HEAVY-FLAVOR PRODUCTION OVERVIEW*

Jeffrey A. Appel

Fermilab, P.O. Box 500, Batavia, IL 60510 USA
e-mail: appel@fnal.gov

This talk serves as an introduction to the Heavy-Flavor session of the XXXIII International Symposium on Multiparticle Dynamics. A major focus of this session is on the production of heavy quarks. The talks which follow review the latest results on heavy quark production in strong, electromagnetic, and weak interactions, as well as some of the physics of the heavy quarks themselves. This talk emphasizes what we can learn from the production measurements, both about underlying QCD theory and the partonic nature of the hadrons which we see in the laboratory.

PACS numbers: 12.38.–t, 12.38.Qk, 13.15.+g, 13.60.–r

1. Dedication

We should start this session by recognizing the loss of Krzysztof Rybicki, until his death a member of the Local Organizing Committee and mover to have this session on heavy flavor reintroduced to the Multiparticle Dynamics program. Krzysztof was the original organizer of this session, outlined its content, and personally invited me to participate. We will all miss Krzysztof's presence here — his intellectual contributions ... and his wonderful smile. We dedicate this session to the memory of Krzysztof Rybicki.

2. Introduction

Today's program is filled with results from a large variety of physics environments, involving production of heavy quarks in hadronic, electromagnetic, and weak interactions. We will see a lot of data in the next six talks, [1–6] some of it quite new. In what is presented, there are some themes

---

* Presented at the XXXIII International Symposium on Multiparticle Dynamics, Kraków, Poland, September 5–11, 2003.

of particular interest. In the area of QCD dynamics, there are results which test basic QCD theory and even what may lie beyond the Standard Model. The data should help in navigating among recent theory improvements — from next-to-next-to-leading-order and k_t-factorization calculations to various resummation techniques. Also, there will be results which tell us about the structure of hadrons. This information is more than just an input to QCD calculations, but fundamental information on the nature of and parameters describing quarks and gluons in hadrons. By the end of the session, we should see what we have learned and what remains a mystery [7].

3. Testing QCD

Last month, Thomas Gehrmann, in his Lepton Photon Symposium 2003 review, "QCD Theoretical Developments", said that the "testing QCD"-era has been over for some time [8]. I think that this is, perhaps, part of the general euphoria about the Standard Model. Nevertheless, a quick search of SPIRES finds a significant number of papers with titles including "test of" or "testing" QCD. The numbers are given in Table I. A significant fraction of the papers come from experiments with new results. Testing is the job of experiments, after all; to probe the theory. So, testing is not over yet!

TABLE I

Recent SPIRES listings on tests and testing of QCD

Year	1998	1999	2000	2001	2002	2003
No. papers	4	10	8	4	11	3 (so far)

3.1. Some recent surprises and old mysteries still with us

We have had an unusual number of surprises this year involving heavy flavor production:

Double charm production rate in the e^+e^- continuum

Production rate of double charm baryons by Σ's

Better agreement with theory for charm than beauty production in γ-γ collisions at LEP.

Older mysteries are still with us. Consider the

b quark production rates at Tevatron Collider energies;

J/ψ and ψ' production rates at fixed target and collider energies.

3.2. Heavy-flavor cross sections

The context for most thinking about heavy-flavor production depends on the factorization of the cross section, σ_{QCD}, into (1) a hard scattering of incident partons which have come from (2) distributions in the incident particles and (3) a hadronization process of the outgoing partons that result from the hard scattering. The hard scattering is often drawn as a box. We might describe the thinking in this context as thinking "inside the box" — to use an American colloquialism.

Typically, the measured cross sections are much larger than leading-order (LO) QCD predictions, even when renormalization and factorization scales and masses are set low. Cross sections are still larger than next-to-leading-order (NLO) predictions, typically by factors ~ 2, at least in some kinematic regions. Recently, adding resummation effects (Next-to-Leading-Log, NLL, in p_{t}) and refined fragmentation functions are helping agreement. How should we interpret this progression? Real progress? Yes. Furthermore, Jung, using a k_{t}-factorization calculation [9], finds even better agreement with the data. In this calculation, done with an appropriate set of parton distribution functions coming from HERA, some higher-order (resummed) terms are inherently included. The technique also works surprisingly well for charm using the same parton distribution functions [10].

Perhaps it is worth noting that data is typically in a limited kinematic region. An important step has just been made by CDF in triggering and analyzing B production down to p_{t} of zero (using decays to J/ψ's).

One of the more disturbing things to note in the way we think about new theoretical calculations is our willingness to keep any Standard Model effect which increases the predicted σ_{QCD}. This is hardly unbiased science.

