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Phenomenology of New Particle Production

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August 1980

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PHENOMENOLOGY OF NEW PARTICLE PRODUCTION

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ABSTRACT

Charm and beauty production on hadron targets are compared to parton models with QCD interactions.

INTRODUCTION

To make a manageable story this talk concentrates on the successes and failures of simple parton models for c and b production, via low-order QCD interactions. Theoretical papers have been appearing for years¹⁻²⁴; what's new in 1980 is that much better data have come along and much more significant comparisons can be made.

The special magic of charm and beauty is that they establish large mass scales, which we presume allow us to play with perturbative QCD (see Fig.1).

PHENOMENOLOGY OF NEW PARTICLE PRODUCTION *

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* Rapporteur talk at the XX International Conference on High Energy Physics, Madison, Wisconsin, July 1980.

Fig. 1 Charm allows us to play with perturbative QCD

cc PHOTOPRODUCTION

The lowest-order QCD process for both real³⁻⁹ and virtual^{8,15} photoproduction is gamma-gluon fusion: see Fig.2.

Fig. 2 γg fusion

$$\alpha_s(\mu^2) = 12\pi / [(33 - 2f) \ln(\mu^2/\Lambda^2)] \quad (1)$$

where $f = 4$ is the number of active flavours and the parameter Λ is usually set around $\Lambda = 0.5$ GeV (an assumption, not too critical).

The mass scale μ is often taken to be the $c\bar{c}$ invariant mass $m \equiv m(c\bar{c})$, but the alternative Q^2 -dependent form

$$\mu^2 = m^2 + Q^2 \quad (2)$$

is suggested by the following argument¹⁷. If a virtual photon of invariant mass square $-Q^2$ materializes as a pair of charmed quarks of mass square m^2 , it is off-shell by an amount $\Delta E = \sqrt{Q^2 + m^2}$ in the Breit frame. This large ΔE defines a short time and distance scale $\Delta t = 1/\Delta E$ within which things have to happen, corresponding to the large mass and momentum scale of Eq.(2). Furthermore Eq.(2) correctly gives $\mu^2 \sim Q^2$ for very large Q^2 . In principle we can find the best mass scale by calculating higher order contributions (see the talk by Llewellyn Smith) but this has not yet been done.

Bound $c\bar{c}$ production. A semilocal duality argument¹ suggests that production of $c\bar{c}$ pairs with invariant mass below the open charm threshold (i.e. with $2m_c < m < 2m_p$) corresponds to charmonium production of which a fixed fraction F is ψ . This gives

$$\sigma(\psi) = F \int_{2m_c}^{2m_p} \sigma(m) dm \quad (3)$$

where F is an empirical constant to be found from experiment. However, the $c\bar{c}$ invariant mass is not sacred¹⁰ and can very well be changed by the final hadronization process (we routinely allow massless quarks and gluons to materialize as massive hadrons). So the narrow duality interpretation seems out of place. Instead it is plausible to assume that the production of ψ is proportional to the density of $c\bar{c}$ states produced near the ψ mass, which gives effectively the same formula without dogmatic constraints (ref.22 gives a particular realization). In particular, the remaining fraction $1 - F$ can appear mostly as unbound charm states; rather

small fractions may be expected for ψ' (almost unbound) and χ_c (unfavoured quantum numbers).

Another approach^{10,18} is to assume charmonia are produced only by direct hard scattering processes such as $\gamma g \rightarrow \psi g$. Today however we shall use Eq.(3), and compare various $\gamma N \rightarrow \psi X$ data, looking at both ν and Q^2 dependence.

"Elastic" $\gamma N \rightarrow \psi X$. The muon experiments^{25,26} distinguish "elastic" events with little accompanying hadronic energy, typically $E_{HAD} < 5$ GeV; low energy real photon experiments²⁷ have similar cuts in acceptance. These data are well fitted by γg fusion plus Eq.(3); presumably this mechanism leads mostly to N and low N^* final states (a coherent nuclear peak is seen).

Figure 3 shows the cross section versus energy ν for real photons ($Q^2 = 0$); the two high-energy FNAL photoproduction points include inelastic events. The solid line is γg fusion with

$$G(\eta) = 3(1 - \eta)^5 / \eta \quad (4)$$

normalized to carry half the nucleon momentum as required by the momentum sum rule. With $F \approx 1/6$ we fit the ψ data²⁰.

