Fermi National Accelerator Laboratory

FERMILAB-Conf-93/328

# Heavy Quark Production and Spectroscopy

Jeffrey A. Appel

*Fermi National Accelerator Laboratory*
*P.O. Box 500, Batavia, Illinois 60510*

November 1993

Invited talk at the *XVI International Symposium on Lepton-Photon Interactions*, Cornell University, Ithaca, New York, August 1993

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

## Disclaimer

# Heavy Quark Production and Spectroscopy

Jeffrey A. Appel*

* *Fermi National Accelerator Laboratory*[1]
*Batavia, Illinois 60510*

This review covers many new experimental results on heavy flavor production and spectroscopy. It also shows some of the increasingly improved theoretical understanding of results in light of basic perturbative $QCD$ and heavy quark symmetry. At the same time, there are some remaining discrepancies among experiments as well as significant missing information on some of the anticipated lowest lying heavy quark states. Most interesting, perhaps, are some clearly measured production effects awaiting full explanation.

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[1]Work supported by the U.S. Department of Energy under contract No. DE-ACO2-76CHO3000.

## INTRODUCTION

Let me begin this review with a question. Why is this set of heavy quark topics here in this $QCD$ session? Why wasn't this review of new results on the production and spectroscopy of heavy quarks with the rest of the heavy quark physics earlier in the symposium?

The agreement of CDF data with the $QCD$ theoretical understanding of jet production over nine orders of magnitude shown by Marjorie Shapiro in the previous talk is very impressive.[1] Nevertheless, there remains a need to test perturbative $QCD$ in other environments. Marjorie even referred to the "pathological" case where the current $QCD$ predictions fail, namely in the inclusive bottom quark production at CDF. Indeed, it is in the cases where we find discrepancies that we usually learn the most, not those cases where agreement masks the interesting questions. Additional motivation comes from recent progress in applying heavy quark symmetry for which heavy flavor physics provides the crucial workshop.

Production and spectroscopy are probes of the quark model itself and also, as you will see during the talk, a probe of the nature of forces. Production is a probe of the internal structure of hadrons; and here I am not talking only about the hadrons which contain the heavy flavors, but also about the lower mass hadrons as well. Finally, for those motivated by other physics topics, (e.g., the top quark and non-Standard Model physics signals), heavy quark production is an absolutely crucial part of understanding backgrounds for these topics.

Now, in all of our talks here at the Lepton Photon Symposium and in other conferences, we all need to make a number of opening remarks. It is unfortunate that there isn't an official catalog so we can quote the numbers instead of taking valuable time for these nevertheless important comments. To do it right takes real time. Clearly, (1) I need to thank all who have been very helpful in getting this talk together. (2) The amount of material is enormous. (3) I must apologize to those whose work I will leave out. (4-17) And so on. With a catalog for reference, I could save a little time for one joke, one that I'm reminded of by this cataloging. Since it involves one of our senior colleagues, Leon Lederman, I was encouraged to tell it.

I don't know how many of you are aware that Leon's brother is actually a professional comedian, a stand-up comic. Anyway, on one occasion Leon went with his brother to a symposium of stand-up comics where they had a banquet on the last evening. There was an after dinner speaker, a well know comedian. He got up after an introduction and he said "17." Immediately, the entire hall was rolling in laughter. When the laughter died down he said "13" and again, everybody broke up with enormous laughter. It turns out that each of these numbers referred to the jokes that they all knew very well, even by catalog number. This went on for 5 or 10 minutes. Then he said "32" and there was an embarrasing silence in the hall. Leon, leaned over and asked his brother *"So what was wrong with number 32?"* His brother replied, *"He always gets the punch line wrong on that one."* So, using catalog numbers doesn't solve all problems.

# PRODUCTION

## Strong Coupling Constant

Marjorie Shapiro has already discussed the fact that $\alpha_s$ is the same in couplings to light and heavy quarks. This is one of the most fundamental elements of the Standard Model. It is also fundamental to this talk being in this *QCD* session. One other measure of this comes from measurements made at PETRA,[2] MARKII,[2] and SLD[3]. The difference in the away side hadron multiplicity in heavy flavor events relative to light flavor events is independent of the CM energy over the range 20 to 100 GeV. Over this range, there is a doubling in the total multiplicity per event. "This supports the notion that *QCD* remains asymptotically free down to the scale $Q^2 \sim M_b^2$"[3] and below.

## Fixed-Target Charm Production

At the Heavy Flavor Conference in Montreal last month, Pat Burchat[4] showed a large list of experiments which have historically, and are currently contributing to charm physics. Since I am focusing on production and spectroscopy, I won't spend time on all the current experiments. However, one must note the spectacular increase over time in the numbers of reconstructed charm decays. In photoproduction, the first experiments were lucky to get 100's. Now, we have gone from 10,000 reconstructed decays in the milestone Fermilab experiment E-691 to 80,000 in E-687. Historically, hadroproduction has been much harder. Yet, Fermilab experiment E-791 projects over 200,000 reconstructed decays. Furthermore, in all of the channels examined so far, the hadroproduced signals can be made as clean as those in photoproduction.

Next-to-leading order (NLO) *QCD* calculations are necessary to explain the production cross-sections for these charm events. The hadroproduction cross-section predictions, which are dominated by gluon-gluon fusion, match the data within the theoretical uncertainty.[5] The energy dependence fits well. However, there is a factor of three uncertainty in magnitude due to uncertainty in the calculation scale. There are many measurements with pion beams, proton beams, and even two with kaon beams. The shape of the differential distribution, $d\sigma/dx_F$, for inclusive charm mesons from hadroproduction experiment E-769[6] with a 250 GeV pion beam, is shown in Fig. 1 as a function of Feynman x ($x_F$), the scaled longitudinal momentum of the charm particle. Plotted in the same figure is a theoretical calculation for charm quark production. The distribution looks the same for the mesons measured in the laboratory as for the theoretical predictions for the quarks. If you fold in any kind of fragmentation function for the quarks, the theoretical curve will fall much faster. There is a need to understand what is going on here. The experimental fits to the data are ordinarily of the form $(1-x_F)^n$. A large number of experiments with pion beams obtain a consistent value of $n$ between three and four.[7] Protons lead to a softer, faster falling distribution, i.e., higher value of $n$. In a recent preliminary measurement from CERN WA89[8] with a 340 GeV $\Sigma^-$ beam, $n = 6.3 \pm 0.9$, very much like the proton value. Baryons, including $p$'s and $\Sigma^-$'s, are thought to have softer gluon distributions than pions. This leads to the softer charm $x_F$ distribution.