3.3. Charmonium issues

Measurements of J/ψ production at fixed-target energies are a factor 7 too large, and $\sigma_{(}\psi')$ is a factor 25 too large relative to the older leading-order calculations [11]. Can this be due to the color-octet mechanism in addition to the usual color-singlet mechanism? Are color-octet matrix-elements as relevant at fixed-target energies as at the Tevatron Collider? Actually, the color-octet parameters from the Tevatron do not work at HERA. Furthermore, the polarization predicted at high p_{t} for color-octet contributions has not been seen at the Tevatron. What is going on here? Where is all the charmonium coming from?

Direct charmonium production is a small fraction of the total charm production. Yet, color-octet hard scattering is a possible contribution, color evaporation, too. "Thinking outside the box" leads to the possibility of Non-Standard Model sources — *e.g.*, light SUSY (see below). We will need data

over broader kinematic ranges to sort things out (*e.g.*, lower p_t where the cross section is largest). Also, note the p_t-spectrum dependence of resummation in p_t. This may be part of the answer to our questions. Theory is only credible when terms are universal, non-process specific. Yet, we have trouble, as noted, in relating color-octet contributions in hadronic interactions to electromagnetic interactions. The direct charmonium production "K factors" do not look like "simple" higher order effects to me.

3.4. Thinking outside the box

This has all been thinking "inside the box". However, there is also "thinking outside the box". Ed Berger and his colleagues have noted the possibility that new physics could account for an excess of b production at the Tevatron [12]. They assume the existence of a low-mass color-octet, spin $1/2$ gluino and a low-mass color-triplet spin-0 bottom squark. Proton-antiproton collisions could produce pairs of the gluinos which can decay to bottom quarks and squarks. When they model the Tevatron excess, they find masses for the gluino of 12–16 GeV and for the bottom squark of 2–5.5 GeV. While this scenario is not standard mSUGRA or gauge mediated SUSY, it is consistent with all available constraints from precision measurements at the Z, from low-energy e^+e^- experiments, *etc.* Recent ALEPH analysis does require that the lifetime of the bottom squark be less than a nanosecond.

4. Partons in the light hadrons

In the hard scattering box, gluons dominate the heavy quark production process for incident hadrons. In the case of neutrino production, the dominant hard-scattering (via W exchange) occurs off strange quarks in the sea. Thus, fixed-target measurements of charm quark production can tell us about the nature and details of the partons in light hadrons. HERA measurements can tell us about the charm content of resolved γ's. Neutrino and anti-neutrino production of charm quarks can tell us about the strange anti-quarks and quarks in target nucleons. The observed charm particle distributions are sensitive to the parton distributions in the incident particles, as well as to hadronization effects and the hard scattering $\sigma_{c,\bar{c}}$ which produces the charm quarks in the first place.

4.1. Gluon distributions in mesons and nucleons

From D-meson production in Fermilab experiment E769, [13] it is clear that the longitudinal momentum production distributions for incident mesons (pions and kaons) are about the same, and much harder than that for incident protons. Given the dominance of gluon–gluon fusion in the production process, it is clear from simple kinematics alone that the gluon

distributions in pions and kaon are about the same, and that the gluons in these mesons, carry more momentum than those in baryons. This conclusion should be fairly independent of the details of the hard scattering and of the hadronization processes. Is it not reassuring that the gluons shared between two quarks typically would carry more momentum than the gluons shared among three quarks?

4.2. Strange quarks and antiquarks in the nucleon sea

In neutrino experiments, a strong opposite-sign dimuon signal is observed. We may expect that one muon (the higher momentum one) comes from the charged-current interaction, the other from a charm semileptonic decay. The dimuon cross section is dominated by strange quarks; the d-quark term is small, since $|V_{cd}|^2/|V_{cs}|^2 \sim 1/20$.

The most recent results come from NuTeV, E815 at Fermilab, an experiment using a high-energy, sign-selected, quadrupole-triplet, neutrino beam with a massive steel detector and from the previous CCFR experiment with the same detector. In the CCFR experiment, the beam is wide-band and undifferentiated by sign, thus mixing neutrinos and anti-neutrinos. The data analysis requires a comparison of data to Monte Carlo models of production and detector. Parameterization is needed (charm mass, fragmentation, and for the sea quark distribution of interest). Nevertheless, as summarized in Table II, the strange sea is measured to be $\sim 40\%$ of the non-strange sea. So far, the analysis is only done using a leading-order model [14].

