CORRELATION OF CHARM PARTICLES FROM GLUTON-GLUON
FUSION IN HADRONIC COLLISIONS

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ABSTRACT

In the framework of fusion process, \( \approx 90\% \) of which is \( g + g \rightarrow c + \bar{c} \), we have calculated rapidity correlation and \( p_T^2 \) of charm particles produced in hadronic collisions. The experimental observation of rapidity correlation by the LEBE-EHS Collaboration is in good agreement with the calculation. From the ratio of double to single charm production an estimate of fusion cross section is made.

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1. INTRODUCTION

There are two production mechanisms which are generally considered to be responsible for the associated production of charm states in hadronic interactions. These are, see fig. 1,

(a) fusion process

\[ g + g \rightarrow c + \bar{c}, \quad q + \bar{q} \rightarrow c + \bar{c}, \]  

(1)

and (b) flavour excitation process

\[ g + c \rightarrow g + c, \quad q + c \rightarrow q + c, \quad \bar{q} + c \rightarrow \bar{q} + c. \]  

(2)

These have been used extensively for the study of production cross sections and \( x \) distributions of charm hadrons, see for example refs [1-4]. The relative importance of the two mechanisms is still not clear. The reasons are the following: (a) the cross section depends strongly on the choice of \( M_{\text{c}} \), the mass of the charm quark, and \( \Lambda_c \), the strong coupling parameter, (b) the excitation process has additional problems due to poor knowledge of the charm structure function and the choice of \( L_{\text{min}} \) - the minimum momentum transfer of the gluon needed to excite a \( c\bar{c} \) pair; it is also not clear whether the excitation process is distinct from the fusion one [1,4] and (c) the poor understanding of the recombination/fragmentation of the charm quark to form a \( D \) or \( \Lambda_c^+ \) hadron.

It is conceivable that the problem (c) mentioned above is minimal for the study of the correlation between the \( D \bar{D} \) pair (\( \Lambda_c^+D \) is more complicated because of one extra quark in \( \Lambda_c^+ \) compared to \( D \)). The \( p_T^2 \) distribution of the charm quark is also expected to be nearly the same as that of \( D/\bar{D}/\Lambda_c^+ \) because of the massiveness of the charm quark. In this paper we would like to exploit the above argument to see how far one can understand the production of charm particles in the framework of the fusion process (without incorporating fragmentation/recombination) by comparing with the existing data. In sect. 2 we describe the details of the calculation. Numerical results and the comparison with the data are presented in sect. 3. In sect. 4 we have made an attempt to estimate the fusion cross section from the experimental data at \( \sqrt{s} = 26 \) GeV [5] and the summary in sect. 5.
2. DETAILS OF THE CALCULATION

The cross section for the production of a pair of charm quarks in a
hadron-hadron collision is given by

\[ \sigma_{cc} = \int dx_1 dx_2 F_{1/A}(x_1, Q^2) F_{2/B}(x_2, Q^2) \cdot \frac{1}{x_1 x_2} \frac{d\hat{s}}{d\hat{t}} \cdot d\hat{t} \]  \hspace{1cm} (3)

where \( \hat{s} \) is the cross section for the subprocess \( 1 + 2 \rightarrow 3 + 4 \) and the
total cross section is obtained by summing over all the distinct sub-
processes as given by (1) and (2); \( \hat{t} \) is the square of the 4-momentum
transfer between partons 1 and 3. The structure functions \( F_{1/A} \) and
\( F_{2/B} \) are the fractional momentum distributions of the partons inside the
hadrons A and B; \( x_1 \) and \( x_2 \) are the momentum fractions carried by the
partons 1 and 2 (0 < \( x_1, x_2 < 1 \)). In terms of the variables \( x_L \) and \( \hat{s} \),

\[ x_L = x_1 - x_2, \hspace{1cm} (-1 < x_L < +1) \]

\[ \hat{s} = s x_1 x_2 \]  \hspace{1cm} (4)

with \( x_L \) as the forward longitudinal momentum of the two partons 1 and 2,
and \( \hat{s} \) as the subprocess energy in the fusion process, the eq. (3) can be
rewritten as