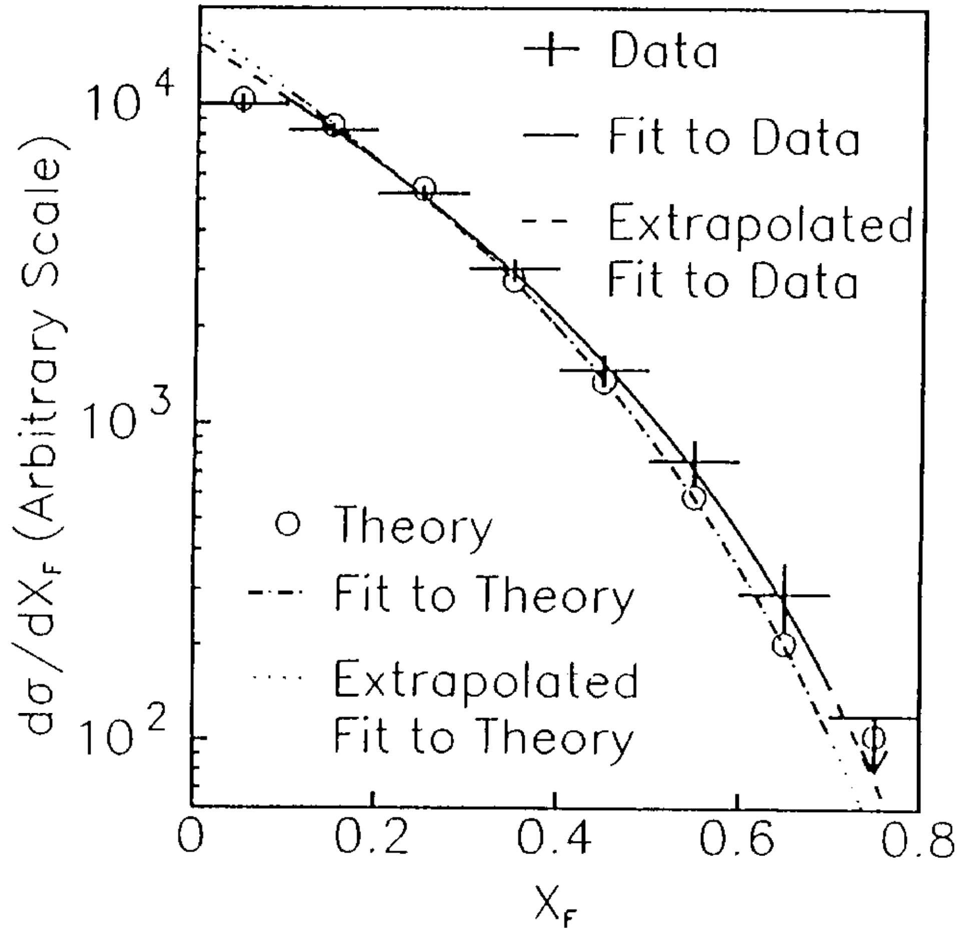


Fig. 1. Feynman $x$ distribution of charm particles ($D$ mesons) compared to theoretical predictions for charm quarks. This figure demonstrates the unexpected similarities of these distributions.

But why do quarks in theoretical calculations look like mesons in the laboratory? To suggest an answer, I turn to work by Mangano, Nason, and Ridolfi[9] who, in addition to calculating the shapes for $x_F$ and $p_t$ distributions in NLO perturbative $QCD$, have studied the effect of something you might call "color drag." That is, they take a Monte Carlo program, HERWIG in particular, and examine the effect of hadronization. What happens to the charm quark due to the string connections to the other quarks in the hadronic environment? The net effect is that the charm quarks (the heavy quarks) are pulled forward in a way which compensates for the $e^+e^-$ type of fragmentation. This is a possible explanation, at least, for an effect which is not well understood, but well measured.

People have made fits to the $x_F$ distribution data for both leading and non-leading production of mesons. A leading charm meson is one which has the non-charm valence quark the same as one in the incident particle. A plot of the leading/non-leading asymmetry (Fig. 2) shows this leading effect much more dramatically than the comparison of the $n$ values of the $(1-x_F)^n$ fits.[10] There are 50 - 60% asymmetries in the production of charm particles at $x_F \sim 0.6$. Also note that the effect is not explained by either NLO effects nor by the PYTHIA string fragmentation model. Since the fraction of the cross-section at such large $x_F$ is very small, it doesn't show up as a big difference in the total cross-section. This asymmetry is not a strong function of $p_t$. This is the kind of information which is coming to be available to help us understand the hadronization process. There is also new, very solid photoproduction data. Older data from Fermilab E-691[11] has been corroborated and extended by E-687 to higher energies[12] and by NA14/2 at CERN.[13]

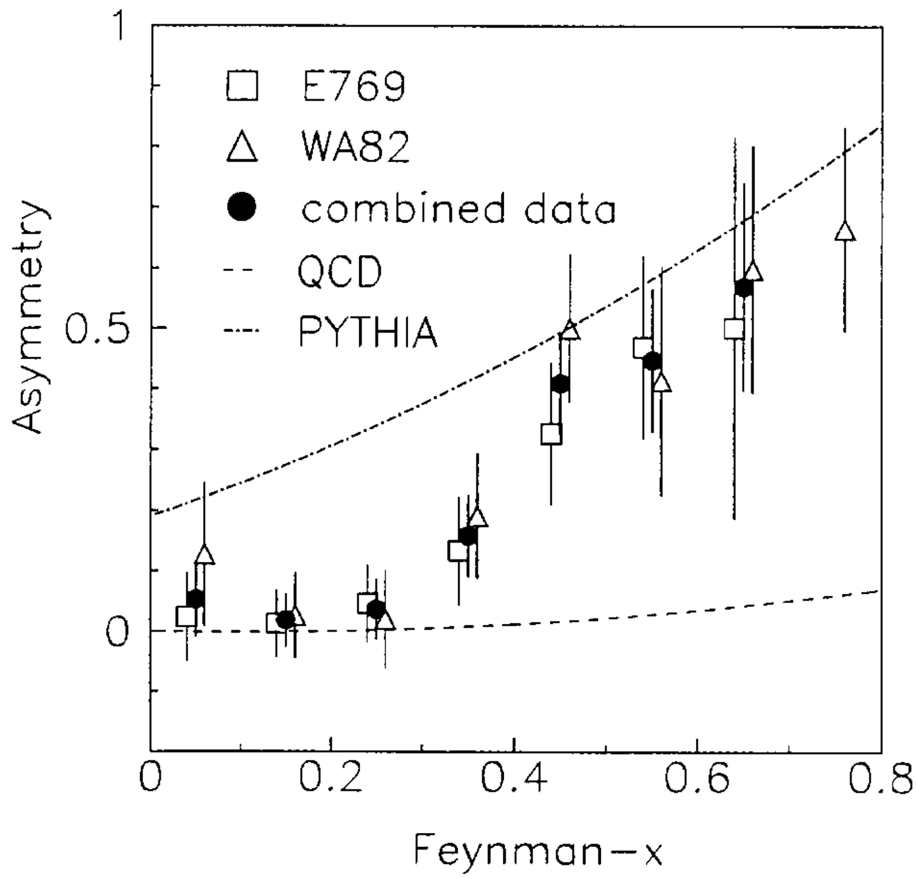


Fig. 2. Leading/non-leading charm particle asymmetry in hadroproduction of charm mesons by WA82 and E-769 pion beams. The asymmetry is defined as,

$$A \equiv \frac{\sigma(\text{leading}) - \sigma)\text{non} - \text{leading})}{\sigma(\text{leading}) + \sigma(\text{non} - \text{leading})}$$

where, for example, *σ(leading)* is the cross section for the leading charm particle of a given species. The dashed curve is from a NLO calculation and the dot-dashed curve is from the PYTHIA string fragmentation simulation.

E-687, having a much larger photoproduced charm sample than E-691, has a significant number of cases, over 300, where they see both the charm and the anti-charm mesons reconstructed in the same event.[14] This allows them to look, for example, at the $p_t$ of the charm pair, the effective mass, the opening angle, and how nearly back to back the charm mesons are produced. The data can be compared to NLO calculations by Frixione, Mangano, Nason, and Ridolfi[15] which have just been received this month.

Thus, there is a lot of data coming available and being compared to NLO perturbative $QCD$. How valid should the calculations be? One test of this is the target atomic weight dependence (A dependence) of the cross sections. The earliest experiments[16] saw an A-dependence which was characteristic of diffractive processes, e.g., the total inelastic cross section. These nuclear cross sections rise as $A^{\alpha}$ with $\alpha = 0.71$.[17] The hard scattering for which perturbative $QCD$ is relevant produces heavy quarks without being aware of the nucleus in which a target parton exists. In fact, the dominant partons, being gluons, ought to be independent of whether they are in neutrons or protons. If it were just a question of the number of partons, the cross-section would go like $A^{\alpha}$ (with $\alpha = 1$), the number of nucleons and, therefore, the number of partons in the target. The most recent experiments, WA82 at CERN[18], gets an exponent, $\alpha = 0.92 \pm 0.06$ the same value as was seen a couple of years ago for the $J/\psi$ by Fermilab's E-772.[19] E-769 has just published[20] the value of $\alpha = 1.00 \pm 0.05 \pm 0.02$ and a preliminary result from E-789 is about 1 as well, $1.01 \pm 0.06$.[21] Thus, all this effort looking at charm quark production in terms of perturbative $QCD$ is consistent. On the other hand, we have to understand the fragmentation/hadronization.

