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TRANSVERSE CORRELATION OF CHARM PAIRS, $\psi\psi$ AND PARTONS TRANSVERSE MOMENTA

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ABSTRACT

Assuming the partons within the initial hadrons to have transverse momentum we have calculated in the framework of the fusion process the transverse angular distributions of the charm pairs and of the $\psi\psi$ pairs produced in hadronic collisions. The transverse angle is defined as $\cos\phi = \vec{p}_{T3}\cdot\vec{p}_{T4}/(|p_{T3}||p_{T4}|)$, where p_{T3} and p_{T4} are the transverse momenta of the charm pairs/$\psi\psi$ pairs. By comparing with the data we find that the effective transverse momentum of the partons is $\sim$ 0.6 GeV/c.

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1. INTRODUCTION

There are experimental indications from hard scattering processes that partons within a hadron possess some transverse momentum and it arises from two sources. Firstly, since partons are confined within a hadron and therefore from the uncertainty principle they must have some transverse momentum called intrinsic transverse momentum $(k_T)_{int}$. Secondly, partons acquire dynamically an additional transverse momentum due to bremsstrahlung of gluons, $(k_T)_{brem}$. Assuming the distributions to be Gaussian the effective transverse momentum of the partons can be written as $\langle k_T^2\rangle_{eff} = \langle k_T^2\rangle_{int} + \langle k_T^2\rangle_{brem}$. We summarise below the results from the hard scattering processes namely the large p_T hadron production, the dimuon production and the hadrons from deep inelastic scattering.

In the large p_T sector from hadronic collisions one observes non-coplanarity of the beam, target and the two outgoing quark fragments and this has been interpreted as due to the k_T of the colliding partons; some of the references are: theory [1,2], experiments [3]. These experiments yield $\langle k_T\rangle_{eff} \sim 0.8$ GeV/c.

The muon pairs produced in hadronic collisions are kown to have large transverse momentum. In the standard Drell-Yan picture the p_T of the dimuon will arise from the k_T of the two annihilating partons. There are also other elementary processes: $q + \bar{q} \to g + \mu^+\mu^-$, $q(\bar{q}) + g \to q(\bar{q}) + \mu^+\mu^-$ (g is a gluon) which contribute to the p_T of the dimuon. Some of the references are: theory [4,5], experiments [6]. From a detailed study of multiple soft gluon emission in Drell-Yan processes it has been deduced [5] that $\langle k_T\rangle_{int} \sim 0.4$ GeV. From fits to the energy dependence of $\langle p_T^2\rangle_{\mu\mu}$ produced in hadronic collisions on s, the square of the c.m. energy, and interpreting the intercept at s = 0 due to $\langle k_T^2\rangle$ of the colliding partons, it has been deduced [7] that $\langle k_T\rangle_{int} \sim 0.5$ GeV/c which is in agreement with ref. [5].

The transverse momentum of the charged hadrons produced in deep inelastic lepton-hadron scattering shows a strong dependence on z (= energy of the hadron/energy of the current) which yields information on the k_T [8]. The data of 280 GeV muon-proton scattering is found to be consistent with $\langle k_T \rangle_{eff} \sim 0.8$ GeV/c; after taking into account the soft gluon emission the data is consistent with $\langle k_T \rangle_{int} \sim 0.4$ GeV/c [9].