\[ \sigma_{cc} = \int_{s_{th}}^{+\infty} ds \cdot s_{th}^{-\frac{1}{2}} \cdot F_{1/A} \cdot F_{2/B} \cdot \frac{1}{s(x_1 x_2)} \cdot \frac{d\hat{s}}{d\hat{t}} \cdot d\hat{t} \]  \hspace{1cm} (5)

where \( s \) is the square of the c.m. energy of the initial hadrons A and B.
The threshold value \( s_{th} \) of \( \hat{s} \) is taken as \( 4M_c^2 \) with \( M_c \) mass of the charm
quark and the \( Q^2 \) has been taken [1] as \( \hat{s}/2 \) for \( gg \rightarrow cc \) and \( \hat{s} \) for \( q\bar{q} \rightarrow cc \).

The \( Q^2 \) scale enters in the calculation through the structure functions and
the QCD running coupling constant \( \alpha(Q^2) = 12\pi/[25 \ln(Q^2/\Lambda^2)] \).  

In the c.m. system of the initial hadrons A and B, we define
\( x_3 = 2p_{3\perp}/\sqrt{s} \) and \( x_4 = 2p_{4\perp}/\sqrt{s} \) for the final charm pairs 3 and 4; the
corresponding rapidities are \( y_3 \) and \( y_4 \). The double differential
cross sections for the fusion process are then given by (see Appendix for
the derivations)
\[ \frac{d^2 \sigma}{dx_1 dx_2} = \int d\hat{s} \frac{F_{1/A}(x_1, Q^2) \cdot F_{2/B}(x_2, Q^2)}{(x_L^2 + 4\hat{s}/s)} \frac{d\sigma}{d\hat{t}} \]  \space (6)

\[ \frac{d^2 \sigma}{dy_1 dy_2} = \int dp_T^2 \cdot F_{1/A}(x_1, Q^2) \cdot F_{2/B}(x_2, Q^2) \frac{d\sigma}{d\hat{t}} \]  \space (7)

where \( p_T^2 \) is the transverse momentum squared of the partons 3 and 4. The expressions for \( d\sigma/d\hat{t} \) are taken from ref. [1]. The variables \( x_L \) and \( \hat{s} \) are related to the kinematic variables of the outgoing charm quarks by the following expressions

\[ x_L = x_3 + x_4 \]

\[ x_{3,4} = 2 \cdot \hat{s}^{-1/2} \cdot (M_C^2 + p_T^2)^{1/2} \cdot \sinh y_{3,4} \]

\[ \hat{s} = 2(M_C^2 + p_T^2)[1 + \cosh(y_3 - y_4)] \]  \space (8)

From eqs (4) and (8) one can obtain the value of \( x_{1,2} \) required for the structure functions in terms of \( x_{3,4} \) (or \( y_{3,4} \)).

3. NUMERICAL RESULTS

The numerical calculations are carried out for the fusion process by using the following parametrizations of the structure functions:

(a) Proton

(\textsuperscript{(*)}) Valence quarks: parametrization of Buras and Gaemers [6], sea quarks: Owens and Reya [7] and gluons: from the neutrino data of the CDHS Collaboration [8].

(b) Pion: We have used counting rule distributions for valence, sea and gluons corrected by the QCD \( Q^2 \) dependence [7].

\textsuperscript{(*)} It may be mentioned that the total fractional momentum from these structure functions turns out to be 1.11. As the major contribution to the fusion process is due to the gluons (\( \approx 90\% \)) we have not made any attempt to normalise the total fractional momentum to unity.
The calculation of the cross section, as mentioned in sect. 1, depends strongly on the values of $M_C$ and $\Lambda$; in order to see the effects we have used for $M_C$ values in the range 1.2 to 1.5 GeV and for $\Lambda$ in the range 0.2 to 0.5 GeV (the variation in $\Lambda$ matters only for the absolute value of the cross section).