## Fixed-Target Beauty Production

Because of its heavier mass, fixed-target beauty production is widely believed to be more reliably predicted by perturbative $QCD$. Three fixed-target production cross-section measurements, two of them new, are in very good agreement with NLO calculations. The number of events here are not large. For example, in E-672 at Fermilab, nine dimuon decays of $J/\psi$'s coming from air gaps between their targets lead to a forward $\pi^-$ cross-section at 530 GeV of $28 \pm 9 \pm 8$ nb/nucleon ($x_F > 0.1$).[22] E-653, an emulsion experiment at Fermilab, obtained $33 \pm 11 \pm 6$ nb/nucleon for all $x_F$ from 9 $b\bar{b}$ events.[23] The experiment has good acceptance even in the backward $x_F$ direction. Their fit to $(1-|x_F-0.6|)^n$ for incident 600 GeV pions gives $n = 5.0\ ^{+2.7}_{-2.1} \pm 1.7$ and a much flatter $p_t$ dependence, $e^{-bp_t}$, with $b = 0.13\ ^{+0.05}_{-0.04}\,^{+0.02}_{-0.02}$ $\mathrm{GeV}^{-2}$ instead of about 1 $\mathrm{GeV}^{-2}$ for charm.

## Collider Beauty Production

Fixed-target measurements can be understood in terms of the predictions of current $QCD$ calculations, albeit with the large uncertainties associated with the scale and $c$ and $b$ quark masses. The same cannot be said of collider $b$ measurements.

There has been some re-analysis of the UA1 $b$ production data at CERN.[24] The data has already been seen except that now there are four individual points at lower $p_t$. Although the UA1 data is widely cited as agreeing with NLO $QCD$ calculations, the central value of the $QCD$ prediction really isn't quite the one that matches the data. In fact, the data are on the high side of what's allowed by the uncertainty in the theory.

UA1 has examined the azimuthal distribution of $B$ mesons by looking at decay leptons. There is a very strong back-to-back peaking associated with the $b\bar{b}$ production. On the other hand, there is a very long tail. The events in this tail are interpreted as three-body production. This provides a handle to split the events into those related to leading order and those related to next-to-leading order (in the sense of having a gluon emitted in the hard scattering subprocess).

The pathological $QCD$ case that Marjorie Shapiro referred to is at CDF. The data for $b\bar{b}$ production (Fig. 3) appears to be a factor 2 above the top of the theoretically predicted band.[25]

The data from 1988-89 included some points at lower $p_t$ from measurements which involve the $J/\psi$, for example, and was a factor more than 4 above top of the theory band. In the new data from the 1990-91 run, many of those very high points have come down. On the other hand, they now agree with the pathology of being a factor about 2 higher than the top of the theory band. One of the new tools used in the new data is the silicon microstrip system. This allows CDF to tag those decays which occur away from the interaction point. This, in turn, allows lifetime measurements for average $B$'s decaying to $J/\psi$'s. But what is interesting in the production context is that this allows determination of the fraction of the $J/\psi$'s coming from the primary interaction and what fraction comes from $B$ decays. In the run just completed, Run 1A so-called, only about 15% of the $J/\psi$'s actually come from $B$'s. You may remember that the result where the cross-section is the factor of 4 or more above the prediction actually assumed that (63 $\pm$ 17) % of the $J/\psi$'s came from $B$'s.[26] Having seen these two numbers, note that the acceptance has changed in Run 1A with its much wider acceptance and lower $p_t$ threshold relative to the 1988-9 run. Using the 1988-9 cuts, only about 25% of the $J/\psi$'s come from $b$ decays. Thus, the old cross-section value was too large. The silicon vertex detector also helps generate clean plots of specific decay modes including $B_s \rightarrow J/\psi\ \phi$. The $p_t$ distribution (Fig. 4) of the fully reconstructed $B^+ \rightarrow J/\psi\ K^+$ mesons also disagree with NLO predictions.[27] Even the shape in $p_t$ is not well explained in the "pathological," but very real physics environment of heavy flavor production at the Collider. The azimuthal distribution of opposite sign electrons and muons in $b\bar{b}$ candidate events is less back-to-back peaked[28] than that from UA1.[24] Thus, the effect of the radiation of gluons is much more strongly felt at CDF. The UA1 and CDF events in which $e$ and $\mu$ from $b$ and $\bar{b}$ come out nearly in the same direction may be evidence for gluon splitting, a higher order process, or non-perturbative effects.

D0 is also in the game now.[29] Their single high $p_t$ muon data go out to higher rapidities than at CDF. D0 is also showing isolated and non-isolated muon signals separately. Isolated $\mu^+\mu^-$ events show peaking at both the $J/\psi$ and Upsilon masses. The non-isolated $\mu$ pairs have peaking only at the $J/\psi$ mass, corresponding to $b$ jets hadronizing as $B$'s and decaying to $J/\psi$'s.

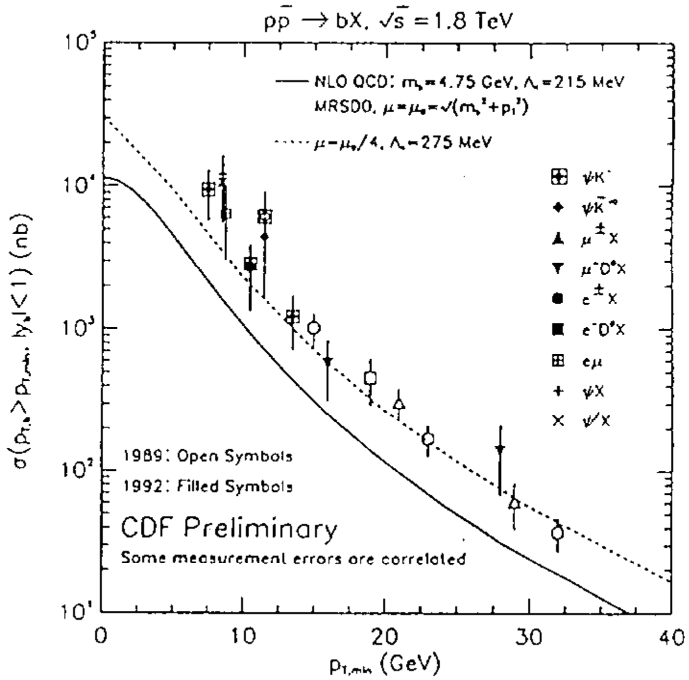


Fig. 3. Integral *D* meson production from CDF, showing greater than predicted cross sections and the changes in results at low $p_t(min)$ with the more complete, recent data of 1992.

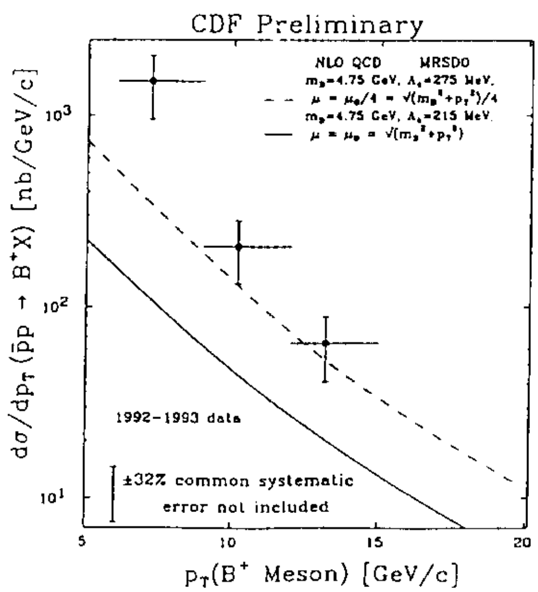


Fig. 4. $P_t$ distribution of $B^+$ mesons from CDF showing disagreements with theoretical expectations at low $p_t$ (where the cross section is highest).

Trying to understand the scale dependence of the theoretical calculations turns out to be really quite complicated. So far, calculations are done in fixed order. The effective number of quarks in these calculations is one issue. When does the charm quark, for example at these collider energies, become one of the light quarks like the strange quark? And how does that get included in the calculations? Also, the scale dependence in the next to leading order calculation is not reduced very much compared to leading order.

There are significant new efforts aimed at extending the current next-to-leading order calculations.[5] Some of these look at the summation of terms which are not really understood as you go up in energy, as for example, to the new Collider energies. How should one sum terms of the form $\log^n(1/x)$? As you go up in energy, the $x$ of the gluons that are involved in producing the heavy flavors are getting very small indeed. And so, summation of terms like this is not at all obvious. Such terms are sometimes written in the form $\log^n(s/m^2)$. As the $s$ gets very large, say at the Tevatron and, Congress willing, at the SSC, how do you do the series sum? In fact, is this relevant to the differences in the "pathological" case of heavy flavor production relative to jet and di-jet events where theory and experiment agree better. Photon-hadron heavy flavor production is also calculated only in fixed order so far. What does this say about the HERA measurements to come?