TABLE II

Strange sea quarks as a fraction of the non-strange sea quarks.

	from ν	from $\overline{\nu}$
$k = 2s/(u+d)_{\mathrm{sea}}$	0.36 ± 0.05	0.38 ± 0.04

4.3. Experimental evidence on intrinsic charm

If there are strange quarks in the nucleon sea, why not charm quarks? Initially, significant numbers of charm quarks and antiquarks among the partons in the sea were proposed to explain apparently very large forward Λ_c production at CERN ISR experiments. These intrinsic charm quarks were suggested to carry 1–2% of the proton momentum. Such intrinsic charm pairs would be co-moving with the valence quarks of the parent projectile — making coalescence of valence and intrinsic charm quarks easy, and producing large particle/antiparticle asymmetries in the forward direction at low p_{t} [18]. So, intrinsic charm might have explained both forward

charm excesses and, combined with recombination effects, observed particle/antiparticle production asymmetries, However, differential cross sections for J/ψ production at high x_F from Fermilab experiment E789, limit intrinsic charm to less than 1% of this prediction (corresponding to less than 0.02% of proton) [15]. Furthermore, observed particle/antiparticle production asymmetries in hadroproduction appear to be essentially flat with p_t, [19] as in Pythia's modeling of the effect, but not as predicted by intrinsic charm models [19].

4.4. Intrinsic k_t

So far, we have focused mostly on the longitudinal parton distributions. What can we say about the transverse momentum distribution of partons in hadrons? The expression intrinsic "k_t" applies to this initial parton transverse momentum. It is cited as accounting for the very large final-state charm particle transverse momentum seen in experiments. However, the values for intrinsic k_t which result from analyses turn out to be unphysically large, 1 or 2 GeV or more, even for particles with rest masses below 1 GeV. Clearly, intrinsic k_t is a misnomer for something else. What is it?

Intrinsic k_t is used in models also to soften the back-to-back correlations of heavy-quark production, for example of D and anti-D production in fixed-target experiments. The smearing is significantly greater in hadroproduction, where there is k_t in both target and projectile, than in photoproduction, where there would be significant k_t only for the target. Detailed fits have not been performed. However, k_t of about 2 GeV is needed to explain hadroproduction smearing, [16] while 1 GeV seems to be about right for photoproduction [17]. See the presentation of Erik Gottschalk later in these proceedings [1].

5. Summary

There is a lot we can learn from heavy-flavor production in the large variety of environments to be covered at this Multiparticle Dynamics Symposium. We will see tests of QCD — the processes that matter, and how to treat them quantitatively. We will see fundamental quantities entering each process, and use the heavy quark to tag the processes of interest. On to the data and their interpretation!

REFERENCES

[1] E. Gottschalk (Fermilab – FOCUS), *Acta Phys. Pol. B* **35**, 85 (2004), these proceedings.
[2] M. Negrini (Ferrara – E835), *Acta Phys. Pol. B* **35**, 91 (2004), these proceedings.

[3] P. Pakhlov (Moscow, ITEP – BELLE), *Acta Phys. Pol. B* **35**, 97 (2004), these proceedings.

[4] A. Sciaba (Pisa – ALEPH), *Acta Phys. Pol. B* **35**, 101 (2004), these proceedings.

[5] Bob Olivier (DESY – H1), *Acta Phys. Pol. B* **35**, 107 (2004), these proceedings.

[6] K. Rinnert (Karlsruhe – CDF), *Acta Phys. Pol. B* **35**, 115 (2004), these proceedings.

[7] T. Mehen (Duke)*Acta Phys. Pol. B* **35**, 121 (2004), these proceedings.

[8] See link from http://conferences.fnal.gov/lp2003/program/index.html.

[9] H. Jung, *Phys. Rev.* **D65**, 034015 (2002) and also *Acta Phys. Pol. B* **35**, 247 (2004), these proceedings.

[10] H. Jung, private communication and to be published.

[11] E789 Collaboration, M.H. Schub *et al.*, *Phys. Rev.* **D52**, 1307 (1995).

[12] E. Berger *et al.*, *Phys. Rev. Lett.* **86**, 4231 (2001).

[13] E769 Collaboration, G.A. Alves *et al.*, *Phys. Rev. Lett.* **77**, 2392 (1996).

[14] NuTeV Collaboration, M. Goncharov *et al.*, *Phys. Rev.* **D64**, 112006 (2001).

[15] E789 Collaboration, M.S. Kowitt *et al.*, *Phys. Rev. Lett.* **72**, 1318 (1984).

[16] Fermilab E791 Collaboration, E.M. Aitala *et al.*, *Phys. Lett.* **B403**, 185 (1997).

[17] FOCUS Collaboration, J.M. Link *et al.*, *Phys. Lett.* **B566**, 51 (2003).

[18] R. Vogt, S.J. Brodsky, *Nucl. Phys.* **B478**, 311 (1996).

[19] Fermilab E791 Collaboration, E.M. Aitala *et al.*, *Phys. Lett.* **B371**, 157 (1996).