3.1 Rapidity gap

No significant difference is found in the calculated rapidity gap, $\Delta y = |y_1 - y_2|$, distributions from $\pi p$ and $pp$ collisions. Figs 2(a)–2(c) show these distributions from $pp$ collisions at $\sqrt{s} = 26$ and 62 GeV. $\Delta y$, $\Delta y_{FOR}$ and $\Delta y_{F-B}$ in these distributions refer respectively to the overall rapidity gap, the rapidity gap with both the charm quarks in the forward hemisphere in the $A-B$ c.m. system, and the rapidity gap with the two charm quarks in opposite hemispheres. The forward direction is taken to be the beam direction. The solid curves (with $M_C = 1.2$ GeV) and the dashed curves (with $M_C = 1.5$ GeV) are for $\sqrt{s} = 26$ GeV, and the dotted curves (with $M_C = 1.2$ GeV) are for $\sqrt{s} = 62$ GeV. It is seen from the figures that (a) the distributions are not sensitive to the choice of $M_C$ in the range 1.2 to 1.5 GeV and (b) rapidity gap broadens with the increase of energy.

Table 1 summarises the average values of the rapidity gaps for the three above mentioned configurations of the $c\bar{c}$ pair; $\langle \Delta y \rangle$ as obtained here for $\pi p$ (column 2) is in agreement with the calculation of ref. [9]. We have also listed in the table the fraction of events expected with both the charm quarks in the forward hemisphere.

The only result that exists for the rapidity gap is that of the LEBC-EHS Collaboration [5] at $\sqrt{s} = 26$ GeV. They have observed 5 $D\bar{D}$ pairs with both charm mesons in the forward hemisphere in the $\pi^-$ $p$ data and 1 in the $pp$ data. The mean rapidity gap observed in the $\pi p$ data from the 5 $D\bar{D}$ pairs is $\gamma = 0.5$ which is in good agreement with our calculation of 0.56, see column 4 of table 1.
3.2 $x$ and $p_T^x$ distribution

Figs 3(a) and 3(b) show the Feynman $x$ distributions of the charm quark (with $M_C = 1.2$ GeV) in $\bar{p}p$ and $pp$ collisions at $\sqrt{s} = 26$ GeV and are compared with the charm meson distributions as observed by the LEBC-EHS Collaboration. It is seen from the figures that the calculated $x$ distributions (without incorporating hadronization of the charm quark to form $D$ mesons) are not in good agreement with the data.

No significant difference is found between the calculated $p_T^x$ distribution of the charm quark in $\bar{p}p$ and $pp$ collisions namely, the $<p_T^x>$ from $\bar{p}p$ and $pp$ collisions at $\sqrt{s} = 26$ GeV are found to be 0.747 and 0.750 (GeV/c)$^2$ for the choice of $M_C = 1.2$ GeV. In fig. 4 we show the $p_T^x$ distributions for $\sqrt{s} = 26$ and 62 GeV with $M_C = 1.2$ GeV; for $p_T^x \leq 3$ (GeV/c)$^2$ the distributions are reasonably exponential. The calculated values of $<p_T^x>$ for the choice of $M_C$ in the range 1.2 to 1.5 GeV are,

$$<p_T^x> = 0.75 - 1.0 \text{ (GeV/c)}^2 \text{ at } \sqrt{s} = 26 \text{ GeV},$$

$$<p_T^x> = 1.0 - 1.4 \text{ (GeV/c)}^2 \text{ at } \sqrt{s} = 62 \text{ GeV}.$$  

These values are in reasonable agreement with the experimental data of $D/\bar{D}$ production which give $<p_T^x> = 0.9 \pm 0.2 \text{ (GeV/c)}^2$ at $\sqrt{s} = 26$ GeV [5] and $<p_T^x> \sim 0.9 \text{ GeV/c}$ at $\sqrt{s} = 62$ GeV [10].