## SPECTROSCOPY

### Charmonium

There are very beautiful data from the $p\overline{p}$ formation experiment in the Fermilab $\overline{p}$ Accumulator (E-760). One can directly measure the masses and the widths of the charmonium states[30] that are produced there, in particular the $\chi_c$'s which cannot be directly produced at $e^+e^-$ machines. $J/\psi$, $\psi'$, $\chi_{c1}$ and $\chi_{c2}$, are seen via their electromagnetic decays with virtually no background (see Fig. 5 for examples). The beams which produce these states are precisely known, the beam smearing typically being about 300 keV. Mass values, all related to a normalization at the $\psi'$ mass, are much more precise than the current values summarized by the Particle Data Group. The $\chi_{c1}$ and $\chi_{c2}$ measurements offer the really spectacular changes, basically an order-of-magnitude reduction in the uncertainty in the masses and the widths. New values of the width of the $J/\psi$ and $\psi'$ have just appeared.[31] Almost a year ago, E-760 announced the discovery of the $^1P_1$ state.[32] It is a particularly interesting workshop for *QCD* calculations because of its analogy with positronium. The mass is measured to quite high precision, but the width is only an upper limit. Also, E-760 do not see the $\eta_c\,\gamma$ decay mode. The continuation of this work (E-835) will look further with more data in the future. Fermilab's E-705 has seen a small bump in the same $^1P_1$ mass region, but with much less resolution. They see it, more or less, in data with incident pions and protons at about the $2.5\,\sigma$ level of significance altogether.

For $\chi_{c2}$, there is data both from CLEOII[33] and from the $p\overline{p}$ experiment.[34] They have comparable numbers of events. What is interesting here is the width. From the ratio of the hadronic decay width to the di-photon decay width, we get a direct measure of $\alpha_s$. This is a very low energy measurement of $\alpha_s$ and is useful in terms of the running of $\alpha_s$.

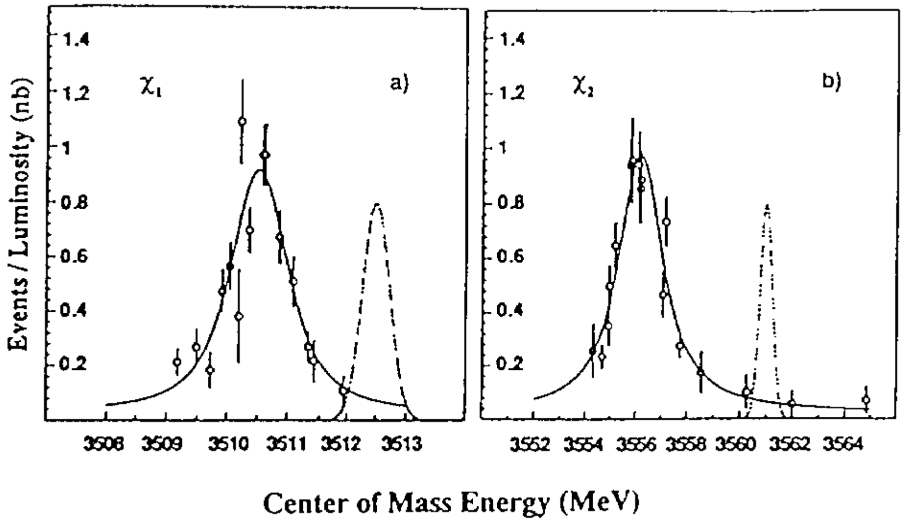


Fig. 5. E-760 measured cross sections for the energy scans at the a) $\chi_{c1}$ and b) $\chi_{c2}$. The solid lines represent the best fits to the data. The dashed curves show a typical center-of-mass energy distribution (arbitary vertical units).

Experiment E-672 at Fermilab resolves the $\chi_{c1}$ and the $\chi_{c2}$. They don't see the decay photons directly, but rather by looking at conversion electron-positron pairs. These measurements lead to a test of the production mechanisms for the $\chi_c$ mesons. In a review by Peter Garbincius,[35] a comparison of data is made to three production models: gluon fusion, quark fusion, and evaporation. New data this year from fixed-target experiments E-705 and E-672 for pions seem to be consistent with the evaporation model. The proton induced production is more consistent with gluon-fusion. Neither pion nor proton production is consistent with the quark-fusion mechanism for production.

New data on the $\eta_c$, have appeared from E-760,[36] CLEOII,[37] and L3.[38] Two photon production of the $\eta_c$ allows the measurement of the decay width to photon pairs. This is also measured, with smaller errors, by $p\bar{p}$ formation of $\eta_c$ followed by decay to two photons. CLEO reports (5.73 $\pm$ 1.34 $\pm$ 1.57) keV for the width. The L3 value is (7.8 $\pm$ 2.3 $\pm$ 2.4) keV. The width is interesting because of its sensitivity to $\alpha_s$ through QCD corrections. However, more precision is still required for this. The mass of the $\eta_c$ measured by E-760 is rather different from the Particle Data Group mass, almost 10 MeV different. This change will cause a shift in the value of the hyperfine splitting for the *s*-wave charmonium states which, in turn, are important in understanding spin-spin forces.

What about the $\eta_c'$? There is no definitive news here. E-760 does not see it. The $\eta_c'$ was first reported by the Crystal Ball experiment at SLAC.[39] The observation was not confirmed by the Crystall Ball when moved to DESY, or by others. In fact, the mass value of the original observation is theoretically rather unlikely, given today's understanding. E-760 did a scan for the $\eta_c'$ within one $\sigma$ in mass, from 3612 to 3621 MeV, and did not see any evidence of it.[36] The resulting limit is not particularly useful yet. More interesting will be to get more data in a wider mass range. So the $\eta_c'$, which is not in the current Particle Data Group's compilation, still needs to be discovered.

## Charm Flavored Mesons

Very nice spectroscopy results on open charm mesons are coming out of CLEOII and E-687. These are interesting in terms of understanding the color forces and their contributions to mass-splittings. Sometimes you read in the newspapers, next to the sports pages, about how the source of mass is the thing that we are building the SSC to discover. However, we all know there are lots of forces that we understand and which contribute to masses. That is what these mass-splittings are all about. It's not that the Higgs, or whatever it is that breaks electroweak symmetry, is the only source of mass.

By measuring heavy flavor mass-splittings we actually can understand those forces better. Harry Lipkin[40] points out that by looking at the isotopic mass differences between the $D$'s and $D^*$'s you get information about the much less well measured strange baryons. Lai-Him Chan[41] and an earlier paper by Amundson, Rosner, and Stone[42] have also pointed out that the value of, the $D$ meson decay constant, $f_D$, can be calculated by looking at these mass splittings. The value determined this way may be more precise than that found by any other method. So far, we have only experimental upper bounds otherwise.