It is clear from the above discussions that the partons do have $\langle k_T \rangle_{eff} \sim 0.8$ GeV/c with intrinsic component as $\langle k_T \rangle_{int} \sim 0.4$ GeV/c (this leads to $\langle k_T \rangle_{brem}$ as ~ 0.7 GeV/c). In general it is $\langle k_T \rangle_{eff}$ that matters in parton-parton collisions. In this note we would like to explore the effect of k_T on charm production in hadronic collisions with the assumption that the charm pairs are dominantly produced via fusion processes: $g + g \to c\bar{c}$ and $q + \bar{q} \to c\bar{c}$. A preliminary result has been reported by the LEBC-EHS collaboration [10] where the charm pairs have been observed to have an average angle of $\sim 125°$ between them in the transverse plane. In our calculation we will not incorporate the fragmentation/recombination of the charm quark to form a charm hadron similar to what has been used in ref. [11] for rapidity correlation of the charm pairs. In sect. 2 we describe the details of the calculation. Numerical results on angular distribution between the charm pairs are presented in sect. 3. It has been proposed recently [12,13] that probably the dominant mechanism for the $\psi\psi$ production as observed in π-N collisions [14] is the fusion process. If this is the case then the angular distribution between the $\psi\psi$ in the transverse plane seen in the data [14] should be due to the transverse momentum of the colliding partons. Results are summarized in sect. 4.

2. DETAILS OF THE CALCULATION

The differential cross section to produce a charm quark in a hadron-hadron collision (A and B) is given by

$$E_3 \frac{d^3\sigma}{d^3p_3} = \int d^2k_{T1} \int d^2k_{T2} \int dx_1 \int dx_2 F_{1/A}(x_1, k_{T1}, Q^2) F_{2/B}(x_2, k_{T2}, Q^2) \cdot \frac{1}{x_1 x_2} \cdot E_3 \frac{d^3\hat{\sigma}}{d^3p_3} \qquad (1)$$

where $\hat{\sigma}$ is the cross section for the subprocess $1+2 \to 3+4$; $x_{1,2}$ are the longitudinal momentum fractions and $k_{T1,2}$ are the effective transverse momenta of the partons 1, 2 in the hadrons A, B respectively; $F_{1/A}$ and $F_{2/B}$ are the structure functions. We use the factorised ansatz [1] for the structure functions

$$F_i(x_i,\ k_{Ti}, Q^2) = \frac{x_i}{\tilde{x}_i}\ F_i(x_i, Q^2) \cdot f_i(k_{Ti}) \tag{2}$$

with

$$\tilde{x}_i^2 = x_i^2 + 4k_{Ti}^2/s \tag{3}$$

and

$$\int d^2k_{Ti} f_i(k_{Ti}) = 1 \tag{4}$$

s = c.m. energy square of the initial hadrons A and B.

Using the following relation

$$E\ \frac{d^3\sigma}{d^3p} = \frac{1}{\pi}\ \frac{d^2\sigma}{dy\,dp_T^2}$$

$$= \frac{1}{\pi}\ \frac{d\sigma}{dt}$$

eq. (1) becomes

$$\frac{d^2\sigma}{dy_3\,dp_{T3}^2} = \int d^2k_{T1} \int d^2k_{T2} \int dx_1 \int dx_2\, f_1(k_{T1}) f_2(k_{T2}) F_{1/A}(x_1, Q^2) F_{2/B}(x_2, Q^2) \cdot \frac{1}{\tilde{x}_1 \tilde{x}_2} \cdot \frac{d\hat{\sigma}}{d\hat{t}} \tag{5}$$

where y_3 and p_{T3} are the rapidity and the transverse momentum of the charm quark 3 and $\hat{t}$ is the square of the 4-momentum transfer between 1 and 3.

Assuming the colliding partons as massless and the charm quark of mass M we can write the following relations (with the +ve z axis along the hadron A)

$$p_{1/\!/} = x_1\sqrt{s}/2, \quad p_{2/\!/} = -x_2\sqrt{s}/2, \quad E_i^2 = x_i^2\ s/4 + k_{Ti}^2, \quad o < x_{1,2} < 1$$

$$p_{3/\!/} = \hat{M}_3 \sinh y_3, \quad \hat{M}_3^2 = p_{T3}^2 + M^2$$

$$E_3 = \hat{M}_3 \cosh y_3 \tag{6}$$

$$p_{4/\!/} = (x_1 - x_2)\sqrt{s}/2 - p_{3/\!/}$$

$$p_{T4}^2 = (E_1 + E_2 - E_3)^2 - p_{4/\!/}^2 - M^2$$

In the transverse plane (x-y) we define the x-axis along the transverse momentum vector of the parton 1,