Kinematics relates the gluon momentum fraction to the $c\bar{c}$ invariant mass m by $m^2 = 2m_N \eta - Q^2$. Hence by Eq.(3) production at given ν , Q^2 is controlled by $G(\eta)$ in a narrow band of η : thus the ν -dependence of $\sigma(\psi)$ directly determines^{19,20} the η -dependence of $G(\eta, m_\psi^2)$. This is shown on the axes in Fig.3, with G unnormalized. The dashed line is the broad gluon distribution²⁹

$$G(\eta) = (1 + 9\eta)(1 - \eta)^4 / \eta \quad (5)$$

believed to be approximately correct for mass scale $\mu^2 \approx 4 \text{ GeV}^2$; QCD evolution brings this to a shape somewhat similar to Eq.(4) at the scale $\mu^2 \approx 10 \text{ GeV}^2$ of present interest^{23,29}.

The shape of ηG falls between the CDHS³⁸ result $(1-\eta)^{5.3}$ at $Q^2 \approx 20$ and the CFS result $(1-\eta)^{4.1}$ at $Q^2 \approx 36$ (see Lefranc's talk).

Figure 4 shows the Q^2 dependence of $Q^2 d\sigma/dQ^2$ for muonproduction^{25,26}, averaged over ν and normalized to 1 at $Q^2 = 0$. The dotted line is the VMD prediction $(1 + Q^2/m_\psi^2)^{-2}$; the dashed line is γg fusion with Eq.(4) and $\alpha_s(m_\psi^2)$; the solid line has the extra Q^2 -dependence from taking $\alpha_s(m_\psi^2 + Q^2)$. In the narrow-mass-window approximation²⁰, the formulas for ψ production reduce to

$$Q^2 \frac{d\sigma}{dQ^2} \approx (\text{constant}) \alpha_s \frac{\eta G(\eta)}{(m_\psi^2 + Q^2)^2} \left[\frac{\nu}{4E^2} + \frac{E - \nu}{2\nu E} \right] \quad (6)$$

with $\eta = (m_\psi^2 + Q^2)/(2m_N \nu)$. Beside the standard VMD factor, this formula has Q^2 dependence from $\eta G(\eta)$ that looks after the threshold behaviour (ignored by VMD), and possible further Q^2 -dependence from α_s . There is excellent agreement with data.

Fig. 3 Elastic $\gamma N \rightarrow \psi X$ crosssection versus η (at $Q^2 = 0$)

Fig. 4 $Q^2 d\sigma/dQ^2$ ($\mu N \rightarrow \mu \psi X$) normalized to 1 at $Q^2 = 0$

In principle the Q^2 -dependence could provide an independent determination of $G(\eta)$ but the data shown are not adequate for this. However both the BFP and EMC groups find significant Q^2 dependence beyond the VMD factor.

"Inelastic" $\gamma N \rightarrow \psi X$. EMC's find inelastic ($E_{HAD} > 5$) production rates comparable to the elastic rates²⁶. Some of these events presumably come from ψ' production with $\psi \rightarrow \pi^0$ decay, but this can only explain a small fraction. The remainder may come from the next-order QCD subprocesses $\gamma g \rightarrow c\bar{c}g$ and $\gamma q \rightarrow c\bar{c}q$: see

order diagrams has a singularity near $p_T = 0$ and needs careful handling there. However, ref.24 gives results away from $p_T = 0$ that show a striking similarity to the data (the normalization shown is arbitrary but common to elastic and inelastic events, distinguished by E_{HAD}). It seems that inelastic and high- p_T elastic ψ production can probably be explained this way.

Open charm production. The lowest order process is still $\gamma g \rightarrow c\bar{c}$ but we now have to describe the final hadronization to $D\bar{D}^*$, $\Lambda_c^+ \bar{D}^0$, etc. At least two distinct types of hadronization pattern are imaginable, as shown in Fig.7:

Fig. 7 Possible hadronization patterns

A) Patterns that are flavour-disconnected from the target. In such cases we expect the $c\bar{c}$ pairs to hadronize rather like those produced in e^+e^- collisions; i.e. we should borrow fragmentation functions from SPEAR and work in the $c\bar{c}$ rest frame.