A new measurement of the $D_S^*$ mass results from the two dimensional Dalitz plot like distribution of the $D_S\,\gamma$ decay data (Fig. 6). With sufficient data, selecting limited kinematic regions removes backgrounds and leads to new, more precise mass

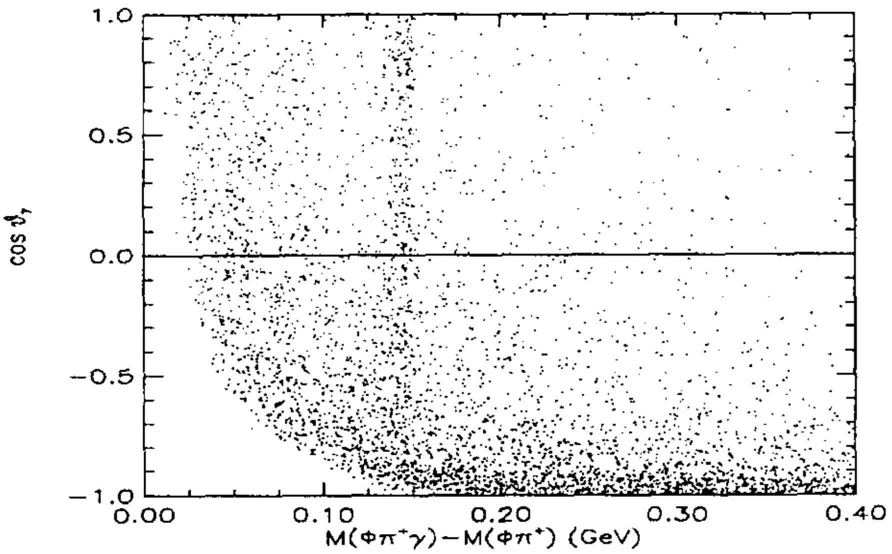


Fig. 6. Scatter plot from CLEO II used to obtain the signal for the $D_S^{*+}$ and determine the vector-pseudoscalar mass splitting. The cosine of the photon emission angle in the $\phi\,\pi\,\gamma$ frame relative to the $\phi\,\pi\,\gamma$ direction is plotted vs. the candidate $D_S^* - D_S$ mass difference.

difference determinations. CLEOII now obtains a $D_S^* - D_S$ mass difference of 144.2 ± 0.47 ± 0.37 MeV compared to the PDG value of 142.4 ± 1.7 MeV.[43] The $D^{**}$'s are the states where, in the limit of very heavy charm quarks, the heavy charm quark defines the center and an up, down, or strange quark orbits in an angular momentum = 1 state. There are a dozen states expected. About half of them should be narrow enough to see in current experiments. There has been some history of this, but now E-687 sees four states[43] and CLEO sees three of these four.[44] New results from CLEOII show quite large shifts relative to the older CLEO data. There is also disagreement with new E-687 results at a rather uncomfortable level. The data (Fig. 7) show the beauty of these data and also suggest that the difficulties of understanding the background shapes may well be sources of some of the disagreements.

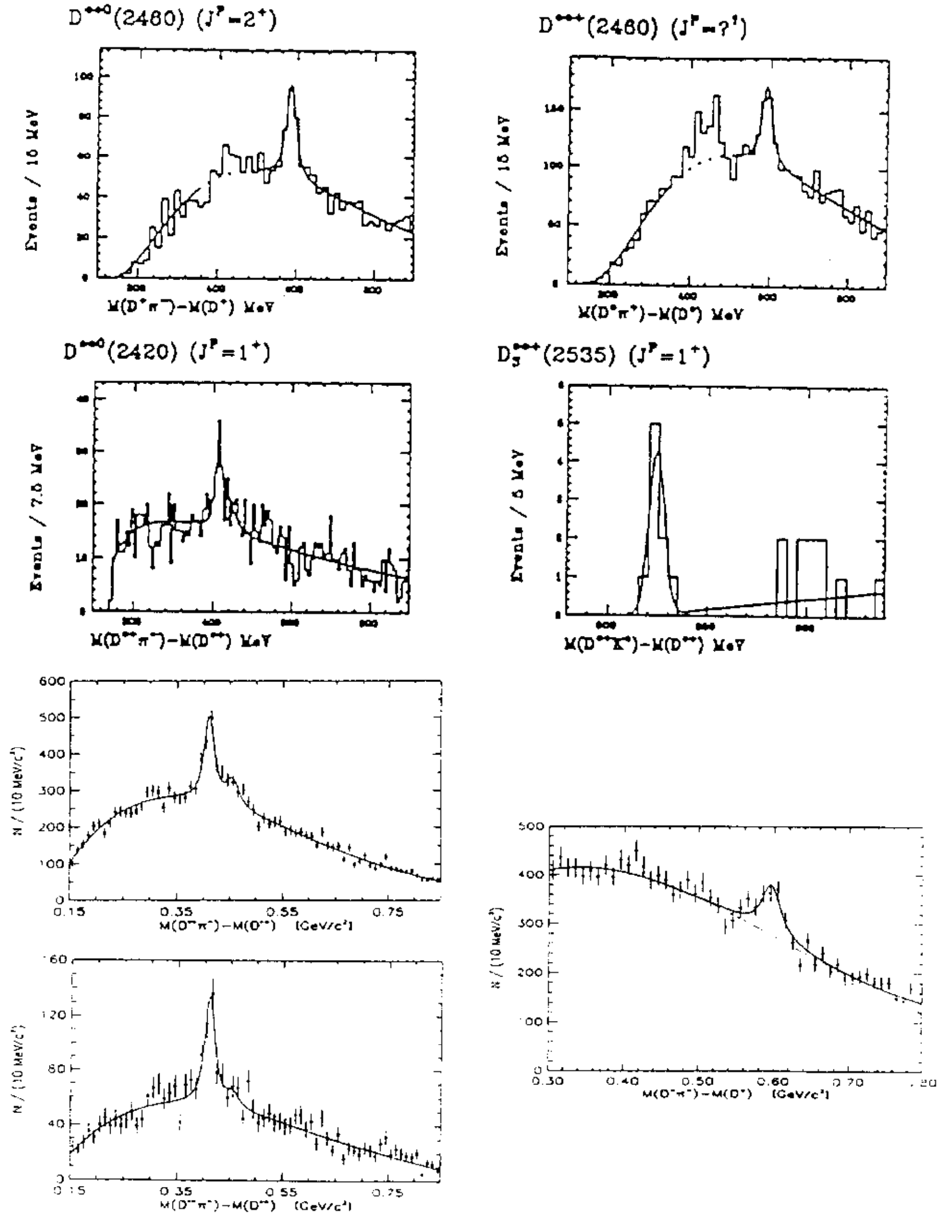


Fig. 7. $D^{**}$ meson data from E-687 (top four) and CLEOII (bottom three) showing the observed signals and the complexity of the background which must be subtracted in determining parameters.

Another sign of the progress resulting from these large data samples is that the experiments can now measure decay angular distributions, looking at the helicity angle from the decays to help identify experimentally the spin of the parent state. In Fig. 8, for example, CLEOII's $D_s$**(2536) decays are a better fit to a $1^+$ parent state than either a $0^-$ or the $1^-$.[45] E-687's $D$**(2420) decays are in agreement with $D$-wave decay of a $1^+$ state.[43]

