PRODUCTION OF HEAVY QUARKS
F. Halzen

To cite this version:
F. Halzen. PRODUCTION OF HEAVY QUARKS. Journal de Physique Colloques, 1982, 43 (C3), pp.C3-381-C3-405. <10.1051/jphyscol:1982369>. <jpa-00221924>

HAL Id: jpa-00221924
https://hal.archives-ouvertes.fr/jpa-00221924
Submitted on 1 Jan 1982

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
PRODUCTION OF HEAVY QUARKS

F. Halzen

Department of Physics, University of Wisconsin, Madison, Wisconsin 53706, U.S.A.


1. Introduction: A Perspective on the Subject. - My goal is to construct a "house of cards" that pulls together the wealth of experimental information on the production of heavy quarks under the umbrella of perturbative QCD and the standard electroweak model. I will almost succeed; failures are potentially very important and will be discussed at the end of the talk. If the structure collapses by the next conference, I will be only mildly disappointed; this is how progress is made.

a) Theoretical Perspective. In the days preceding the advent of QCD the statistical model provided us with a framework to compute particle yields. The probability for producing a particle of mass m is given by

$$P \sim e^{-2m/T},$$

where T is a universal temperature of about 160 MeV. We obtain

$$\pi : \kappa : \lambda = 1 : 10^{-1} : 10^{-5}.$$  

(1)

Alternatively, one can consider the hadronic production of heavy quarks as a tunneling problem, i.e., the probability that a string breaks up into a pair of heavy quarks of mass m_Q. Here

$$P \sim e^{-am^2_T},$$

$$m_T = (m_Q^2 + p_T^2)^{1/2}$$

and a = π/κ. κ is the string constant. The result is

$$(u,d) : s : c = 1 : \frac{1}{3} : 10^{-10}.$$  

(2)

The small estimates for charm production in the "old" physics result from the difficulty in localizing the large energy required to produce a heavy quark pair. This leads to a dynamic exponential suppression of the cross section when increasing the quark mass. Such a suppression is absent in QCD due to the flavor-independent point coupling of quarks to gluons. Much higher rates for charm production, compared to those obtained in Eqs. (2) and (3), are expected. The production of heavy quarks provides us with one of these rare opportunities where the "old" and "new" physics differ qualitatively. The experimental verdict is clear. At the highest energies charm is produced at the $10^{-2} \sim 10^{-3}$ level of.
Fig. 1: Total inclusive cross sections for π, K and charm particles in pp collisions. My best estimates for the total charm cross sections depend on the assumptions made for the A^{3/2} dependence in experiments using nuclear targets (A^{1/2} for triangles, A for squares).

![Graph showing cross sections for π, K, and charm particles](image)

π-mesons (see Fig. 1). QCD is at present the only framework that can accommodate these observations. The discrepancy between the expectations for b-quark production based on QCD and estimates based on Eqs. (1) and (3) is even more dramatic. In the "old" physics b-quarks are practically unobservable in hadronic interactions, contrary to the evidence which will be presented further on.

b) "Technological" perspective. The potential "technological" pay-off from a detailed understanding of the production mechanisms and signatures of heavy quarks is what makes the considerable efforts on this problem definitely worthwhile. In e^+e^- collisions 9 nb (for e^+e^- → ψ_3,77) is a charm factory. What about the 10^5 ~ 10^6 nb accessible in hadron collisions? The possibility of exploiting these large rates will require a very detailed understanding of production mechanisms and signatures. Progress is essential in order to design triggers that can overcome the unfavorable signal/noise in the collisions with the highest rates (see Fig. 2).

The question of heavy quark production touches some of the "great" physics issues presently awaiting definite answers: (i) Are we at the threshold of a proliferation of new quark families or is our world indeed limited to three families with or without the top quark? This question constitutes an experimental attack on the issue of whether quarks are composite or truly fundamental. Progress in our understanding of charm and beauty production is essential in order to perform "generation-counting" with pp-colliders, a mission which has been forecast not to be an easy one.3 (ii) Heavy quarks could be used as signatures in the search for weak bosons. Their leptonic decays are, however, the dominant background in searching for the lepton signatures Z → νν, W → νν. (iii) The search for neutral scalars which appear in electroweak gauge theories either as Higgs bosons or as dynamical bound states remains a high priority task. Until operation of a new generation of e^+e^- colliders only hadron beams have a realistic shot at their discovery. We will illustrate how the study of charm production has generated novel and very promising techniques for Higgs hunting.

c) Experimental perspective. The advent of Si or Ge live targets and CCD devices opens up the possibility of constructing vertex detectors for fixed target as well as collider experiments. A Si-target, presently operating at the SPS, has achieved track resolution of order 10^2 microns and has become a successful tool in detecting the associated production of charm particles.5 Although visual detectors (fancy...
bubble chambers, streamer chambers) can possibly compete in resolution through the use of holography, their observation rate is limited to 10^{-2} nsec by film advancing. The Si-target, previously mentioned, has on the contrary a deadtime of less than 10^{-2} nsec, allowing beam intensities exceeding those for visual detectors by at least two orders of magnitude. Progress on vertex detectors coupled with increased theoretical insight in the design of triggers will hopefully lead in the near future to high statistics heavy quark physics with photon and hadron beams and to meaningful searches for new generations.

2. e^+ e^- Annihilation and Leptoproduction by Neutrinos. The production of heavy quarks in these reactions is so well understood that they are used as "flags" to study other physics issues. This is illustrated by a recent analysis of the CDHS group of over 10^6 opposite-sign dimuon events. The production of heavy quarks by neutrinos proceeds via the diagram shown in Fig. 3. The dominant contributions are summarized in Table 1. For neutrino beams roughly half of the charm particles originate from the (Cabibbo-suppressed) transformation of a valence d-quark into a c-quark by the weak interaction. The other half is due to the (Cabibbo-allowed) transition of a sea s-quark to a charm quark. For antineutrino beams the charge conjugate of the latter transition is the dominant source of charm. Charm particles are detected via their leptonic decay which contributes a opposite in sign to the primary u. The data are shown in Fig. 4; the shape of the Bjorken-x distribution clearly reflects the production of charm off sea-quarks in the case and the presence of an additional valence d - c mechanism for ν-induced production. From these data the strange component of the nucleon can be deduced, the KM matrix elements U_{cd}, U_{cs} can be determined and the shape of the charm fragmentation function has been obtained. It has a "hard" distribution peaking at <x> = 0.68 ± 0.08 in agreement with the expectation of Bjorken and Suzuki. The physics potential of charm triggers could be further enhanced by the study of b-quark production, e.g., c → b off charm in the nucleon. Via the cascade decay b → c → μ same-sign dimuon events result from which the KM element
Unfortunately, same-sign dimuons should be approached with care. We return to this issue at the end of the talk.