B) Patterns that are flavour-connected to the target. Such cases are more similar to neutrino production of charm, where a single produced c or $\bar{c}$ hadronizes on its own; i.e. we should borrow fragmentation functions from neutrino analyses and work in the c.m. or lab frame.

Which to choose? Data help us to decide. At large ν pattern A seems to dominate. The muon events of BFP and EMC collaborations apparently require $c\bar{c}$ to hadronize frequently into fast $D\bar{D}$ pairs carrying nearly all the energy^{25,26}. Also the E87A experiment³⁰ at the Fermilab wideband photon beam finds fast $D\bar{D}$ and $\Lambda_c^+ \bar{D}^0$ pair production (the latter at the 25% level similar to SPEAR) with $\langle E(\Lambda_c^+) \rangle = \frac{1}{2} \langle E(\gamma) \rangle$. Pattern B seems to be important at small ν however, not surprisingly since it offers a lower threshold. The CERN WA4 experiment³¹ at $\nu = 40-70$ GeV finds $D\bar{D}$ mesons and evidence of $\Lambda_c^+ D$ production but no sign of $D\bar{D}$ pairs. Also the WA58 emulsion experiment has a $\Lambda_c^+ D^0$ event in this range³².

$\gamma N \rightarrow c\bar{c} X$ data. We shall look at ν and Q^2 dependence - and also at normalization, since there is now no empirical factor F . The BFP group²⁵ have modelled their dimuon acceptance on the γg fusion model with D production and semileptonic decay, taking relative multiplicities and the fragmentation function from SPEAR data. They then convert their results directly into $c\bar{c}$ production cross sections and structure functions.

Fig. 5 Next-order QCD subprocesses

Fig.5. In these subprocesses the extra final gluon or quark carries away energy and also can give large p_T to the $c\bar{c}$ pair (unlike the lowest order process that is strictly collinear). Alternatively we can imagine that $c\bar{c}$ is produced by the lowest-order process, but sheds some energy during the soft hadronization phase; this however should not generate large p_T . Let experiment decide.

Fig. 6 Inelastic $\gamma N \rightarrow \psi X$ data²⁶ compared to next-order QCD²⁴

Figure 6 shows the p_T and z dependence of the EMC data; note there is quite a lot of p_T . The calculation of the next-

Figure 8 shows the BFP results for $\sigma(\gamma N \rightarrow c\bar{c}X)$ at $Q^2 \approx 1$ versus energy ν . The curve is a γg fusion calculation using Eq.(4) and including a contribution from the range $2m_c < m < 2m_D$; the absolute normalization has been adjusted by less than 20% - well within the theoretical uncertainties - to make a prettier picture.

Fig. 8 $\sigma(\gamma N \rightarrow c\bar{c}X)$ at $Q^2 = 1$ from ref. 25, compared to γg fusion.

Figure 9 shows the same cross section at $Q^2 = 0$, where the real photoproduction data can be included^{30,31}. The WA4 results have been split in three bins, pro rata to their p_0 results that show a threshold behaviour³¹; apart from their highest point there is a good agreement again with the γg fusion calculation (unadjusted).

Figure 10 gives $F_2(\gamma N \rightarrow c\bar{c}X)$ versus Q^2 at $\nu = 100$ and $\nu = 178$ GeV from BFP²⁵. The dotted line is the prediction of the Buras-Gaemers model³³ (using the empirical slow-rescaling variable $x' = (Q^2 + 4m_c^2)/(2m_N \nu)$); here it was assumed that the $c\bar{c}$ sea in the nucleon is negligible for $Q^2 < 1.8$ but evolves thereafter according to the QCD relations with $m_c = 0$, which evidently gives too much charm. The dashed line is a somewhat old-fashioned γg fusion

Fig.9 $\sigma(\gamma N \rightarrow c\bar{c}X)$ at $Q^2 = 0$ from refs.25,30,31 compared to γg fusion prediction, in which contributions from $m < 2m_D$ are excluded and α is defined at $\mu^2 = m^2$; as noticed by the experimenters²⁵, this is a bit unsatisfactory at large Q^2 . The solid line is a more modern γg fusion prediction in which 5/6 of the cross section from $m < 2m_D$ is included and α is defined at $\mu^2 = m^2 + Q^2$; this does much better.