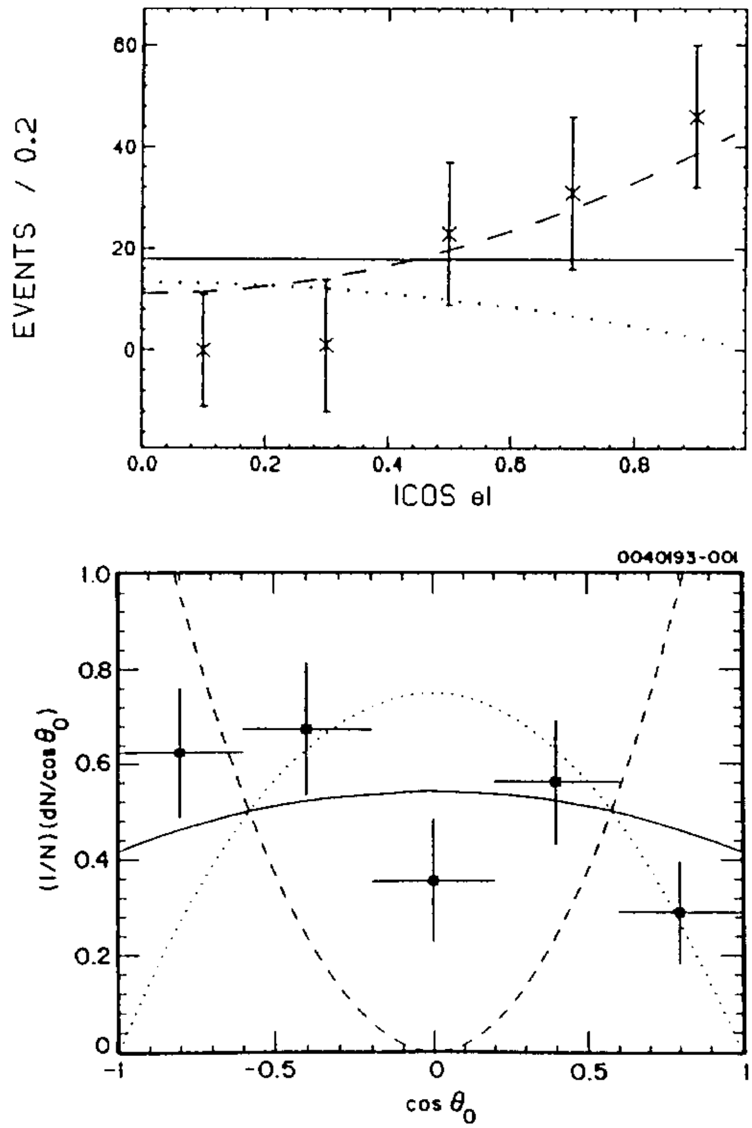


Fig. 8. Evidence for the spin assignments of excited $D$ and $D_s$ mesons: (top) Cosine distribution of the helicity angle for $D^{**0}(2420)$ from E-687 with expectations (solid) for $S$ wave decay of a $1^+$ state, (dashed) for a $D$ wave decay of a $1^+$ state and (dotted) for a $D$ wave decay of a $2^+$ state. (bottom) Cosine distribution of the helicity angle for $D_s^{**+}(2536)$ from CLEO II with expectations (solid) for $1^+$, $2^-$ or $3^+$, (dashed) for $1^-$, $2^+$ or $3^-$ and (dotted) for a $0^-$ state.

## Bottom Flavored Mesons

The bottom system has been measured in $e^+e^-$ annihilations for some time now. Nevertheless, experiments need to combine many final states in mass plots, still resulting in very clear signals. These allow the best measurements of the masses. However, CDF is coming up quickly, with much larger numbers of events and reasonably clean signals also. Clear $B^+$, $B^0$, and $B_s$ signals are seen at CDF. There is one very nice $B_s$ event from ALEPH which provides a very precise mass measurement.[46] The precision (5368.6 ± 5.6 ± 1.5 MeV) comes because so much of the $B_s$ mass is taken up in the rest masses of the decay products, $\psi'$ and $\phi$. The decay vertex has a clear separation from the interaction point in the event and there are very clear measurements in the rest of the detector.

Larger uncertainties in the $B_s$ mass come from the other recently observed decays. These all have less massive decay products: four events at DELPHI[47], two events at ALEPH,[46] one event at OPAL,[48] and 14.0 ± 4.7 events at CDF. The CDF events also lead to small mass uncertainty due to the large mass of the $J/\psi\ \phi$ decay particles (5383.3 ± 4.5 ± 5.0 MeV).[49] These latest measurements at LEP and by CDF fall between the two solutions from the old CUSB indirect measurement at the Upsilon(5S).[50]

All of these measurements, which are getting more and more precise, can be looked at systematically as in Fig. 9 from Eichten, Hill, and Quigg.[51] The $1^+ - 1^s$ mass splittings of $K$ mesons through $D$, $D_s$, $B$, and $B_s$ show only a small systematic dependence on the reduced mass of the constituent quarks. The theoretical predictions come from heavy quark symmetry with first order corrections from a non-relativistic potential model. The new result from ALEPH[52] is not clearly resonant in the raw data, but apparently not related to the $1^+$ state in any event. New predictions are also coming out for $B_c$ states which may not be too long in being confronted with data![53]

## Bottom Flavored Baryons

Last year UA1 reported some 16 events of the $\Lambda_b$ decaying into $\Lambda\ J/\psi$ with 9 background events.[54] None of ALEPH, DELPHI, OPAL or CDF has confirmed the observation before this meeting. Now from OPAL there are 7 events, with maybe 1 background event, in the $\Lambda_c\,\pi$ decay mode.[55] When two experiments among a large number with similar capabilities see different decay modes from some parent state, it is fair to ask if they are real or not? Are event fluctuations simply enhanced into signals by cuts. ALEPH, DELPHI, OPAL, and CDF all have only branching ratio product limits to compare to the UA1 value. We have to wait to see convincing evidence of exclusive decays of the $\Lambda_b$.

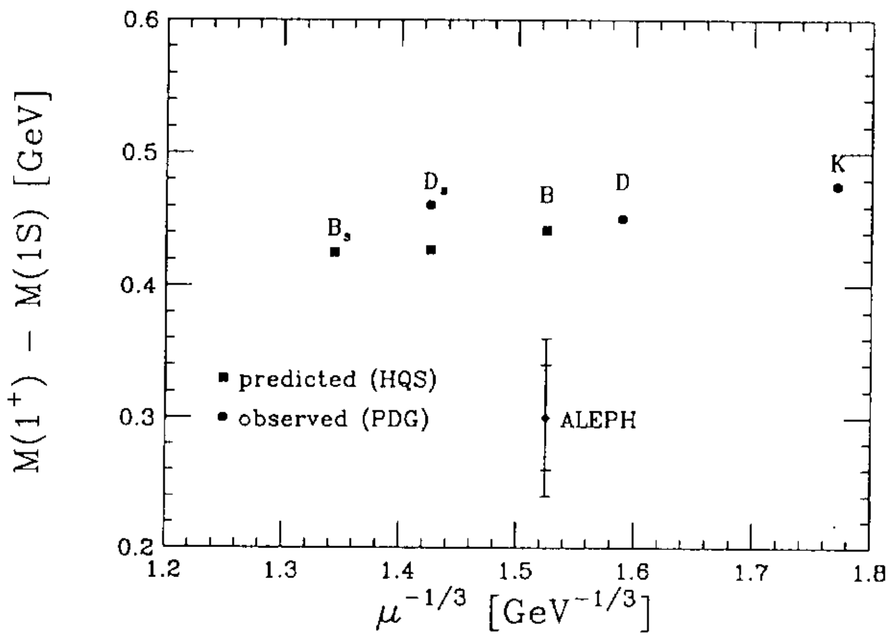


Fig. 9. The meson mass-splittings between the $1^+$ excited state and ground state as a function of the reduced mass $\mu^{-1} = m_{light}{}^{-1} + m_{heavy}{}^{-1}$. The predictions are for heavy quark symmetry (HQS). The similarity of the values is due to this symmetry and corrections come from a potential model which gives a linear dependence on $\mu^{-1/3}$.

## Charm Flavored Baryons

There are clear signals for most of the low lying charm baryon states, the best recent ones coming from ARGUS,[56] CLEOII,[57] and E-687.[58] WA89 at CERN is starting to see the fruits of their long labors in the $\Sigma^-$ beam at the $\Omega$ spectrometer.[8] However, results are just beginning to appear. The $\Sigma_c$'s are very nicely measured at CLEOII, including the isospin mass-splittings for $\Sigma_c{}^0$, $\Sigma_c{}^+$, and $\Sigma_c{}^{++}$.[59] These splittings are all very small. WA89 sees the neutral, but not the doubly charged state. They speculate that this is due to a leading particle production effect.[8]

For the $\Omega_c$, a state composed of "*ssc*" quarks, there is less consistency among experiments. ARGUS recently saw it in the $\Xi$ K $\pi\pi$ mode.[60] Recently, ARGUS showed an $\Omega\pi\pi\pi$ mass spectrum[61] with an enhancement at the same mass value as before and E-687 has shown a peak[62] in the $\Omega\pi$ spectrum. On the other hand, CLEO has looked at all three claimed decay modes and sees no evidence of any of them.[63] The masses of the 3 observations, while not wildly different, are not compelling in their agreement. That none of the experiments sees the signal that another sees means that the $\Omega_c$, sometimes called the SSC, needs confirmation. The SSC is in trouble.