3. Photoproduction and Leptoproduction

A typical diagram for the production of a heavy quark pair by photon or lepton (i.e., virtual photon) beams is shown at the top of Table 2. The $c\bar{c}$ pair is detected as a $D\bar{D}$, $\Lambda_{c\bar{c}}\ldots$ pair or as a $\psi$ bound state. It is very important in discussing this problem to separate events where the $\psi$ or charm pair carry the incoming photon's energy (elastic events, $z = 1$) from events where they carry only a fraction of the beam energy (inelastic events, $z < 1$). The variable $z$ measures the fraction of the $\gamma, \gamma^*$ energy carried by the produced $c\bar{c}$ pair. Elastic events are beautifully described by the leading order diagram $\gamma \gamma \rightarrow c\bar{c}$. As pictured on the left in Table 2, this is the Bethe-Heitler process of QCD. Given the gluon structure function, it correctly describes the magnitude and energy dependence of elastic charm production by photons as illustrated in Fig. 5. It is imperative to use $m_c = 1.5\text{ GeV}$ as shown in Fig. 6. The same calculation successfully accommodates data on elastic $\psi$'s provided one introduces a phenomenological parameter $f = 10^{-1}$ describing the frequency that $c\bar{c}$ pairs materialize into $\psi$'s.

In inelastic events the $c\bar{c}$ pair carries a fraction of the beam energy. The residual energy is carried by a gluon, as illustrated on the right-hand side of Table 2. Inelastic production is therefore a higher order process involving $O(m_{c\bar{c}}^2)$ diagrams of the type $\gamma \gamma \rightarrow (c\bar{c})g$.

![Figure 5](image1.png)

Fig. 5: Elastic $c\bar{c}$ production by photon or lepton beams ($Q^2 = 0$). Also shown is the result of a calculation based on the leading order diagram $\gamma g \rightarrow c\bar{c}$.

![Figure 6](image2.png)

Fig. 6: Same as Fig. 5. The choices $m_c = 1.2$ and $1.5\text{ GeV}$ in the photon-gluon fusion calculation are contrasted.
In the case of $\psi$ photoproduction one can again invoke some duality factor $f^1$ converting $c\bar{c}$'s into $\psi$'s. One hereby explicitly denies that color plays a fundamental role in the production mechanism, a treatment of the color quantum number often encountered in lifetime calculations. Alternatively, one can treat color as an exact quantum number, i.e., only diagrams where the $c\bar{c}$ pair is in a color singlet with the $\psi$ quantum numbers are included. This leaves one diagram for the inelastic production of $\psi$, shown in Fig. 7. Whatever the details, both approaches agree that the inelastic cross section is $O(\alpha_s)$ of the elastic. It is therefore expected to be roughly 0.2 of the elastic. This result is readily obtained from the "bleaching" diagram in Fig. 7 which is related by crossing to the decays $\psi \rightarrow ggg$ or $\psi \rightarrow g+\gamma$. This result is, however, at variance with the data. Elastic and inelastic yields of open or bound charm are roughly equal, as illustrated in Table 3. Correcting this disaster by changing the mass of the charm quark would ruin the agreement of the leading order diagram with the elastic data (Fig. 6).

<table>
<thead>
<tr>
<th>Elastic</th>
<th>Inelastic</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma^* N \rightarrow \psi$ (209 GeV $\mu$-beam)</td>
<td>$\gamma N \rightarrow \psi$ (178 GeV)</td>
</tr>
<tr>
<td>$0.36 \pm 0.08$ nb</td>
<td>$0.28 \pm 0.08$ nb</td>
</tr>
<tr>
<td>$24 \pm 5$ nb</td>
<td>$26.4 \pm 3.5$ nb</td>
</tr>
<tr>
<td>$\gamma N \rightarrow c\bar{c}$ (\sim 100 GeV)</td>
<td>$\sum \geq 1$ (\mu) channels</td>
</tr>
<tr>
<td>$0.56^{+2.16}_{-1.16}$ (\mu)b</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Comparison of elastic and inelastic cross sections for bound and open charm.

Experience has taught us, however, that normalizations are rather flexible when evaluating QCD diagrams explicitly. Another feature of inelastic charm production is that once a gluon has been emitted to share the beam energy with the $(c\bar{c})$ pair, the latter can recoil against the gluon and originate with large $p_t$. In Fig. 7 the $\psi$ recoils against the accompanying gluon: increase in inelasticity therefore inevitably results in an increasing population of the high $p_t$ region with $\psi$'s. High statistics BFP data\[\text{15}\] fail to show this effect by directly comparing the shapes of the $p_t$-distribution in bins $0.7 < z < 0.9$ and $z < 0.7$ (Fig. 8).

![Fig. 7: "Bleaching" diagram for the inelastic photoproduction of $\psi$'s.](image1)

![Fig. 8a: Comparison of the $p_t$-distributions for the production of elastic and inelastic $\psi$'s.](image2)
Although earlier EMC data showed hints in the right direction (Fig. 8), the same collaboration submitted to this conference a beautiful set of data with increased statistics allowing a more detailed analysis of this problem. We can indeed compare the large-$p_T$ tail ($p_T = 1 \sim 10$ GeV) for 6 different bins in $z$. Elastic $\psi$'s are described by a fit $p_T \sim 3.87$, which I simply superimposed in Fig. 8b on the five inelastic bins. No evidence for increased $p_T$ of the $\psi$'s with increased inelasticity (smaller $z$-values) can be found. I attempted various approaches to analyze the data: e.g., calculating $\langle p_T^2 \rangle$ for $p_T > 1$ or fitting $p_T$ in every bin. Notice, e.g., how well the $p_T$ dependence for $0.4 < z < 0.6$ is described by the EMC fit to the $p_T$ distribution for elastic $\psi$'s. In this kinematic region the bleaching diagram of Fig. 7 correctly predicts the normalization (which is here insensitive to the exact value of $m_c$), but the basic large $p_T$ character of the diagram awaits confirmation. This conclusion still leaves 80% of the inelastic data unexplained. Alternatively, one might conclude that the large yield of inelastic $\psi$'s point at the existence of non-perturbative sources of charm quarks.