$$\vec{k}_{T1} = (k_{T1}, 0)$$

$$\vec{k}_{T2} = k_{T2}(\cos\beta, \sin\beta)$$

$$\vec{p}_{T3} = p_{T3}(\cos\theta_3, \sin\theta_3) \qquad (7)$$

$$\vec{p}_{T4} = p_{T4}(\cos\theta_4, \sin\theta_4)$$

$$\cos\phi = (\vec{p}_{T3}\cdot\vec{p}_{T4})/(|p_{T3}|\cdot|p_{T4}|)$$

In the c.m. of the colliding hadrons A, B the invariant variables of the subprocess are

$$\hat{s} = 2\, k_{T1}k_{T2} \cosh\,(y_1-y_2) - 2\, \vec{k}_{T1}\cdot\vec{k}_{T2}$$

$$\hat{t} = M^2 - 2\, k_{T1}\hat{M}_3 \cosh\,(y_3-y_1) + 2\, \vec{k}_{T1}\cdot\vec{p}_{T3} \qquad (8)$$

$$\hat{u} = M^2 - 2\, k_{T2}\hat{M}_3 \cosh\,(y_3-y_2) + 2\, \vec{k}_{T2}\cdot\vec{p}_{T3}$$

with limits on $\hat{s}$ and $\hat{t}$ as

$$4M^2 < \hat{s} < s$$

$$M^2 - \frac{\hat{s}}{2}\,[1 + (1-4M^2/\hat{s})^{1/2}] < \hat{t} < M^2 - \frac{\hat{s}}{2}\,[1-(1-4M^2/\hat{s})^{1/2}]$$

The constraints are

$$\hat{s} + \hat{t} + \hat{u} = 2M^2$$

$$\vec{k}_{T1} + \vec{k}_{T2} = \vec{p}_{T3} + \vec{p}_{T4} \qquad (9)$$

The angular distribution $d\sigma/d\phi$ is obtained by changing the variable p_{T3}^2 to $\cos\phi$

$$\frac{d\sigma}{d\phi} = \sin\phi \int d^2k_{T1}\int d^2k_{T2}\int dx_1\int dx_2\int dy_3 \left|\frac{dp_{T3}^2}{d\cos\phi}\right| \cdot f_1(k_{T1})\cdot f_2(k_{T2})\cdot$$

$$\cdot F_{1/A}(x_1,Q^2)\cdot F_{2/B}(x_2,Q^2)\cdot \frac{1}{\tilde{x}_1\tilde{x}_2}\cdot\frac{d\hat{\sigma}}{d\hat{t}} \qquad (10)$$

with

$$\frac{d\cos\phi}{dp_{T3}^2} = \frac{A/\hat{M}_3 - 2}{2p_{T3}p_{T4}} - \frac{\cos\phi}{2p_{T3}^2 p_{T4}^2} [p_{T4}^2 + p_{T3}^2(1 - A/\hat{M}_3)] \qquad (11)$$

$$A = k_{T1} \cosh(y_3 - y_1) + k_{T2} \cosh(y_3 - y_2) \qquad (12)$$

We need now to express p_{T3}^2 in terms of the variables ϕ, $\vec{k}_{T1}$, $\vec{k}_{T2}$, x_1, x_2 and y_3. This is done by using the constraint eqs (9) and one obtains the following biquadratic equation(*) in $\hat{M}_3$ ($= (p_{T3}^2 + M^2)^{1/2}$):

$$\hat{M}_3^4 - 2A\hat{M}_3^3 + (C/B - 2M^2)\,\hat{M}_3^2 + (2AM^2 - A\hat{s}/B)\hat{M}_3 + [M^4 + (D - M^2C)/B] = 0 \qquad (13)$$

with

$$B = \sin^2\phi,$$

$$C = \hat{s}\,\sin^2\phi - K^2 \cos^2\phi + A^2,$$

$$K = |\vec{k}_{T1} + \vec{k}_{T2}|,$$

$$D = A^2M^2 + \hat{s}^2/4,$$

The values of p_{T3}^2 are obtained by solving eq. (13) and those values which satisfy the constraint eqs (9) are kept; the $d\sigma/d\phi$ is obtained using eq. (10) by summing over these final states.