There are very nice new signals on excited $\Lambda_c$'s. Here, the experiments with significant numbers of events and bascially the same mass near 2627 MeV, ARGUS,[64] CLEOII,[65] and E-687[66] all see evidence for $\Lambda_c^* \to \Lambda_c\pi\pi$. The CLEOII plots first submitted to this Symposium are cut-off around 315 MeV for the mass difference between the $\Lambda_c\pi\pi$ and $\Lambda_c$. There is some evidence in the ARGUS data of something below 315 MeV. There's data above their background fit even in E-687. On the other hand, neither ARGUS nor E-687 show what CLEOII has held under wraps until just now.[67]

In their very late submission (Fig. 10) there is a clear $\Lambda_c^*$ signal at (342.1 $\pm$ 0.4 $\pm$ 0.4) MeV mass difference ($\Lambda_c\pi\pi$ - $\Lambda_c$) as in their earlier and the other experiment results. However, there is also evidence for another peak at 308 MeV. When they demand that the $\Lambda_c$ and one of the pions, in either charge state, agrees with the $\Sigma_c$ mass, they see even clearer evidence for the $\Lambda_c^*$ at (308 $\pm$ 0.4 $\pm$ 2.0) MeV. Not much is left of the originally large signal at 344 MeV when a $\Sigma_c$ is required. The heavier $\Lambda_c^*$ doesn't seem to decay into the $\Sigma_c\pi$. On the other hand, the lighter $\Lambda_c^*$ is

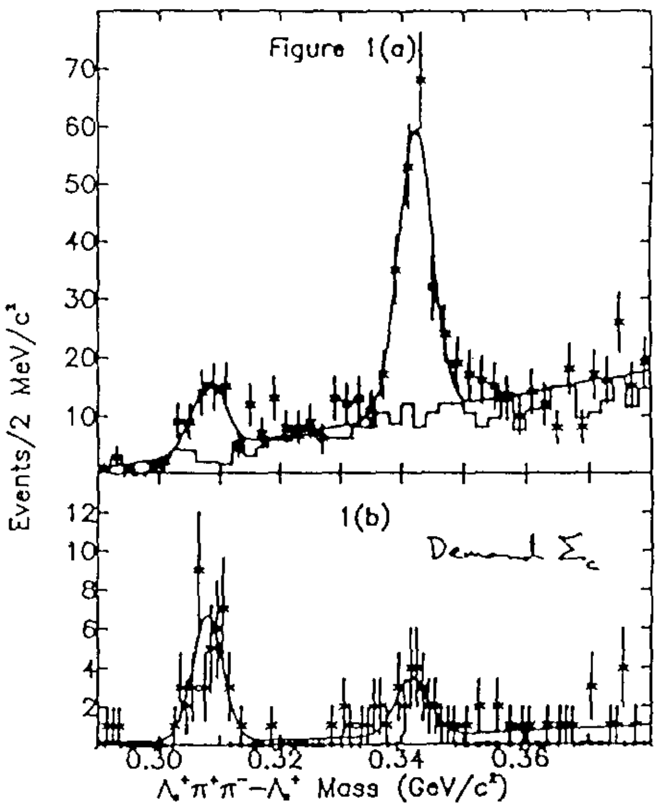


Fig. 10. CLEOII data on excited $\Lambda_c$ showing (top) two resonances and (bottom) the lower mass resonance enhanced by decays through the $\Sigma_c$.

essentially all $\Sigma_c\pi$. Mike Peskin, just 2 weeks ago, suggested an explanation.[68] The $\Lambda_c$ is J = 1/2 with the *ud* di-quark orbiting around the heavy charm quark in an l = 0 state. A corresponding di-quark orbiting with l = 1 has both a J = 1/2 and a J = 3/2 possibility. This may be exactly what appears in the CLEOII spectra. The $\Lambda_{c1}$*(2627) with J = 3/2 is not massive enough to decay into the $\Sigma_c$* which would be preferred. It is forced to decay into the $\Lambda_c\pi\pi$. The $\Lambda_{c1}$(2593), the J = 1/2 state, can decay into $\Sigma_c\pi$. So it actually all holds together. And finally, the SCAT group, a bubble chamber experiment at Serpukov using a broad-band neutrino beam, proposes the first evidence for the $\Sigma_c$* at a mass of 2530 MeV.[69] If this is the $\Sigma_c$*, then indeed, the $\Lambda_{c1}$* cannot decay into $\Sigma_c^* \pi$.

## SUMMARY

This has been something of a whirlwind tour over a wide range of topics. There is very beautiful new data. There are improved theoretical interpretations of that data. I've tried to give you the *flavor* of where we are with heavy *flavour* production and spectroscopy. Clearly, there are questions: issues of fragmentation, color drag, or something else to explain the $x_F$ distributions of the charm mesons in fixed-target interactions. I must say that when I see these effects in fixed-target data, I have to ask myself what are the implications for the colliders? It may be that when one observes very high $p_t$ particles, hadronization effects may be unimportant. However, as you push the thresholds down to lower and lower values, there are likely to be effects like those we're seeing in fixed-target experiments. So, we better pay some attention here.

We also need to account for the $log^n(1/x)$ terms in calculations. Everytime you see beautiful data covering 9 orders of magnitude, ask what are the relevant values of parton $x$. That's what goes into these calculations and the parton distributions may not be valid there, not to mention the validity of the calculation itself.

We need to resolve the differences among the precise numbers from the $p\bar{p}$ and $e^+e^-$ charmonium experiments. Find the $\eta_c'$; find out why the $^1P_1$ wasn't seen in the $\eta_c\gamma$ decay mode. Confirm the $\Omega_c$; and where is the $\Lambda_b$ hiding?

So, as you've seen, there is actually a very large set of ever more precise measurements. The theory and experiments are each developing very rapidly. It is a fertile period for both, with rapid feedback. On the other hand, there is also a lot of hard work, as always when there is more precision. In my opinion, CLEOII and the $\bar{p}p$ annihilation and photoproduction experiments at Fermilab are at the forefront today. However, we see the possibility that many other efforts will come in and share the lime-light, if not displace the current leaders. Watch for the hadron experiments like CDF and E-791.

And a final word, if I may remind you of catalog remarks #1, #3, #4, #5, #7, and #12.

Thank you!

## ACKNOWLEDGEMENTS

I acknowledge the following people for sharing results and insights with me as I prepared this review: A. Ali, M.W. Bailey, D. Beeson, J.N. Butler, H. Cheung, R. Clare, M. Dameri, F. DeJongh, K. Ellis, H.E. Fisk, P. Garbincius, R.W. Gardner, P. Grannis, R.J. Hemingway, S. Igarashi, D. Jansen, R. Jesik, S. Kwan, A. Maciel, R. Mattingly, A. Mazzari, J. Mueller, V. Papadimitriou, S. Paul, S. Pordes, C. Quigg, L. Rossi, M. Schub, J. Skarha, F. Ukegawa, W. Venus, and R. Wang. Furthermore, I want to give special thanks to Treva Gourlay for preparing this manuscript.

## COMMENTS OR QUESTIONS?

*Spencer Cline from Santa Cruz: Do you have any comments or results on the widths of the* $\Lambda_c{}^*$, *either theoretical or experimental?*

Some of the states are expected to be narrow, a few MeV. Certainly there are those which are consistent with that. The widths of the observed states are about the same scale as the resolution. There could be mixing, in the $1^+$ states, and there are many things that can happen then. We are just at the threshold of really working on these issues. That's part of the fun.

*Question from audience: Can you comment on* $\chi_{c0}$

I have nothing on the $\chi_{c0}$ in my review because there is no new data on it.

## REFERENCES

1. M. Shapiro, previous invited talk at this Symposium and CDF Collaboration, FERMILAB-Conf-93/204-E.
2. B.A. Schumm et al., *Phys. Rev. Lett.* **69**, 3025 (1992) and references therein.
3. SLD Collaboration, *SLAC Preprint*, SLAC-PUB-6284 (July 1993), submitted to *The Int'l Europhysics Conf. on High Energy Physics*, Marseille, July 22-28, 1993 and submitted to this Symposium, (Paper #95).
4. P. Burchat, in *Proc. of The 5th Int'l Symposium on Heavy Flavour Physics*, Montreal, Canada, July 6-10, 1993.
5. J. Smith and W.K. Tung, *Proc. of the Workshop on B Physics at Hadron Accelerators*, Snowmass, Co., June 21-July 2, 1993, and references therein, S. Mishra and P. McBride, eds. FERMILAB-CONF-93/267 and SSCL-SR-1225.
6. (E-769) G.A. Alves et al., *Phys. Rev. Lett.*, **69**, 3147 (1992).
7. J.A. Appel, *Ann. Rev. Nucl. Part. Sci*, **42**, 367 (1992).
8. (WA89) F. Dropmann, in *Proc. of The 5th Int'l Symposium on Heavy Flavour Physics*, Montreal, Canada, July 6-10, 1993.
9. M.L. Mangano et al., *Nucl. Phys.* **B373**, 295 (1992).
10. (WA82) M. Adamovich et al., *Phys. Lett.*, **B305**, 404 (1993).
    (E-769) G.A. Alves et al., *Fermilab Preprint*, FERMILAB-PUB-93/310-E.
11. (E-691) J.C. Anjos et al., *Phys. Rev. Lett.* **62**, 513 (1989).
    (E-691) J.C. Anjos et al., *Phys. Rev. Lett.* **65**, 2503 (1990).