Hints that abundant sources of charm quarks exist in the very small $z$ region (presently inaccessible by muon detectors as EMC and BFP) can be found by comparing experiments with varying acceptance. The WA4 experiment,\cite{17} using a tagged $\gamma$ beam and the Omega spectrometer, has a very broad $x$ acceptance and is very unlikely to miss any source of charm due to the lack of coverage. Its measured photoproduction cross section (now confirmed by WA57\cite{17}) exceeds those measured by muon detectors which are only sensitive to elastic charm (Fig. 9). The WA58 experiment,\cite{18} detecting charm particle pairs in an emulsion exposed to the same beam, observes $\Lambda^0\bar{D}$ events with $x_F < 0$. Again, these types of events are not detected by experiments like EMC or BFP.

These large photoproduction cross sections of heavy quarks are a complete mystery from the point of view of perturbative QCD. We recall that at best 20% of the inelastic events observed by the small acceptance muon detectors could be accommodated by perturbative calculations. Is perturbation theory only part of the story? The answer is possibly affirmative; I will illustrate this in a striking way by showing how to calculate all photo- and hadroproduction cross sections in a non-perturbative framework.\cite{20} We will basically extend the additive quark model to include photons and gluons. The procedure is pictorially described in Fig. 10. In photoproduction the photon fragments into a quark-antiquark pair (as described by the photon structure function); one of the quarks subsequently scatters off the target (with a nominal $qN$ cross section of 10 mb). The hadroproduction cross section is then obtained...
Fig. 10: Non-perturbative calculation of heavy quark photo- and hadro-production.

by photon-gluon substitution (see Fig. 10). It is important to realize that the heavy quark scattering off the target is off-mass-shell; for details see Ref. 20. The results are intriguing (see Figs. 9, 11) and are a warning that perturbative QCD might not be the end of the world in this subject. Even more puzzling is the fact that these calculations can describe light quarks as well, e.g., for $E_Y = 170$ GeV we find

$$
\sigma(\gamma N + u,d) = 104 \text{ mb}
$$

$$
\sigma(\gamma N + s) = 5 \text{ mb}
$$

$$
\sigma(\gamma N + c) = 2 \text{ mb},
$$
giving a reasonable value of the total cross section of 110 mb. If these arguments have some element of truth, they will provide future high-energy, large acceptance experiments with over twice the number of events expected on the basis of conventional $\gamma$-gluon fusion models.

4. Hadroproduction of Heavy Quarks

- a) Experimental status of open charm. Up to now a multitude of experiments employing a wide variety of techniques has given us at best a nebulous view of the systematics of open charm production. I will first argue that the confusion is mostly (possibly exclusively) created by an absence of sufficient care in comparing various experiments. Problems emerge when (i) comparing experiments using nuclear targets with those using exclusive protons and forgetting that the $A_A$ corrections involved have not been experimentally determined, (ii) invoking limits on charm production from the observed lepton/pion ratio and (iii) using words like "central" and "diffractive" production without giving them a precise meaning. Before confronting the data, I will attempt to remedy this situation.

What is the $A_A$ dependence of charm production? Non-perturbative or truly diffractive models argue for $A_A = 2/3$, whereas models based on perturbative QCD (which the data strongly favor, as will be argued further on) require $A_A$. Such arguments are, however, dangerously over-simplified, as illustrated by the
following example. Everybody knows that $\alpha$ should be $2/3$ for the diffractive production of strange particles. Well ... It is not as shown in Fig. 12. Around Feynman $x$ of 0.6 the value of $\alpha$ becomes as small as 0.45 for both $K$ and $\Lambda$ production. So even if one expects $A^{0}$, "nuclear physics" might play tricks on us and make the observed value say, $A^{0}/3$. $A^{0}/3$ makes a lot of difference when one is using a tungsten target! I will assume $A^{0}/2$ and this is not necessarily a bad value if you like perturbative QCD as illustrated by glancing at the situation for strange particles. Measuring $\alpha$ is, however, a high priority task for the future.

My message regarding limits on charm cross sections from lepton/pion ratios is simple: approach with care! My point is illustrated in Fig. 13 where we have calculated $\rho/\pi$ from the leptonic decay of $D$ mesons assuming a $8\%$ leptonic branching ratio and a nominal (and intentionally outrageous) total yield of 1 mb. $D$'s are produced according to a momentum distribution

$$E \frac{d\sigma}{dp_T} \sim (1-x)^n e^{-bp_T}$$

(5)

Figure 13a illustrates the sensitivity of $\rho/\pi$ to the detailed shape of the $D$ decay distribution by alternatively assuming $D \rightarrow K$ (or $K^*\ell\nu$). Figure 13b illustrates the same point regarding the exact value of $b$ in Eq. (5). Figure 13c finally illustrates how one can stretch the error bars on $n$, $b$ and the decay distribution to slip a 1 mb cross section under the observed $\rho/\pi$ ratio.

Fig. 13: $\rho/\pi$ ratios at $\sqrt{s} = 62$ GeV from $D \rightarrow K$ (or $K^*\ell\nu$) assuming Eq. (5), a leptonic branching ratio of $8\%$ and a nominal value of the $D$ production cross section of 1 mb.
Finally, let us agree on a working definition of the words "central" and "diffractive". As a guide (and as a guide only) we use the diagrams for leading particle production shown in Fig. 14. It is easy to calculate their large $x$ behavior, e.g., using the counting rules of Ref. 28. Protons produce leading $\Lambda_c$'s with $(1-x)^1$ and $\bar{D}$'s with $(1-x)^3$. It is easy to understand that $\bar{D}$'s are relatively softer: they contain 1 fast valence quark, not 2 as is the case for $\Lambda_c$. This situation is familiar: diffractive $K$'s are softer than $\Lambda_c$. $\pi$ beams produce an equal amount of $D^0$ and $\bar{D}$ particles with a $(1-x)^1$ distribution. In this picture the Feynman $x$ dependence of central production is $(1-x)^2$. These estimates neglect the masses of the charm particles. Especially at lower energies the observed $x$-dependence could therefore be significantly softer. We discuss the data next.