4. ESTIMATION OF FUSION CROSS SECTION

In the previous section we have seen that the rapidity gap and $p_T$ distribution of the experimentally observed charm mesons can be explained in terms of the fusion process. The next obvious point is to estimate the fusion cross section. This can be deduced from the experimental ratio of double to single charm production in the forward hemisphere. The expected ratio from the fusion process (column 6 of table 1) is 0.6 to 0.7 at $\sqrt{s} = 26$ GeV. The last column of table 1 gives the experimental data at $\sqrt{s} = 26$ GeV. Clearly this number is a lower estimate because (a) more topological pairs are seen [5] but they cannot be reconstructed because more than one decay particles are outside the spectrometer acceptance, and (b) $\Lambda_c^+ \bar{D}$ pairs are not seen probably
because $\Lambda_+^c$ has too short a lifetime ($\sim 10^{-11}$ s) to be distinctly visible in LEBE; this also explains why one sees less pairs in pp collisions compared to $\pi p$. We therefore estimate a lower limit on the contribution of the fusion process in $\pi p$ collisions (with the assumption\(*) that the charm pairs in the forward hemisphere are all due to this process) and it is \(\gtrsim 70\%\), i.e. the total fusion cross section is \(\gtrsim 30 \, \text{nb} \) at $\sqrt{s} = 26 \, \text{GeV}$. A note of caution: the result is based on poor statistics.

We now evaluate the fusion cross section by making numerical integration of eq. (3). Because of the dominance of the gluon-gluon fusion ($\gtrsim 90\%$) the results from $\pi p$ and pp collisions are essentially the same within 10%. The numerical results are therefore presented in table 2 for pp collisions at $\sqrt{s} = 26$ and 62 GeV. For the sake of completeness we have also presented the cross sections from the excitation process based on the prescription of ref. [1] with charm structure function of ref. [6] and with $\hat{s} = M_c^2 + s x_1 x_2$; for the excitation process $\hat{t}_{\text{min}} = 2M_c^2$ is preferred [11]. The effects on the cross section due to variation in the values of $M_c$, $A$ and $\hat{t}_{\text{min}}$ are clearly seen from the table. It is interesting to note that one could get charm production cross section of 38 and 140 nb - with $M_c = 1.2$ GeV and $A = 0.5$ GeV - from fusion process at $\sqrt{s} = 26$ and 62 GeV respectively, which are not too low.

5. SUMMARY

In this paper we have made an attempt to see to what extent the fusion process can explain charm production in hadronic collisions. We have not incorporated recombination/fragmentation of the charm quark; this could be the reason for obtaining a steeper $x$ distribution than the experimental data. As regards rapidity gap and $p_T$ distributions we believe that this effect is minimal. Indeed we find that our calculated values are in good agreement with the existing data. We have also made an estimate of

\(*) It may be noted that in the excitation process according to the QCD Monte-Carlo calculation of Odorico [3] the struck and the spectator charm quark fall in opposite hemisphere at these energies.
the fusion cross section as \( \gtrsim 30 \, \mu \text{b} \) at \( \sqrt{s} = 26 \, \text{GeV} \) by comparing the experimental ratio of double to single charm production in the forward hemisphere with the calculated one, but much better experimental data are needed before a firm conclusion can be drawn. The expected value of the fusion cross section at this energy is 38 \( \mu \text{b} \) with the choice of \( M_c \) as 1.2 \( \text{GeV} \) and \( \Lambda \) as 0.5 \( \text{GeV} \).

Acknowledgements

One of us (S.N.C.) would like to thank Drs L. Montanet and S. Reucroft for the warm hospitality given to him in the CERN EHS group.
Derivation of the double differential distributions in terms of $x$, $y$ and $p_T$ for $c\bar{c}$ in fusion process:

In the fusion process $1 + 2 \rightarrow 3 + 4$, where 3 and 4 are the $c\bar{c}$ pair and 1 and 2 are the massless colliding partons with the $+ve$ z axis along the parton 1, the square of the 4 momentum transfer between 1 and 3 can be written in the 1-2 c.m. system as,

$$t = M_c^2 - 2E_1E_3 + 2p_1\cdot p_3$$

$$= M_c^2 - \hat{s}/2 + \sqrt{\hat{s}} \cdot p_3^*$$

(A1)

where $\hat{s}$ is the square of the c.m. energy of the 1-2 system and $M_c$ the mass of the $c$ quark. We neglect transverse momentum of the colliding partons. We now express $p_3^*$ in terms of variables defined in the c.m. system of the initial hadrons A and B using the Lorentz factors,

$$\gamma = (x_1 + x_2)(s/4\hat{s})^{1/2}$$

$$\gamma_8 = (x_1 - x_2)(s/4\hat{s})^{1/2}$$

(A2)

where $x_1$ and $x_2$ are the momentum fractions carried by the partons 1 and 2 in the A-B c.m. system and $s$ is c.m. energy square of the A-B system

$$p_3^* = \gamma(p_{3\gamma} - \gamma_8 E_3)/(1 + \gamma_8^2)$$

$$= \frac{1}{2} \gamma (\sqrt{s} x_3 - \gamma_8 \sqrt{\hat{s}})/(1 + \gamma_8^2)$$