3. NUMERICAL RESULTS

We have used the following parametrizations of the structure functions:

(a) *Pion:* counting rule distributions corrected by the QCD Q^2 dependence for valence quarks, sea quarks and gluons as given by Owens and Reya [15].

(b) *Proton:* valence quarks as given by Buras and Gaemers [16], sea quarks from ref. [15] and gluons from the neutrino data of the CDHS collaboration [17].

We take an effective value for Q^2 as $4M^2$, Λ as 0.5 GeV and the strong coupling constant $\alpha(Q^2) = 12\pi/[25\,\ell n\,(Q^2/\Lambda^2)]$.

(*) The eq. (13) reduces to a quadratic one for $\phi = 0$, $\pi/2$ and π.

For the transverse momentum distributon $f(k_T)$ of the partons we have used the Gaussian distribution,

$$f(k_T) = \frac{A}{\pi} e^{-Ak_T^2} , A = \frac{\pi}{4<k_T>^2} \quad (14)$$

We have checked that the final results are not changed by using an exponential distribution $(B^2/2\pi) \exp(-Bk_T)$, with $<k_T> = 2/B$.

3.1 Transverse correlation of charm pairs

The expressions for $d\hat{\sigma}/d\hat{t}$ are taken from ref. [18]. The mass of the charm quark M is taken as 1.2 GeV; no significant difference is found by varying M in the range 1.2 to 1.5 GeV. The gluon-gluon fusion is the dominant process for both πp and pp collisions. The numerical results are found to be essentially the same at $\sqrt{s}$ = 26 GeV for πp and pp collisions although the gluon structure function is different for π and p.

Fig. 1(a) shows the transverse angular distribution(*) $d\sigma/d\phi$ for the charm pair at $\sqrt{s}$ = 26 GeV from πp collisions with the average effective transverse momentum of each of the colliding partons as 0.1, 0.5, 0.7 and 0.9 GeV/c. As expected the peak of the distribution is shifted to lower angles with increasing transverse momentum of the colliding partons.

In fig. 2 we show the variation of the mean transverse angle $<\phi>$ with different choices of $<k_T>_{eff}$; the $<\phi>$ as expected decreases with the increasing $<k_T>_{eff}$. The top scale in the figure refers to $\sqrt{2}.<k_T>_{eff}$ which is essentially the average transverse momentum of the charm pair (convolution of the two Gaussian distributions in k_T of the colliding partons). The experimental value of $<p_T>_{D\bar{D}}$ is 0.9 ± 0.1 GeV/c [10] which yields $<k_T>$ as 0.64 ± 0.07 GeV/c (the two arrows in the fig. refer to the values of $<k_T>_{eff}$ as 0.57 and 0.71 GeV/c). From fig. 2 we therefore expect the value of $<\phi>$ to lie between 119° to 128° which is in good agreement with the experimental value of $\sim$ 125° [10].

(*) Small fluctuations seen in fig. 1 are due to the numerical evaluation of the multifold integral in eq. (10). The integrals are performed by using the program RGAUSS of the CERN Library which uses six point Gaussian quadrature method.

3.2 Transverse correlation of $\psi\psi$

We have used only q-$\bar{q}$ annihilation diagram(*) for the production of $\psi\psi$ and the expression for $d\hat{\sigma}/d\hat{t}$ is taken from ref. [12]. The value of M for the expressions described in sect. 2 is taken as 3.097 GeV, i.e. the ψ mass.