The observation of "diffractive" or leading charmed particles, produced with large Feynman $x$, was for a long time the monopoly of ISR experiments. This situation has radically changed. Leading $D$'s from a pion beam are now observed in five experiments. Illinois et al.29 and ACCMOR30 see leading $D$'s from $D$ decay, produced with a broad $x$ distribution consistent with $(1-x)^2$. These observations are confirmed by preliminary data from the Fermilab MPS;31 they obtain as a best fit to the longitudinal momentum distribution $(1-x)^{1.5 \pm 0.7}$. The LEBC experiment32 furthermore presented evidence for two components in the $x$-distribution $(1-x)^n$, with $n$ shifting from a typical central value at small $x$ to a value consistent with unity when $x$ approaches 1. Beam-dump experiments as a group33 have been unable in the past to find any trace of leading charm particles. This situation is finally reversed by the detection of leading $D$ particles from a 278 GeV $\pi^-$ beam with the Fermilab $\mu$-beam dump facility.34 Let us recall that we expect (Fig. 14) a $\pi$ beam to fragment into equal numbers of leading $D^0$ and $\bar{D}$ particles following a $(1-x)^1$ distribution. The experiment observes $D$'s through their semi-leptonic decay into $\mu^\pm$. It is important to remember that

$$\frac{B(D^0 \rightarrow \mu^+)}{B(D^0 \rightarrow \mu^-)} = \frac{\tau(D^0)}{\tau(D^0)} > 1,$$

i.e., the longer lifetime of charged $D$'s will be reflected into a larger leptonic branching ratio. Therefore, the observed leptonic decays of $D^+$, $D^0$ will differ, with
The experiment indeed observes an excess of prompt $\mu^-$ within acceptance. This number has to be interpreted with care, the value being x-dependent. Clearly the best place to detect a leading charm component is in $P$ events (Eq. (7)). Their data are shown in Fig. 15. The momentum distribution of the $\mu^-$ is compared with the expected distribution

$$\sigma(\mu^-) \sim (1-x)^{1.9} e^{-2.5p_T}.$$  

They obtain

$$B\sigma(\mu^-) = 2.9 \pm 0.2 \text{ fb} \quad (x > 0 \text{ only}). \quad (10)$$

Here I used again $A_{2/3}^1$. Assuming roughly equal cross sections for $x > 0$ and $x < 0$ and a nominal branching ratio of 10%, Eq. (10) translates into a "diffractive" cross section of order 50 pb, only a factor 4 below that observed at the ISR.

Four experiments now support the observation of leading $\Lambda_c^+$ at the ISR if one includes the indirect evidence from a CDHS$^{34}$ result. Indeed, their observation of a $V, B$ asymmetry in the beam-dump results can be interpreted as a consequence of leading $\Lambda_c^+$ decay. A Serpukhov experiment$^{35}$ observes a 100 $\Lambda_c^+$ peak in the decay $\Lambda_c^+ \rightarrow pK^0_S\pi^-$. All events are contained in a 30 MeV bin. Puzzling, however, is the fact that their production cross sections are as large as those observed at the ISR, despite the low energy of their neutron beam. The Tata group$^{31}$ presented new evidence for $\Lambda_c$ from an emulsion exposure at Fermilab. The production angle in the emulsion reflects the leading character of the $\Lambda_c^+$'s. Although backgrounds are formidable, the observation of associated $D^+$'s in two events lends further support to their analysis. Further evidence for $\Lambda_c$ production is shown in Fig. 16.
Although the statistics are low, the LEBC experiment using hydrogen is very clean. One notices the clustering of $\Lambda_c$ events at a larger x-value when comparing to D events shown in the same figure.

The absence of any direct evidence for leading $\Lambda_c$'s from proton beam-dump experiments is still puzzling. Before jumping to conclusions, one should keep the following precautions in mind: (i) The value for the leptonic branching ratio of the $\Lambda_c$ (4.5%) is only known within large error bars; the actual value might be smaller. (ii) The lepton from $\Lambda_c$-decay could be much softer than one estimates assuming a three-body decay. A higher multiplicity of hadrons in the final state of the $\Lambda_c$-decay (as observed for D semileptonic decay) would reduce the estimated acceptance of the experiments. (iii) As already mentioned, even leading $\Lambda_c$'s could have an x-distribution significantly softer than $(1-x)^3$, an estimate that neglects the heavy quark mass. (iv) Leading D's, expected to be softer than $(1-x)^3$, could be confused with those centrally produced.

Figure 17 shows a compilation of experimental values for $\Lambda_c$ and D production in NN collisions (additional nN data are shown in Fig. 21). To the extent that the total inelastic cross section is roughly independent of energy in the $\sqrt{s}$-range under consideration, the threshold represents the rise of the charm particle multiplicity. This threshold dependence is very reminiscent of the observed increase of $K,\Lambda$ multiplicities at ISR energies, as well as the sharp rise in $K,\Lambda$ multiplicities observed in $e^+e^-$ annihilation at PETRA. This is shown in Fig. 18, where we have converted the $e^+e^-$ annihilation energy to an effective NN energy using

\[
\frac{s}{\sqrt{s}} = \langle x^2 \rangle x
\]

Equation (11) translates hadron-hadron energy to parton-parton energy by removing the beam jets. The procedure is familiar in the study of total multiplicity where
one concludes\textsuperscript{39} that $\langle x \rangle = 0.2$. The universal threshold for heavy particle production displayed in Fig. 18 is indeed reminiscent of the universal behavior of charged particle multiplicities\textsuperscript{22} provided a comparison is made between $e^+e^-$ and NN induced reactions using Eq. (11). Finally, Fig. 19 shows how experimental values for charm production on nuclear targets "fall through the floor" when $A'$ is assumed. This can be taken as evidence for an $A''$ dependence closer to $A''$, but by no means diminishes the need for an experimental measurement.

b) Perturbative QCD confronts the data. The $O(\alpha_s^2)$ graphs which constitute the leading order QCD mechanisms for producing heavy quarks are listed in Fig. 20. Neglecting the charm structure inside the proton, i.e., neglecting the diagrams of Fig. 20c, we are left with the fusion model where charm is hadro-produced by the fusion of quarks (Fig. 20a) and gluons (Fig. 20b). Using standard choices for the light quark and gluon structure functions we obtain the charm cross section labelled "fusion" in Fig. 21. The fusion diagrams underestimate the observed charm yields by over one order of magnitude. It is

---

*Fig. 19:* Same as Fig. 18 assuming $A'$ in deducing charm cross section from experiments using nuclear targets.