12. (E-687) J. Wiss, in *Proc. of XIII Int'l Conf. on Physics in Collision, Heidelberg, Germany*, June 16-18, 1993.
13. (NA14/2) M.P. Alvarez et al., *CERN Preprint*, PPE-92-028 (1992).
14. (E-687) P.L. Frabetti et al., *Phys. Lett.* **B308**, 193 (1993).
15. S. Frixione et al., *CERN Preprint*, CERN-TH.6921/93 and GEF-TH-15/1993.
16. (E-613) M.E. Duffy et al., *Phys, Rev. Lett.* **55**, 1816 (1985). (WA78) H. Cobbaert et al., *Phys. Lett.* **B191**, 456 (1987).
(WA78) H. Cobbaert et al., *Phys. Lett.* **B206**, 546 (1988).
17. (PDG) K. Hikasa et al., *Phys. Rev.* **D45**, S1 (1992).
18. (WA82) M. Adamovich et al., *Phys. Lett.*, **B284**, 453 (1992).
19. (E-772) D.M. Alde et al., *Phys. Rev. Lett.* **66**, 133 (1991).
20. (E-769) G.A. Alves et al., *Phys. Rev. Lett.* **70**, 722 (1993).
21. (E-789), *private communication.*
22. (E-706/672) R. Jesik, *Ph.D. Thesis*, U. of Illinois at Chicago.
23. (E-653) K. Kodama et al., *Phys. Lett.* **B303**, 359 (1993).
24. (UA1) C. Albajar et al., submitted to this Symposium (Paper #231).
25. (CDF) F. Abe et al., *Fermilab Preprint*, FERMILAB-PUB-93/145-E for Fig. 3 and additional details in papers FERMILAB-PUB-93/091-E, FERMILAB-PUB-93/106-E, FERMILAB-PUB-93/131-E, and FERMILAB-PUB-93/200-E. Submitted to this Symposium, (Papers #160, 162, 157, 159, and 164, respectively).
26. (CDF) V. Papadimitriou, *Fermlab Preprint*, FERMILAB-CONF-93/180E. In *Proc. of The XXVIIIth Rencontres de Moriond, High Energy Hadronic Interactions*, Les Arcs, Savoie, France, March 20-27, 1993.
27. CDF Collaboration, submitted to this Symposium, (Paper #164). *Fermilab Preprint* FERMILAB-PUB-93/145-E.
28. CDF Collaboration, Fermilab Preprint, FERMILAB-CONF-93/199-E. Submitted to this Symposium (Paper #119).
29. (D0) S. Abachi, submitted to this Symposium (Paper #102).
30. (E-760) T.A. Armstrong el al., *Phys. Rev. Lett.*, **68**, 1468 (1992).
31. (E-760) T.A. Armstrong el al., *Phys. Rev.* **D47**, 772 (1993).
32. (E-760) T.A. Armstrong el al., *Phys. Rev. Lett.*, **69**, 2337 (1992).
33. (CLEO) V. Shelkov et al., submitted to this Symposium (Paper #273).
34. (E-760) T.A. Armstrong el al., *Phys. Rev. Lett.*, **70**, 2988 (1993).
(E-760) T.A. Armstrong et al., *Nucl. Phys.* **B373**, 35 (1992).
35. (E-687) P. Garbincius, *Fermilab Preprint*, FERMILAB-Conf-93/238. *Invited talk presented at the Hadron '93 Conference, Centro di Cultura Scientifica "A. Volta,"* Villa Olmo, Como, Italy, June 21-25, 1993. *Proc. to be published in Il Nuovo Cimento.*
36. (E-760), *private communication.*
37. (CLEO) A. Bean et al., submitted to this Symposium (Paper #293).
38. L3 Collaboration, submitted to this Symposium (Paper #50).
39. C. Edwards et al., *Phys. Rev. Lett.* **48**, 70 (1982).
40. H. Lipkin, *Weizmann Institute of Science Preprint*, WIS-93/34/Apr-PH TAUP 2044-93,,submitted to this Symposium, (Paper #133).
41. L. Chan, submitted to this Symposium, (Paper #262).
42. J.F. Amundson et al., *Phys. Rev.* **D47**, 3059 (1993).
43. (E-687) P.L. Frabetti et al., *Fermilab preprint*, FERMILAB--PUB-93/249-E.
44. (CLEO) M.S. Alam et al., submitted to this Symposium, (Paper #281).
(CLEO) D. Bortoletto et al., *Phys. Rev. Lett.*, **69**, 2046 (1992) reports the $D^* - D$ mass splittings.
45. (CLEO) G. Crawford et al., submitted to this Symposium, (Paper #282).
46. ALEPH Collaboration, *CERN Preprint*, CERN-PPE/93-97. Submitted to *Physics Letters B* and to this Symposium, (Paper #206).

47. (DELPHI) Y. Arnoud et al., "A Measurement of the $B_s^0$ Meson Mass," *private communication.*
48. (OPAL), P.D. Acton et al., *Phys. Lett.* **B295**, 357 (1993).
49. (CDF) F. Abe et al., *Phys. Rev. Lett.* **71**, 1685 (1993).
50. (CUSB) J. Lee-Franzini et al., *Phys. Rev. Lett.* **65**, 2947 (1990).
51. E.J. Eichten et al., *Fermilab Preprint,* FERMILAB-Pub-93/255-T.
52. (ALEPH) B. Jacobsen, submitted to this Symposium, (Paper #207).
53. C. Quigg, *Fermilab preprint,* FERMILAB-Conf-93/265-T, *Proc. of Snowmass Workshop on B Physics at Hadron Accelerators,* Snowmass, Co., June 21-July 2, 1993, S. Mishra and P. McBride, eds. and references therein.
K. Cheung, *Northwestern University Preprint,* NUHEP-TH-93-19. Submitted to this Symposium, (Paper #75).
54. (UA1) C. Albajar et al., *Phys. Lett.* **B273**, 540 (1991).
55. OPAL Collaboration, *OPAL Physics Note PN111* (July 1993), *private communication.*
56. (ARGUS) N. Paulini, "*B's* and Baryons from ARGUS," In *Proc. of The XXVIIIth Rencontres de Moriond, High Energy Electroweak Interactions,* Les Arcs, Savoie, France, March 16, 1993.
57. (CLEO) P. Avery et al., *Phys. Rev. Lett.* **71**, 2391 (1993) and references therein.
58. (E-687) H.W.K. Cheung, Fermilab Preprint, FERMILAB-Conf-93/164-E. Talk presented at *The XXVIIIth Rencontres de Moriond, High Energy Hadronic Interactions,* Les Arcs, Savoie, France, March 20-27, 1993.
59. CLEO Collaboration, *CLEO Preprint,* CLNS 93/1230 CLEO 93-09.
60. (ARGUS) H. Albrecht et al., *Phys. Lett.* **B288**, 367 (1992).
61. (ARGUS) J. Siewe, *Proc. of the XXVI Int'l Conf. of High Energy Physics,* Dallas, Texas, August 1992, p. 1076.
62. (E-687) P. Frabetti et al., *Phys. Lett.* **B300**, 190 (1993).
63. (CLEO) M. Battle et al., "Search for the $\Omega_c^0$ in $e^+e^-$ Annihilations," submitted to this Symposium.
64. (ARGUS) H. Albrecht et al., "Observation of a New Charmed Baryon."
65. (CLEO) D. Acosta et al., submitted to this Symposium, (Paper #275).
66. (E-687), *private communication.*
67. (CLEO) M. Battle et al., submitted to this Symposium, (Paper #303).
68. M. Peskin, *private communication.*
69. (SKAT) V.V. Ammosov et al., submitted to this Symposium, (Paper #42).