The γg fusion curves are independently normalized to the data and both assume Eq.(4); ideally the Q^2 -dependence of $G(n)$ should be included too, and this would add a little more curvature still. Incidentally, the linear rise of F_2 at small Q^2 is simply kinematics and there are no prizes for fitting this part; a small departure from linearity at very small Q^2 may be an effect of nuclear shadowing³⁴.

The EMC results²⁶ for dimuon and trimuon production by muons are also well explained by the γg fusion model, when conventional backgrounds have been subtracted. This group do not extract F_2 but instead put the model into a Monte Carlo calculation of their acceptance, and compare directly to cut cross sections: Fig. 11 shows some of their dimuon data with γg fusion comparison.

The overall agreement is very encouraging, but remember (i) Higher orders are not yet included for open charm; they

Fig. 10 $F_2(\gamma N \rightarrow c \bar{c} X)$ from ref. 25 compared to models.

Fig. 11 Dimuon cross sections from ref. 26 compared to $\gamma\gamma$ fusion

account for perhaps half of ψ . Many distributions should remain rather similar but the normalization should change.

(ii) B-type hadronization has not been fitted in yet.

(iii) $\gamma\gamma$ fusion is not a complete theory: it is just a model for the cross section (not for the amplitude).

Further tests and extensions. The $\gamma\gamma$ fusion mechanism also predicts an asymmetry of the $c\bar{c}$ production plane relative to incident γ polarization. Both real²¹ and virtual³⁵ photon cases have been studied. This offers an interesting further test of the model - or alternatively a determination of the gluon spin - although the hadronization and decay processes will presumably blur the asymmetry somewhat.

A remarkable similarity between $\gamma\gamma$ fusion and triple-Regge models has been noticed³⁶ in the case of $s\bar{s}$ production. Although this is a marginal region for either model, it suggests a possible overlap of the $\gamma\gamma$ models that might prove useful.

In neutral current neutrino scattering, the direct analogue of

Fig. 12 Z_0 fusion

Fig. 13 Wg fusion

$\gamma\gamma$ fusion is the Z_0 fusion process shown in Fig. 12. This is interesting because it offers a direct probe of the $c\bar{c}$ sector of neutral currents, difficult to reach otherwise. Elastic ψ production can be calculated with the same input that successfully describes muonproduction. Unfortunately the predicted cross section times branching fraction is rather small, of order 2×10^{-6} of the charged-current cross section (averaging over the CERN 350 GeV wide-band beam)²⁰. The cross section is the same for ν and $\bar{\nu}$. See also ref. 18.

Another analogous process is charged-current antineutrino charm production $\bar{\nu}N \rightarrow \mu^+ c \bar{s} X$ where $\bar{c} \rightarrow \bar{s} \nu \ell^+$ decay leads to dileptons as usual. The lowest-order mechanism here is Wg fusion^{12,15}; Fig. 13 shows the dominant diagram with $\bar{s}$ exchange, but there is also a crossed diagram with c exchange. In effect we are making a model here for the $s\bar{s}$ sea, which is dangerous because the s -quark is relatively light and nonperturbative contributions may be expected. Nevertheless it is known to give cross sections in the right ballpark, and also has reasonable threshold behaviour automatically (no need for slow rescaling

variables or other cookery). Since we now have better data, it is interesting to make one more comparison. Figure 14 shows $d\sigma/dx dy$ in units $G^2 M E / \pi$ which is the same as $2x\bar{s}(x)$ in the parton model of charm production from the strange sea; the points are CDHS data³⁷ from dimuon events in the band $\nu = 40-80$; the curves are Wg fusion calculations using Eq. (4), with $m_g = 0.3$ and 0.5 GeV, calculated at $\nu = 63$ and $E = 100$ GeV. The model contains a small contribution from the crossed diagram; it also has an energy-dependence different from that of the naive parton model that was partly used in birthing the data. Nevertheless the agreement is remarkable and deserves further study. The analogue of $\gamma + \psi$ production here is $W^+ \rightarrow F^{*+}$ production, that would also be interesting to study when there are data. For $O(\alpha_s)$ corrections in general see ref. 38.