*Fig. 20:* Leading order QCD diagrams for the production of heavy quarks.

*Fig. 21:* Data on hadroproduction (NN and NN) of charm are compared with a calculation evaluating the fusion diagrams of Fig. 20a,b (dashed line) and with a full $O(\alpha_s^2)$ calculation (solid line).
Faced with this failure we should clearly reconsider the fact that we neglected the flavor excitation graphs of Fig. 20c. The first of these diagrams is shown in detail in Fig. 23: a quark in the beam scatters by gluon exchange off a charm quark in the target. The structure of this diagram is schematically given by exhibiting the fact that these diagrams diverge when $t = 0$ and one hits the gluon exchange pole in Fig. 23. However, the gluon plays the same role as the virtual photon in leptoproduction; therefore, $t$ is similar to the $Q^2$ controlling the QCD evolution of the structure function. When $t = 0$ no charm is present in the target and therefore the divergence in Eq. (12) is controlled. Only when $t = -m_c^2$ have enough charm pairs evolved to give a non-vanishing value for the diagram in Fig. 23. By this argument $t_{\text{min}} = -m_c^2$ in Eq. (12), still yielding large cross sections from flavor excitation. A quantitative evaluation is difficult because of our ignorance of the charm structure function $c(x, Q^2 = m_c^2)$. Odorico used a Monte-Carlo to explicitly generate the charm structure function from evolution. The result is shown in Fig. 21. Flavor excitation diagrams not only allow us to bridge the gap between the fusion diagrams and the data, they "impersonate" diffractional production of charm. Leading $A_c$'s, absent in the fusion model, can now be obtained by the recombination of the spectator $c$-quark in Fig. 23 with a valence $(ud)$ pair in the proton. Alternatively, a spectator $c$ can pick up a $u$ or $d$ valence quark to form a leading $\bar{D}$. It will be softer than the $A_c$ because it contains only one valence quark. The picture emerging is similar to the one presented in Fig. 14 which we used to summarize the experimental data. A sample calculation is shown in Fig. 22. However, unlike truly diffractional mechanisms, flavor excitation does not have a logarithmic energy threshold (which would be clearly at variance with the data; see Fig. 21) and predicts a suppression of the cross section with increasing quark mass which is substantially stronger than $m^{-2}$. We return to this point when discussing $b$-quarks.
It should be clear from this discussion that perturbative QCD is used as a tool to describe the data and cannot be subjected to quantitative tests. The framework is, however, sufficient to describe the data. The situation is similar to that for the hadronic production of large-$p_T$ hadrons. It is in fact questionable whether the perturbative approach to heavy quark production is completely understood; this makes it an interesting study case. The perturbative approach is indeed valid in the (impossible) limit where $s \to \infty$ with $m_Q^2/S$ fixed (see Fig. 24). It is of course impossible to keep the ratio $m_Q^2/S$ unchanged without increasing $m_Q^2$ as well as $S$. This is what is done in the Drell-Yan process and the resemblance of diagrams as the first one in Fig. 24 to Drell-Yan annihilation is misleading. The problem is illustrated by the second diagram. It is indeed easy to show that without increasing $m_Q^2$, the momentum transfer $t \to 0$ when $s \to \infty$. Some propagators become soft and perturbative results are suspicious when $s \gg m_Q^2$. This should be kept in mind, e.g., when calculations of $c$- or $b$-production are extrapolated to collider energies.

What about intrinsic charm?

First, and most important: we do not need it. What I mean by this is very precise: all observed leading particles contain valence quarks. The data completely supports our claim that leading charm particles have large Feynman $x$ because they contain valence quarks with large $x$; the charm quark itself is a soft product of a off-shell gluon (Fig. 23). If the $c$-quarks themselves were valence-like, as in the intrinsic charm picture, this constraint on the quantum numbers of leading particles is lifted and, e.g., leading $0^- (c\bar{c})$ could emerge from proton beams. There is no evidence for this. Instead of continuing to rule out intrinsic charm, we should look for it this way and try to establish whether it exists at some level.

Are valence-like $c\bar{c}$ components in the proton wave function a feature of QCD? The answer is no; the argument is depicted in Fig. 25. The figure shows (uud $c\bar{c}$) Fock states of the proton. In the top diagram the $c\bar{c}$ pair materializes from a gluon with large $Q^2$. Such diagrams can be computed perturbatively and are included in the previous calculations. Intrinsic charm could be generated from diagrams of type shown in Fig. 25b. Here a soft gluon produces a soft $c\bar{c}$ pair that eventually shares the momentum of the valence quarks after multiple interactions. The problem is, however, that the $c$-quarks are far off-shell and are therefore short-time fluctuations: there is not enough time to achieve the momentum sharing with the valence quarks to build up an intrinsic $uudc\bar{c}$ Fock component of the proton. How far the $c$-quarks are off-shell is given in the model of Brodsky et al. and one can derive an upper limit on the lifetime of the $c\bar{c}$ pair.

Fig. 25: $c\bar{c}$ components of the proton wave function.
where $p$ is the proton momentum. This time is much shorter than a typical light quark fluctuation $p/\mu^2$ (with $\mu = 300$ MeV), preventing the $c\bar{c}$ pair from being an intrinsic part of the proton. Building valence-like $c\bar{c}$ components into the proton is intrinsically impossible.

c) Evidence for $b$-quark production. Figure 26 summarizes the experimental status of the hadroproduction of $b$-quarks. Also shown are predictions for $b$- and $t$-quark production based on the full $O(a_s^2)$ calculations described in connection with charm production. First, there are upper limits. NA3 obtains a 100 nb limit at 400 GeV from an emulsion exposure. Cascade decays of heavy quarks have been observed in emulsions exposed to cosmic rays. They cannot be charm; the most conservative assumption is that they are $b \rightarrow c + s$ cascades. Also, narrow parallel muon bundles have been interpreted as cascade decays of $b$-quarks. This evidence puts the $b$-quark cross section in the $10^{-10}$ TeV range at the level of 100 nb. There is the evidence from the BCF group at the ISR. Their result is shown assuming that the branching ratio in the observed mode is given by $B(A_b \rightarrow p \bar{D}^0) = B(A_c \rightarrow p \bar{K}^0)$. $B(A_b \rightarrow p \bar{D}^0)$ has to be of order 1 to avoid conflict with the lepton/pion limit on $A_b$ production also shown in Fig. 26.