There is no significant difference between the angular distribution obtained for $\sqrt{s}$ = 16.8 GeV and 23 GeV and therefore we present in fig. 1(b) the transverse angular distribution between the $\psi\psi$ pair averaged over $\sqrt{s}$ = 16.8 and 23 GeV for the values of $\langle k_T \rangle_{eff}$ as 0.5, 0.7 and 0.9 GeV/c. Compared to the $c\bar{c}$ production at a given $\langle k_T \rangle_{eff}$ the angular distribution for the $\psi\psi$ is peaked at larger angle. This can be understood as follows. The ψ's are produced with larger p_T than the charm particles - $\langle p_T \rangle_\psi \sim 1.5$ GeV/c and $\langle p_T \rangle_D \sim 0.9$ GeV/c. The effect of the transverse momentum of the colliding partons is basically to give a transverse boost to the outgoing $c\bar{c}/\psi\psi$; for the same boost one therefore expects a smaller transverse angle between the $c\bar{c}$ compared to the $\psi\psi$.

The variation of $\langle \phi \rangle$ with $\langle k_T \rangle_{eff}$ is shown in fig. 2. In fig 3 we compare the experimental angular distribution based on 13 events [14] with the calculated ones with $\langle k_T \rangle_{eff}$ = 0.5 and 0.7 GeV/c. We find that the general trend of the data is well reproduced.

4. SUMMARY

We have attempted to understand the transverse correlation of the charm pairs and the $\psi\psi$ pairs produced in hadronic collisions in the framework of the fusion process. The transverse correlation is generated by introducing transverse momentum to the colliding partons. No distinction is made between quarks and gluons as far as transverse momentum is concerned. We have not dressed charm quarks to form charm

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(*) At $\sqrt{s}$ = 16.8 and 23 GeV at which the data exist, the mean values of $\hat{s}$ expected from g-g and q-$\bar{q}$ are $\sim$ 10 GeV^2 and $\sim$ 60 GeV^2 respectively. The value of $\hat{s}_{th}$ for $\psi\psi$ production is 36 GeV^2 and therefore the g-g fusion is suppressed.

hadrons. The effect of dressing to the transverse momentum is believed to be small as we are dealing with heavy quark. One may need to do this fine tuning once data with high statistics becomes available.

In this framework the resultant transverse momentum of the colliding partons is the same as that of the charm pair/$\psi\psi$ pair. Experimentally one finds indeed that $\langle p_T \rangle_{D\bar{D}}$ and $\langle p_T \rangle_{\psi\psi}$ are the same within errors, 0.9 ± 0.1 GeV/c. This leads to the mean effective transverse momentum (assuming Gaussian distribution) of the partons as 0.64 ± 0.07 GeV/c. We find that this transverse momentum can reasonable explain the experimental transverse correlation of the charm pairs and the $\psi\psi$ pairs. This value is also in agreement with $\langle k_T \rangle_{eff}$ deduced from other hard scattering processes.

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FIGURE CAPTIONS

Fig. 1 (a) Normalised transverse angular distribution between the $c\bar{c}$ pairs at $\sqrt{s}$ = 26 GeV from πp collisions with the average transverse momentum of the colliding partons as 0.1, 0.5, 0.7 and 0.9 GeV/c. The curve for $\langle k_T \rangle$ = 0.1 GeV is reduced by a factor of 5.

(b) Normalised transverse angular distribution between the $\psi\psi$ pairs at $\sqrt{s}$ = 16.8 and 23 GeV with the average transverse momentum of the colliding partons as 0.5, 0.7 and 0.9 GeV/c.

Fig. 2 The variation of the mean transverse angle, $\langle \phi \rangle$, with the average transverse momentum of the colliding partons is shown. The dashed curve refers to the $\psi\psi$ while the solide curve refers to the $c\bar{c}$ pairs. The top scale refers to the resultant mean transverse momentum of the two colliding partons.

Fig. 3 Transverse angular distribution of the $\psi\psi$ pair from the NA3 data (solid histogram) is compared with the calculation - the dashed curve is for $\langle k_T \rangle_{eff}$ as 0.7 GeV/c and the dotted curve for $\langle k_T \rangle_{eff}$ as 0.5 GeV/c. The calculated histograms are normalised to the same total number of events (13 events) as the data.

