	±0.015		±0.017		±0.004		$^{+0.07}_{-0.05}$		±0.012		±0.023

The D_S and D^0 have lifetimes which now differ significantly, by 3σ. More notably, in the charmed baryon sector, final state interactions are large, and helicity suppression in exchange diagrams is not very significant, due to the presence of an extra spectator quark, which can exchange soft gluons, overcoming helicity suppression.

Production asymmetries in Feynman x distributions of leading and non-leading charmed mesons produced in $\gamma - g$ fusion have been observed. Production mechanisms and models may be studied by investigating the ${p_T}^2$ and x_F dependences of charmed meson production, and such QCD studies are underway at several FNAL fixed target experiments.

At fixed target experiments at Fermilab it has been determined that not all $J\psi$'s come from B decays; in fact, at E-672/706, it was determined that less than half of J/ψ's detected are direct or from B decays. The remaining $J\psi$'s come from decays of $\psi(2S)$ and χ_c charmonium states. Additionally, the fixed target experiments have reconstructed a handful of B decays to $J/\psi K$ and $J/\psi K^*$.

3.5. Charm at Hadron Colliders

At the TeVatron collider, a few $\times 10^4$ J/ψ candidates have been reconstructed and the CDF precision vertex detector has enabled the determination that most J/ψ's are prompt, the result of gluon fusion, gluon fragmentation and charm fragmentation processes, and not from B decays, previously thought to be the dominant source of J/ψ. Recent advances on the theoretical front in perturbative calculations of fragmentation now correctly predict prompt J/ψ production and J/ψ production from B decays. There remains however a problem with the theory being an order of magnitude away from the measured ψ' production rates. CDF has also measured Compton production of charm and beauty via the production of D^*'s and prompt muons.

4. Conclusions and Outlook

Much progress has recently been made in the field of charm physics. The hierarchy of charmed hadron lifetimes has emerged and measurements may be used to study the effects of spectator and non-spectator decay amplitudes in charmed hadron decays, and interference effects in weak decays. We anxiously await a measurement of the Ω_c lifetime, which will help us fill in more details on non-spectator contributions to heavy quark decay.

CLEO-II, with its superb photon resolution, will continue to measure new decay modes of charm in modes involving neutral particles, and reconstructing B mesons from charmed hadrons to study weak decays in the B system. The BES detector, although no longer running just above D_S^+ D_S^- threshold, will include more decay modes in its double tagging analyses, so we can expect better statistical precision on absolute D_S^+ branching fractions. At HERA, we are just beginning to explore the charm content in the proton and pomeron, performing critical tests of QCD.

In semileptonic decays, form factors are measured, but in order to gain detailed insight into the decays, more data are needed. It will be interesting when statistics are sufficient to study q^2 dependences of form factors in order to distinguish various models and thoroughly test lattice QCD calculations.

The TeVatron is a copious producer of heavy quarks, and detailed studies of charmed quark production from B decays, gluon fusion, and gluon fragmentation provide tests of QCD. Theoretical advances in the understanding of charmonium production (specifically ψ') are necessary, as present calculations fail to reproduce experimental measurements.

LEP, with high charm and beauty statistics, and high precision vertex detectors is contributing much to the field of weak heavy quark decays, both in detailed studies of charm, and the development of charm as a tool for tagging and reconstructing B decays.

Finally, all the theories formulated, and insight and experience gained in studying charm decays will be directly applicable and testable in the B system soon.

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