Fig. 14 $d\sigma/dx dy$ from $\bar{\nu}$ dimuons³⁷ and Wg fusion

The lowest-order QCD subprocesses for charm and beauty hadroproduction are shown in Fig.15 and variously calculated in refs.1-5, 9-11, 13, 14, 16, 18, 20, 22, 23. They include light $q\bar{q}$ fusion similar to Drell-Yan, and gg fusion similar to $\gamma\gamma$ fusion except for the addition of a three-gluon vertex diagram. The $q\bar{q}$ cross section is added incoherently to gg since it gives different kinds of final state.

Fig. 15 Lowest-order heavy flavour hadroproduction

The ingredients for a calculation are as before, plus q and $\bar{q}$ momentum distributions, that can be taken from deep inelastic lepton scattering analyses (for N) or from Drell-Yan analyses (for π , K).

ψ hadroproduction. We use a local-density argument leading to Eq.(3) as before. However we do not expect F to have the same numerical value as before, because²⁰

- i) F can be process-dependent. The colour-rearrangement and hadronization patterns in $\gamma N \rightarrow c\bar{c}X$ and $hN \rightarrow c\bar{c}X$ are quite different. They can also differ between $q\bar{q}$ and gg components.
- ii) F can include $\psi' \rightarrow \psi\pi\pi$ and $\chi \rightarrow \psi\gamma$ cascade contributions; the kinematics here differ a little but not dramatically.

Notice that the model prescribes both s -dependence and y -dependence (x_F -dependence) with only one adjustable function $G(\eta)$, so it is heavily overconstrained. Also the shape of $G(\eta)$ ought to agree with the photoproduction result above.

Figure 16 shows $d\sigma/dy(NN \rightarrow \psi X)$ at $y = 0$ compared to a lowest-order prediction²⁰ using the gluon distribution from photoproduction Eq.(4); there is a good fit using $F = 1/12$. Notice that the $q\bar{q}$ contribution is relatively small. At $y = 0$ there is an approximate point-to-point correspondence between s and the gluon momentum fraction η , $\eta \approx m_\psi/\sqrt{s}$; hence allowing for $q\bar{q}$ the data points can be converted directly into determinations of $G(\eta)$ within an overall normalization controlled by F .

Figure 17 shows a comparison of $nG(\eta)$ values determined in this way from $NN \rightarrow \psi$ at $y = 0$ with values determined from the $\gamma N \rightarrow \psi$ elastic cross section. The shapes agree nicely. At a given c.m. energy $\gamma N \rightarrow \psi$ probes smaller η than $NN \rightarrow \psi$, because the photon is hard; thus γN at $\sqrt{s} = 200$ GeV probes lower η than pp at the ISR.

Fig. 16 s -dependence of $B_{\psi\psi} d\sigma/dy(NN \rightarrow \psi X)$ at $y = 0$ compared²⁰ to the fusion model

Figure 18 shows that the x_F -dependence in NN scattering at 225 and 400 GeV/c and NN scattering at 225 GeV/c is consistent with the same model using $F = 1/9$, $1/12$, $1/12$ respectively²⁰. Fluctuations in F may be attributed to normalization problems in the data (notice for example the data fluctuations in Fig.16). When we take account of the intrinsic p_T carried by the initial quarks and gluons, the simple $q\bar{q}$ plus gg fusion mechanisms above only make sense in the range³⁹

$$s \langle p_T^2 \rangle x_F^2 < m_\psi^4 \quad (7)$$

(A similar limit applies to Drell-Yan). Conservatively assuming $\langle p_T^2 \rangle \lesssim 1$ GeV², this requires e.g. $|x_F| < 0.5$ for 200 GeV beams on a fixed target. At larger x_F , processes where both partons come from the same hadron become important.

Fig. 17 Comparison of $\eta G(\eta)$ extracted from νN and NN data

For $\pi N \rightarrow \psi X$ and $KN \rightarrow \psi X$ the new ingredients are the gluon distributions within π and K , that we can hope to extract. There are not enough data to exploit the s -dependence, but we can extract $G(\eta)$ from the x_F -dependence instead. K^+ is better than K^- because the $q\bar{q}$ term is minimized. Figure 19 shows a log-log plot of $\eta G(\eta)$ versus $1 - \eta$, where $d\sigma/dx_F$ data have been translated directly into G for π and K^+ separately, taking the q , $\bar{q}$ and G_N distributions as known. On this plot simple power parameterizations

Fig. 18 x_F -dependence of $NN \rightarrow \psi X$, $\bar{N}N \rightarrow \psi X$ in the fusion model²⁰.

$$G \sim (1 - \eta)^n / \eta$$

(8)

appear as straight lines; the value $n = 3$ gives approximate fits to both π and K^+ cases²⁰.