(A3)

where $x_3$ is the Feynman $x$ value of the charm quark 3. Substituting the above expression in (A1) we get

$$\hat{t} = M_c^2 + s.(x_3 - x_1).\frac{x_1x_2}{(x_1 + x_2)}$$

(A4)

which is in agreement with that of ref. [2].
Now using (A4) and eq. (5) of sect. 2 we have the following form for the double differential distribution

$$\frac{d^2\sigma}{dx_Ldx^*} = \int d\hat{s} \cdot \frac{F_{1/A}F_{2/B}}{(x_1 + x_2)^2} \cdot \frac{d\hat{\sigma}}{\hat{d}t}$$

since $x_L = x_1 + x_2$, where we define $x_2$ as the Feynman $x$ for the charm quark 4 in the A-B c.m. system, we get

$$\frac{d^2\sigma}{dx_1dx_2} = \int d\hat{s} \cdot \frac{F_{1/A}F_{2/B}}{(x_1 + x_2)^2} \cdot \frac{d\hat{\sigma}}{\hat{d}t} \quad (A5)$$

Similarly, using the reactions

$$x_1, x_2 = 2s^{1/2} \cdot \hat{M} \sinh y_1, y_2$$

$$\hat{M} = (M_C^2 + p_T^2)^{1/2}$$

we obtain the following form for $x_L$

$$x_L = 2s^{1/2} \cdot \hat{M} (\sinh y_1 + \sinh y_2)$$

The differential distribution in terms of $y_1$ and $y_2$ is then given by

$$\frac{d^2\sigma}{dy_1dy_2} = \int d\hat{s} \cdot \frac{F_{1/A}F_{2/B}}{s(x_1 + x_2)^2} \cdot 4\hat{M}^2 \cosh y_1 \cosh y_2 \cdot \frac{d\hat{\sigma}}{\hat{d}t} \quad (A6)$$

Eq. (8) of sect. 2 yields

$$\frac{d\hat{\sigma}}{dp_T^2} = \frac{\left(\cosh y_1 + \cosh y_2\right)^2}{\cosh y_1 \cdot \cosh y_2}$$

substituting this in eq. (A6) we have the form

$$\frac{d^2\sigma}{dy_1dy_2} = \int dp_T^2 \cdot F_{1/A}F_{2/B} \cdot \frac{d\hat{\sigma}}{\hat{d}t} \quad (A7)$$

which is in agreement with ref. [4]. The $p_T^2$ distribution can be obtained from this by integrating over $y_1$ and $y_2$. 
REFERENCES


TABLE 1
Correlation of charm particles(*)

<table>
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<tr>
<th>(\sqrt{s}) (GeV)</th>
<th>(&lt;\Delta y&gt;)</th>
<th>(&lt;\Delta y&gt;)_{F-B one forward and the other backward}</th>
<th>(&lt;\Delta y&gt;)_{For both forward}</th>
<th>Fraction of cc with both in forward hemisphere</th>
<th>Ratio of double to single charm in forward hemisphere</th>
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</thead>
<tbody>
<tr>
<td>26 ((\pi^- p))</td>
<td>0.83</td>
<td>1.21</td>
<td>0.56</td>
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<td>1.20</td>
<td>0.53</td>
<td>0.28</td>
<td>0.6</td>
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<td>0.72</td>
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<td></td>
<td>(1/19 \ [5])</td>
</tr>
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</table>

(*) Calculated values are averaged over \(M_C = 1.2\) and \(1.5\) GeV.
TABLE 2

Charm production cross section in pp collisions

(a) Effect of $M_c$ (with $\Lambda = 0.5$ GeV, $\hat{t}_{\min} = 2 M_c^2$)