But there is new information. The NA3 group has observed a positive signal for the reaction $\pi^- N \rightarrow \psi \pi^-$. The $\psi$'s are detected by their $\mu^+ \mu^-$ decay. The salient features of the events are as follows: (i) the cross section is $30 \pm 10$ pb at 280 GeV; (ii) the events show diffractive characteristics, with one leading $\psi$ ($\langle x \rangle$ is in excess of 0.4); and a slow $\psi$; (iii) the $\psi$ invariant mass is spread from 6.5 to 8.5 GeV. The most obvious interpretation involves the first mechanism shown in Fig. 27. After production of a charm quark pair, another soft $c\bar{c}$ pair is picked up out of the sea to form two $\psi$'s. It is clear that both $\psi$'s will be centrally produced ($x = 0$) with an invariant mass clustered around $2m_{\psi}$. The NA3 events seem to exclude this interpretation. The kinematic features of the events support, however, the alternative interpretation shown in Fig. 27 that $b$-quark production with subsequent $B \rightarrow \psi$ and $B \rightarrow \psi$ decays is the source of $\psi$ events. The observed $\psi$ rate is in agreement with the prediction shown in Fig. 26 provided that the decay fraction $B \rightarrow \psi X$ is of order 1%. It is important to remember that at the energies under consideration flavor excitation (not fusion) is the dominant source of $b$-quarks. The leading $B$ will be the source of a leading $\psi$;
the other B (and $\Psi$) will have lower longitudinal momentum. This is in agreement with the data (see Fig. 28).

This rapidity gap between the B's, as well as the random orientation of the two $\Psi$ decay product will lead to a large, spread out invariant mass $m_{\Psi\Psi}$. The results of a calculation again agree with experiment (see Fig. 28).

Finally, the $\Psi$ decay products are not subject to any constraints from transverse momentum conservation. The b-quarks roughly conserve transverse momentum, the $\Psi$'s do not. The event displayed in Fig. 28 shows these characteristics. For a detailed analysis we refer to Ref. 47. If this interpretation of $\Psi\Psi$ events is correct, experiments detecting muons only can be used in the future to study heavy quark production.

d) Bound flavors. The 'bleaching' of the cF color quantum number when the quarks materialize into a $\Psi$ has made the understanding of bound flavor production very difficult. We already encountered this issue when discussing $\Psi$-photoproduction. New, very clean and high statistics evidence has been obtained\(^5\) for the production of $\Psi$'s via the reaction $pp \rightarrow \chi + \Psi\Psi$. $\chi$'s are a definite piece of the puzzle in understanding $\Psi$-production\(^9\) and calculations along these lines are now very successful\(^5\).

There is also the scaling law of Gaisser et al.\(^{11}\) It is a fact that all data on the production of bound flavors can be understood on the basis of the two following assumptions:\(^{11}\) (i) copious decay of a $(Q\bar{Q})$ state into hadrons results in copious production by hadrons; (ii) let dimensions do the rest. This leads to the statement that

$$
\sigma(Q\bar{Q}) = \frac{\Gamma}{M^3} F^2(s).
$$

Here $\Gamma$ is the direct $(Q\bar{Q} \rightarrow 3$ gluons) width of the $(Q\bar{Q})$ bound state. The success\(^5\) of this approach is shown in Figs. 29, 30. $M^3/f$ is indeed a universal function of $M^2/s$. All attempts to derive Eq. (14), e.g., from QCD, have failed.

To add to the mystery, it has been recently discovered\(^5\) that the scaling function $F(M^2/s)$ is identical in shape to that observed in the Drell-Yan process (see Fig. 30), leading to the relation

$$
\frac{d\sigma}{dy} (pp \rightarrow \chi\chi) = (1.5 \times 10^5) \frac{\Gamma(V \rightarrow ggg)}{f^2} \frac{d\sigma}{d\ln M^2} (pp \rightarrow \mu^+\mu^-\chi).
$$

Here $\gamma$ is the rapidity of the bound state $V(0\bar{0})$.

e) Higgs hunting. To show that at least some of the goals announced in the beginning of this talk are not frivolous, I would like to show the important implications of what we learned about heavy quark production for Higgs hunting.

Figure 31 shows an example of a forgotten\(^5\) (Higgs excitation) diagram and a standard\(^9\) diagram for Higgs production. For a dynamically generated Higgs mass of about 10 GeV, the two mechanisms have a similar cross section (unfortunately in the
Fig. 29: The scaling law of Eq. (14) confronts the data. The function $F(M^2/s)$ in Eq. (14) is the same as the equivalent scaling function in the Drell-Yan process.

pb range, although it could be significantly larger\(^{55}\). Notice that the calculation of $g_c \rightarrow Hc$ type diagrams is very reliable as the Higgs mass controls all $t \rightarrow 0$ divergences. Comparing cross sections is, however, beside the point. Indeed, the old-fashioned fusion diagram requires finding a $H + cc$, $\tau\tau$ peak in a large background of such pairs originating from other sources (e.g., $gg + cc$). This is hopeless given the rate. The signature of production and detection of the Higgs exclusively via heavy particles\(^{53}\) (first diagram in Fig. 31) is, however, spectacular.

Fig. 31: Examples of a forgotten (a) and a standard (b) diagram for Higgs production.

Four fast, long-lived particles $c\bar{c}c\bar{c}$ or $c\bar{c}\tau\tau$ signal the events. We calculated that no competing backgrounds exist. In the $c\bar{c}\tau\tau$ channel this result is again very reliable. A few events can therefore establish the signal! In times of financial restraint, program committees become very conservative, but isn't the Higgs worth a gamble?
5. Problems for the Standard Model? - Two experimental results deserve special consideration: (i) $\nu_e\bar{\nu}_u$ universality breaking in beam-dump experiments and (ii) production of same-sign dimuons in neutrino interactions. It is rather obvious that these observations defied explanation within the framework of perturbative QCD and the standard electroweak model. The point that I would like to make here is much stronger: It is unlikely that these results will be accommodated with minor changes and adjustments of parameters; they seem to require radical changes or the infusion of completely new physics elements into the standard model.