Fig. 19 Determinations of $G_\pi(n)$ and $G_K(n)$ from πN and KN data²⁰

Figure 20 shows $d\sigma/dx_F$ for $\pi N \rightarrow \psi X$ at 240, 225, 39.5 GeV/c and $K^+ N \rightarrow \psi X$ at 225 GeV/c, compared to the model with $n = 3$ for mesons and $n = 5$ for nucleons as before (using $F = 1/14, 1/12, 1/6, 1/12$ respectively). The shapes agree well, remembering Eq.(7).

Hadronproduction. The same model can be applied to $b\bar{b}$ production, modifying the quark mass and the mass scale μ^2 accordingly. The most extensive data are $NN \rightarrow (\Upsilon + \Upsilon' + \Upsilon'')X$ near $y = 0$. The energy dependence can be fitted by a gluon distribution of simple power form Eq.(8) with $n = 6$, as seen in Fig.21. Alternatives we can convert the cross sections directly into determinations of $G(n)$, $\mu^2 = 100$ for the nucleon, as shown in Fig.22.

It may seem surprising that the shape has changed so little between $\mu^2 = 10$ (the ψ case) and the present $\mu^2 = 100$. However Fig. 22 also shows the μ^2 -evolution expected⁴⁰ over this range for a typical choice of parameters, starting with Eq.(4) at $\mu^2 = 10$. The result is certainly compatible with the extracted $G(n)$ shape at $\mu^2 = 100$, but also suggests that the true shape here is not a simple power formula like Eq.(8).

Open $c\bar{c}$ hadronproduction. Now we come to the bad news. The important new ingredient here is the hadronization, which is empirical and quite outside perturbative QCD, so we start by looking at the data. Instantly we meet two problems.

First problem: the model predictions for total charm production - assumed to be independent of hadronization details - are

Fig. 20 x_F -dependence of $\pi N \rightarrow \psi X$, $K^+ N \rightarrow \psi X$ in the fusion model²⁰

Fig. 21 s-dependence of $B_{\mu\mu}$ $d\sigma/dy(NN \rightarrow T + T' + T''X; y=0)$ compared to the fusion model.

too small. Figures 23 and 24 show the $\pi N + c\bar{c}X$ and $NN + c\bar{c}X$ cross sections from available sources⁴¹⁻⁵¹ compared to $q\bar{q}$ plus gg fusion predictions, using Eq.(4) and allowing contributions from $m < 2m_D$. Getting these cross sections from incomplete data is model dependent; however the values shown are generally the smallest possible. Various remedies have been considered.

i) Reduce m to 1.2 GeV, say^{10,22,23}. We gain a factor 4 or so, see Figs. 23,24, but simultaneously spoil the nice agreement with photoproduction.

ii) Nonperturbative enhancements^{6,7}. This is a possible escape (there is controversy about a particular model^{6,52,53}) but why should there not be equally strong enhancements in γN ?

iii) Increase α_s . This has the attractive feature that hadron-hadron interactions (α_s^2) could be enhanced relative to $\gamma N(\alpha_s)$. But it would require scaling α_s at a much smaller μ^2/Λ^2 and there is only limited scope in this direction.

iv) Maybe higher-order corrections are much bigger for hadron-hadron than for γN ? Perhaps, but no solid argument or calculation has yet appeared.

Fig. 22 $nG(\eta)$ at $\mu^2 = m_\gamma^2$ is compatible with QCD evolution.

To summarize, no single clear solution has yet emerged.