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (GeV)</th>
<th>$M_c$ (GeV)</th>
<th>Fusion (µb)</th>
<th>Excitation (µb)</th>
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<td>34</td>
</tr>
<tr>
<td></td>
<td>1.3</td>
<td>25</td>
<td>22</td>
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<td>1.5</td>
<td>11</td>
<td>10</td>
</tr>
<tr>
<td>62</td>
<td>1.2</td>
<td>140</td>
<td>244</td>
</tr>
<tr>
<td></td>
<td>1.3</td>
<td>100</td>
<td>177</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>55</td>
<td>97</td>
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</table>

(b) Effect of $\Lambda$ (with $M_c = 1.2$ GeV, $\hat{t}_{\min} = 2 M_c^2$)

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (GeV)</th>
<th>$\Lambda$ (GeV)</th>
<th>Fusion (µb)</th>
<th>Excitation (µb)</th>
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<td>26</td>
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<td>15</td>
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</tr>
<tr>
<td></td>
<td>0.3</td>
<td>21</td>
<td>15</td>
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<td></td>
<td>0.3</td>
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<td></td>
<td>0.5</td>
<td>140</td>
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</tbody>
</table>

(c) Effect of $\hat{t}_{\min}$ (with $M_c = 1.2$ GeV, $\Lambda = 0.5$ GeV)

<table>
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<th>$\hat{t}_{\min}$</th>
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<td>38</td>
<td>126</td>
</tr>
<tr>
<td></td>
<td>1.5 $M_c^2$</td>
<td>38</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td>2 $M_c^2$</td>
<td>38</td>
<td>34</td>
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<td>$M_c^2$</td>
<td>140</td>
<td>733</td>
</tr>
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<td></td>
<td>1.5 $M_c^2$</td>
<td>140</td>
<td>399</td>
</tr>
<tr>
<td></td>
<td>2 $M_c^2$</td>
<td>140</td>
<td>244</td>
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FIGURE CAPTIONS

Fig. 1  Schematic diagrams for charm production from (a) fusion process: 
\[ g + g + c + \bar{c} \text{ and } q + \bar{q} + c + \bar{c} \], and (b) excitation process: 
\[ g + c + g + c \text{ and } q + c + q + c. \]

Fig. 2  Rapidity gap distributions of charm pairs from pp + c\bar{c} + X, (a) 
all charm quark pairs, (b) both charm quarks in the forward 
hemisphere and (c) charm quarks in opposite hemispheres. The 
solid curves (with \[ M_c = 1.2 \text{ GeV} \]) and the dashed curves (with 
\[ M_c = 1.5 \text{ GeV} \]) are for \( \sqrt{s} = 26 \text{ GeV} \); and the dotted curves 
(with \[ M_c = 1.2 \text{ GeV} \]) are for \( \sqrt{s} = 62 \text{ GeV} \).

Fig. 3  Feynman x distributions of charm for (a) \( p\bar{p} \) interactions and 
(b) pp interactions at \( \sqrt{s} = 26 \text{ GeV} \). The curves present the 
calculations as described in the text, with \[ M_c = 1.2 \text{ GeV} \] and 
\[ \Lambda = 0.5 \text{ GeV} \]. The histograms are experimental data from 
ref. [5]. The curves are normalized to the same total number of 
events as the data.

Fig. 4  \( p_T \) distributions of charm quarks at \( \sqrt{s} = 26 \text{ GeV} \) and 
62 GeV.
Fig. 1
Fig. 2

a) All charm quarks

b) Both forward

\[ \frac{1}{\sigma} \frac{d\sigma}{d\Delta y} \]

- \( M_c = 1.2 \text{ GeV} \)
- \( M_c = 1.5 \text{ GeV} \)

\[ \sqrt{s} = 26 \text{ GeV} \]

- \( M_c = 1.2 \text{ GeV} \)
- \( \sqrt{s} = 62 \text{ GeV} \)

c) Opposite hemispheres

\[ \Delta y, \Delta y_{\text{For}}, \Delta y_{\text{F-B}} \]