Beam-dump experiments are designed to detect the neutrinos from the decay of charm particles produced in hadron interactions in the dump. The various experimental measurements of the prompt $\nu_e/\nu_\mu$ ratio observed in beam-dump experiments are compiled in Fig. 32. If we average these numbers (as only a theorist can do it), we obtain

$$\frac{\nu_e}{\nu_\mu} = 0.58 \pm 0.09,$$

almost a five standard deviation effect. Clearly the CERN experiments do not represent completely independent measurements and if the result were due to some systematic effect they could clearly share the problem. The fact that the Fermilab beam-dump experiment, with a very different design, seems to confirm the CERN experiment, is therefore very meaningful. It is, however, too early to jump to definite conclusions. Indeed, the top Fig. 32 shows their $\nu_e/\nu_\mu$ ratio as a function of the neutrino energy. Low energy neutrinos are the source of the $\nu_e$, $\nu_\mu$ asymmetry. At the higher energies $\nu_e = \nu_\mu$ within very large errors (see last point on the lower Fig. 32). Because of a particular choice of trigger in the early running of the Fermilab beam-dump, the lower energy measurements are subject to large systematic errors, not shown in the figure. Definite results are eagerly awaited, as the observation of a $\nu_e/\nu_\mu$ universality breaking by experiments with very different systems is almost necessary to establish the credibility of these results.

These efforts are very important, as a result like Eq. (16) defies any simple explanation in terms of electroweak theory. Potential explanations come in three categories: (i) neutrino oscillations, (ii) production of an object like a Higgs particle decaying with preference into $\nu_e\nu_\mu$, (iii) or an object like a $\pi$ meson (hopedly not the real $\pi$) with a suppressed $e\nu_e$ branching ratio. Neutrino oscillations (e.g., $\nu_e \leftrightarrow \nu_\mu$) would imply many apparent neutral current events which are not seen and would give a depletion of the $\nu_e$ flux which is not observed elsewhere. Explanations of the type (ii), (iii) could enhance the $\nu_\mu$ flux. However, the hadronic production cross sections cannot be made large enough without inventing some enormous new weak interaction couplings which can be ruled out elsewhere. For details, see Ref. 56.

It has been proposed that the beam-dumps observe genuine charm decays and the $\nu_e/\nu_\mu$ asymmetry stems from nonuniversality of charm decays. This asymmetry could
result from a decay component mediated by a virtual charged Higgs boson (Fig. 33). It is amazing that this proposal cannot be ruled out (yet) on theoretical or experimental grounds. It clearly illustrates my point, however, that explanations are outside the standard model: the Higgs is charged, not neutral, and does not have universal couplings. It couples to $c$ only; any other sizeable couplings are experimentally excluded.

We turn to same-sign dimuons next. Here the experimental situation is clear: all experiments agree.\textsuperscript{57} The apparent spread between the measurements shown in Fig. 34 is only the result of varying cuts on the muon momentum and varying assumptions made in subtracting backgrounds. For details we refer to Ref. 57; they are not important for the discussion that follows. There is furthermore very clear evidence that the secondary $\mu^+$ (see, e.g., Fig. 35) is associated with the hadron vertex, e.g., it could come from the decay of a $Z$-quark. The high rates for $\mu^-\mu^+$ events have defied explanation since their discovery by HPWF. In order to have a feeling for the problem, we evaluate the diagram shown in Fig. 35. Such a calculation is straightforward; the only decision we have to make is how many $c\bar{c}$ pairs result from the hadronization of the $u$-quark jet. This decision can be made in various ways; e.g., I will take

$$\frac{c}{u} = \frac{\sigma(c\bar{c})}{\sigma(\mu^+)}.$$  \hspace{1cm} (17)

\textbf{Fig. 33.} A virtual charged Higgs as a source for $\nu_{\mu}/\nu_{\mu}$ universality breaking in charm decays.

\textbf{Fig. 34:} The same-sign dimuon rate is compared to a calculated upper bound.

\textbf{Fig. 35:} A diagram for the production of same-sign dimuons.
where $\sigma$ refers to the total inclusive cross sections shown in Fig. 1 evaluated at the appropriate effective energy. I used the $seff$ definition discussed in conjunction with Eq. (11), but the results do not qualitatively depend on this or any other details, e.g., what the exact shape of the $c \to D$ fragmentation function is. The result, including appropriate cuts, is shown in Fig. 34 and misses the data by one order of magnitude. It represents an upper bound that all calculations do (or should) satisfy in the sense that: (i) it involves a maximal weak interaction, and (ii) it provides for as many charm pairs in the hadron vertex as allowed by available experimental information.

The same-sign dimuon rate is a mystery; that its origin is possibly not charm or any other heavy flavor is further strengthened by the characteristics of $\mu e$ events observed in Gargamelle. They observe 7 events (with a background of 2) with their most severe cuts $p_\mu > 4.5$ GeV, $p_e > 0.8$ GeV. They measure $\mu e$ events simultaneously and find from this control measurement that if the $\mu e^-$ are of charm origin like the $\mu^+ e^-$ they should find more than 1 $K$ per event. They find none.

Indications of this absence of $K$s in $\mu e^-$ events exist from previous experiments.

6. Conclusions. - The progress made in this subject is obvious; a glance at Phillips’ talk at the Madison conference and Treille’s talk at the Bonn conference should convince anyone that the important experimental and theoretical efforts devoted to this subject are paying off. Rapid progress in the very near future is virtually guaranteed by the advent of higher energy lepton beams at Fermilab and new very large acceptance detectors both at Fermilab and at CERN. Foremost, there will be the new generation of hadron colliders. They will not only widen the energy range, but the scope of their physics results could well depend crucially on their ability to handle heavy quarks either as triggers or as a background. If this extensive experimental effort on heavy quarks leads us to the Higgs particle, then it was all worthwhile. In the meantime, there are the $v_e/\bar{v}_u$ asymmetry and the same-sign dimuons to provide us with real surprises.