Second problem: the model gives rather central $c\bar{c}$ production (just right for the ψ case) whereas open charm production occurs copiously at large x_F . Figure 25 shows the x_F -dependence of $pp \rightarrow A_c^+ X$ production measured by the Lampshade Magnet⁴⁵, UCLA-Saclay⁴⁶ and Split-Field Magnet⁴⁷ groups at the CERN ISR, compared with ordinary Λ^0 production⁵⁴ and with the $q\bar{q} + gg$ fusion model predictions for c -quark production (using $m_c = 1.5$ plus Eq.(4) and including a contribution from $m < 2m_D$). Notice the fierce log

Fig. 23 $\sigma(\pi N \rightarrow c\bar{c}X)$ open charm production versus $\sqrt{s}$, from refs. 41-43. The $b\bar{b}$ upper limit is from ref. 44.

Fig. 24 $\sigma(NN \rightarrow c\bar{c}X)$ open charm production versus $\sqrt{s}$.

scale on the ordinate; at $x \sim 0.6$ the bare quark production is three or more orders of magnitude below the Λ_c^+ data. Remedies?

i) Maybe hadronization puts it right? We can imagine a slow c -quark being picked up by fast valence u and d quarks in one of the incident protons to make a fast final Λ_c^+ . This is the Recombination Model⁵⁵ and it has the right features to explain the leading Λ_c^+ production all right. But for Λ_c^+ production it incorporates a recombination function

$$R(x_c/x, x_u/x, x_d/x)$$

Fig. 25 x_F -dependence of Λ^0 and Λ_c^+ production at ISR

that should reflect the composition of Λ_c^+ , in which the valence c -quark is expected to carry a large fraction of the momentum⁵⁶. Thus R should favour substantial x_c/x , disfavour small x_c/x , making it hard to convert a central c -quark into a leading baryon; the Λ_c^+ data however do not look suppressed! Furthermore fast $D^+(c\bar{d})$ mesons are seen⁴⁷, whereas $\bar{d}$ is not a fast valence quark.

Other soft hadronization mechanisms are not expected to accelerate the original c and $\bar{c}$, nor to form fast $c\bar{c}$ pairs from the vacuum. ii) Postulate a (undec⁵⁷) five-quark Fock component in the incident proton wave function⁵⁷. Such a component would be relatively long-lived. Hence, because of their large masses, the c and $\bar{c}$ would be expected⁵⁶ to carry large momentum fractions - 2/7 each in the

Fig. 26 c -quark probability distribution from ref.57

And what about deep inelastic muon scattering data, that measures $F_2(\text{charm}) \approx (8/9)x_c(x)$ in the parton model? There is already borderline conflict between BFP data²⁵ and the model above, shown in Fig. 27. The data we met already; the dashed lines are the naive parton prediction for the model using standard $x = Q^2/(2m_N\nu)$; the solid lines are model predictions using the slow rescaling variable $x' = (Q^2 + 4m_c^2)/(2m_N\nu)$ instead. The model predictions are presumably additive to the QCD contributions previously shown in Fig.10.

The model almost escapes confrontation with experiment here, because c and $\bar{c}$ are at large x and hence large Q^2 , where the cross section is suppressed. (Going to smaller ν helps, but eventually there is the threshold). However, the experiment has acceptance well beyond the published data points³⁴, so the confrontation can probably be sharpened. The EMC results should also be analyzed in these terms.

CONCLUSIONS

The models considered are parton models with low-order QCD interactions, not complete theories. The hadronization stage, for example, is empirical. However they have fewer parameters than constraints; there are many correlations between ν - and Q^2 -dependences, between s - and x_F -dependences, between one reaction and another. Their successes therefore look significant.

There are problems in understanding hadroproduction of open charm, but these may be outside perturbative QCD - to do rather with final state interactions, wave functions, etc. We do not yet know enough experimentally to pinpoint the problems.

These parton-QCD models are helpful and physically appealing. It seems worthwhile to push them as far as they will go.

model of ref. 57; Fig. 26 shows the probability distribution $c(x)$ for this model, where the integrated probability is about 0.01 per nucleon. The idea is that in pp collisions a (udc) or (uuc) subsystem could be shaken off to form a leading charmed baryon - nothing to do with hard QCD at all.

But how do we simultaneously forbid leading ψ production that is not seen? It may be a difficulty.

Fig. 27 $F_2(\text{charm})$ from BFP compared to the model of ref.57

ACKNOWLEDGEMENT

I am grateful to many colleagues at Rutherford, Madison and elsewhere for helpful discussions and for early information about their results. Special thanks are due to Vernon Barger and Wai Yee Keung.

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