Acknowledgment


References

10. PAKVASA, S. (these proceedings).
55: BEST, C. H. et al., Rutherford Laboratory preprint RL-81-044 (1981); 
COGENT, G., talk at European Physical Society International Conference, 
Lisbon (1981); AUBERT, J. J. et al., CERN preprint CERN-EP/80-84 (1980); 
MOUNT, R. P. et al., in Proc. of the XXth International Conference on High 

16. AUBERT, J. J. et al., paper #773, and CERN preprint (submitted to Nuclear 
Physics B).

17. ASTON, D. et al., Ref. 13; ATKINSON, M. et al., this conference.

18. DIAMBRINI-PALAZZI, G. (these proceedings).


21. For recent reviews, see Ref. 11 and Proc. of the Workshop on Heavy Flavors, 
Les Arcs (1982); DIBITONTO, D., OLSEN, S., ODORICO, R., BRODSKY, S. and 
HWA, P., in Collider Physics-1981; AIP Conference Proceedings #85; ZICHICH, A., 
in Proc. of the EPS International Conference on High Energy 
Physics, Lisbon (1981).

22. Sources of hadroproduction data (ordered by decreasing energy): FUCHI, H. 
et al., 16th International Cosmic Ray Conference & 112 (Kyoto, 1979); 
XXth International Conference on High Energy Physics, Madison (1981); 
CERN preprint CERN-EP/82-31 (1982); FUCHI, H. et al., Nagoya preprint DPNU-82-
on High Energy Physics, Lisbon (1981); WEILHAMMER, P., in Proc. of the Work-
shop on Heavy Flavors, Les Arcs (1982); HUGENTOBLER, E., in Proc. of the 
collaboration, in Proc. of the XXth International Conference on High Energy 
Physics, Madison (1981); A21A, T. et al., Tata Institute preprint TIFR-BC-82-1; 
COOPER, J. W. et al., in Proc. of the XVIth Rencontre de Moriond (1981); 
KOESTER, L. J. et al., in Proc. of the XXth International Conference on High 
Energy Physics, Madison (1981); CHUNG, S. U., Phys. Lett. 74B (1979) 178; 

Rencontre de Moriond (1981); BODEK, A. et al., University of Rochester pre-
print #804, Phys. Lett. B (to be published); REEDER, D. D., in pp Collider 
Physics-1981, AIP Proceedings #85, Madison (1982); LONGO, M. and CONFORTO, G., 
in Proc. of the Workshop on Heavy Flavors, Les Arcs (1982); BALL, R. C. et al., 
papers #668, 679, 680; ALIBRAN, P. et al., Phys. Lett. 74B (1979) 134; 

24. GUSTAFSON, G. and PETERSON, C., Phys. Lett. 67B (1977) 81; AFEK, Y., 
MARGOLIS, B. and POLIYAN, L., McGill preprint (1981); HORGAN, R. R. and 

105; HALZEN, F. and MATSUWA, S., Phys. Rev. D 17 (1978) 1344; JONES, L. M. and 
WYLD, H. W., Phys. Rev. D 17 (1978) 1782; GLUCK, M., OWENS, J. F. and 


Duff, B. (private communication).

NiU, K., in Proc. of the Bartol Conference, AIP Proceedings #49; MurakI, Y., paper #223.

BADER, J. et al., paper #535.


DIFF, B. (private communication).

NiU, K., in Proc. of the Bartol Conference, AIP Proceedings #49; MurakI, Y., paper #223.

BADIER, J. et al., paper #535.


DIFF, B. (private communication).

NiU, K., in Proc. of the Bartol Conference, AIP Proceedings #49; MurakI, Y., paper #223.

BADIER, J. et al., paper #535.


Discussion

P. SCHMID (CERN).— What is the prediction for the x-distribution for charm production in a model consisting of fusion plus flavour excitation?

F. HALZEN.— "Predictions" are discussed in the write up. See e.g. calculations by Odorico.

B. ROE (Univ. of Michigan).— The beam dump evidence against diffractive \( h\bar{\nu} \) production may be stronger than you indicate.

If \((1-x)^1\) were not seen because the \( h\) decay were suppressed, the associated \( \bar{\nu} \) would still decay into \( D \). A \( \nu/\bar{\nu} \) ratio greater than one would be observed (the \( D^0/\bar{D}^0 \) lifetime difference could affect this somewhat). In fact all experiments find \( \nu/\bar{\nu} \) less than or at most equal to one.

Further the extremely low limits on \((1-x)^1\) imply the suppression if the 3-body \( X\bar{\nu} \) decay would have to be very large.

F. HALZEN.— Regarding \( \sqrt{\nu} \), my answer is the same as the one given to Fisher. Regarding the limit on a \((1-x)^1\) component in your experiment it is important to repeat that \((1-x)^1\) is a guess neglecting the heavy quark kinematics. Leading \( k^* \) 's could be much softer at lower energies, making limits less severe. I repeat that limits are implicitly assuming a leptonic branching ratio (which is poorly known) and are assuming a three-body decay (which is almost certainly wrong). I agree however that in the case of nucleon-nucleon interactions bringing the results of beam-dump and other techniques together (e.g. ISR) is still difficult.

C. FISHER (Rutherford Lab.).— Two comments:

1) The LEBC NA10 experiment agrees with the \( \nu \) beam dump data: we do not see an excess of \( \sigma \) states in \( p-p \) events which would be expected from a large \( N^0 \) cross section.

2) The measured cross sections are for interactions producing charm in hydrogen. No A dependence correction is required. We find 20-30 \( \mu \) for \( \sigma(p-p-A) \) at 350 GeV. This is in line with the beam dump assuming \( A^1.0 \). Moreover the NA10 data from the heavy liquid bubble chamber operating in the same beam line supports \( A^1.0 \) by direct composition with LEBC.
F. HALZEN.- Regarding comment 1: I realise that this problem exists. However the "diffractive" component could be in competition with a central component producing \( D\bar{D} \) pairs washing out the excess of leading \( D \)'s which after all are expected to be softer than \((1-x)^2\).

Comment 2: In the talk I have tried to make this type of comparison by averaging all experiments, not two. As one is comparing normalizations, picking two experiments is dangerous. The \( A^2 \) dependence should be measured and then these attempts at guessing \( a \) can be forgotten.

J. BALLAM (SLAC).- Your non-perturbative calculation of photoproduction of charm does not seem to agree with the 20 GeV data. Do you have any comment?

F. HALZEN.- Non-perturbative mechanisms are guesses, not calculations. The mechanism discussed in the talk gives results which are unreliable close to threshold, it depends in detail how the heavy quark kinematics is incorporated into the calculation.