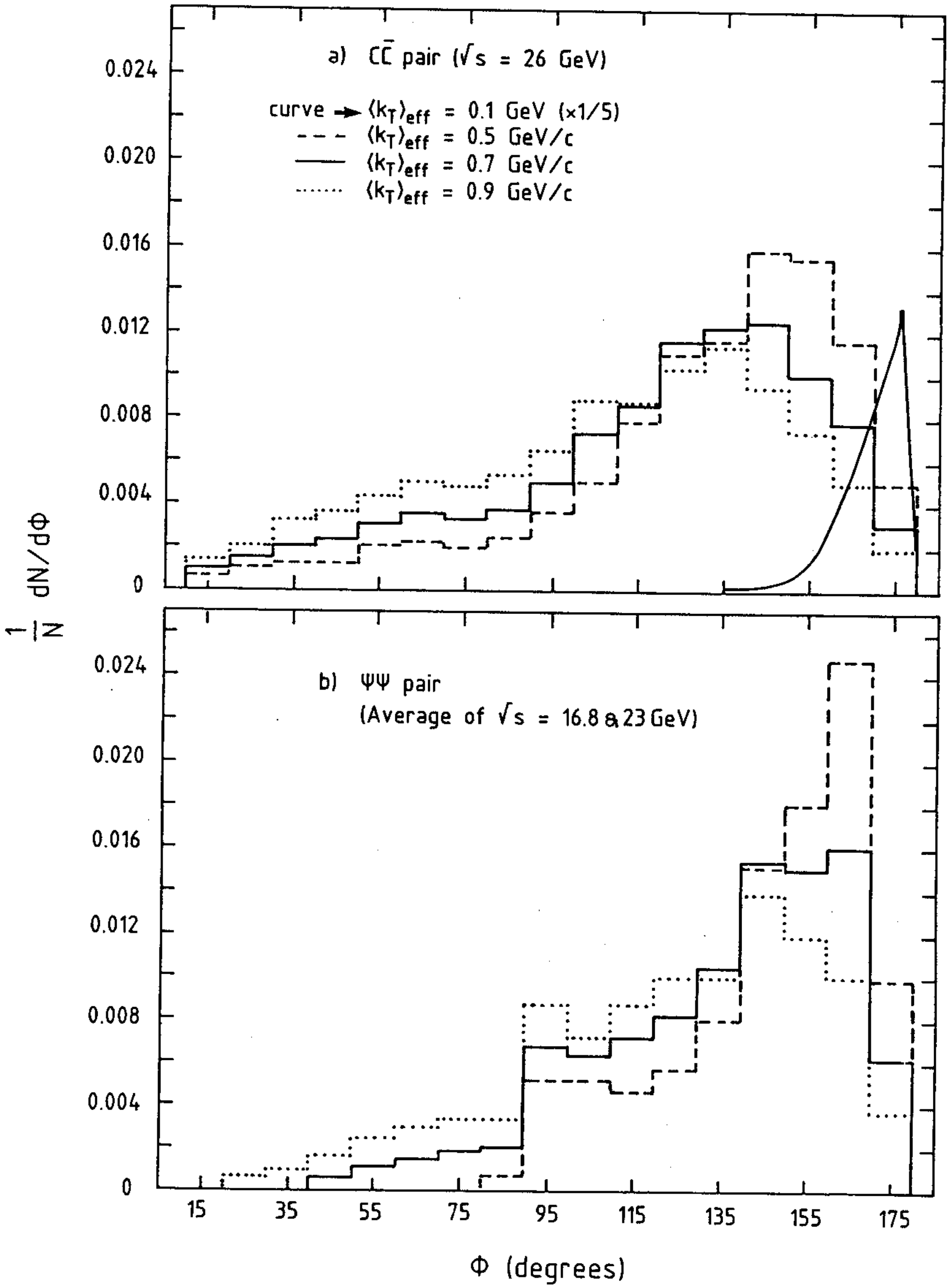
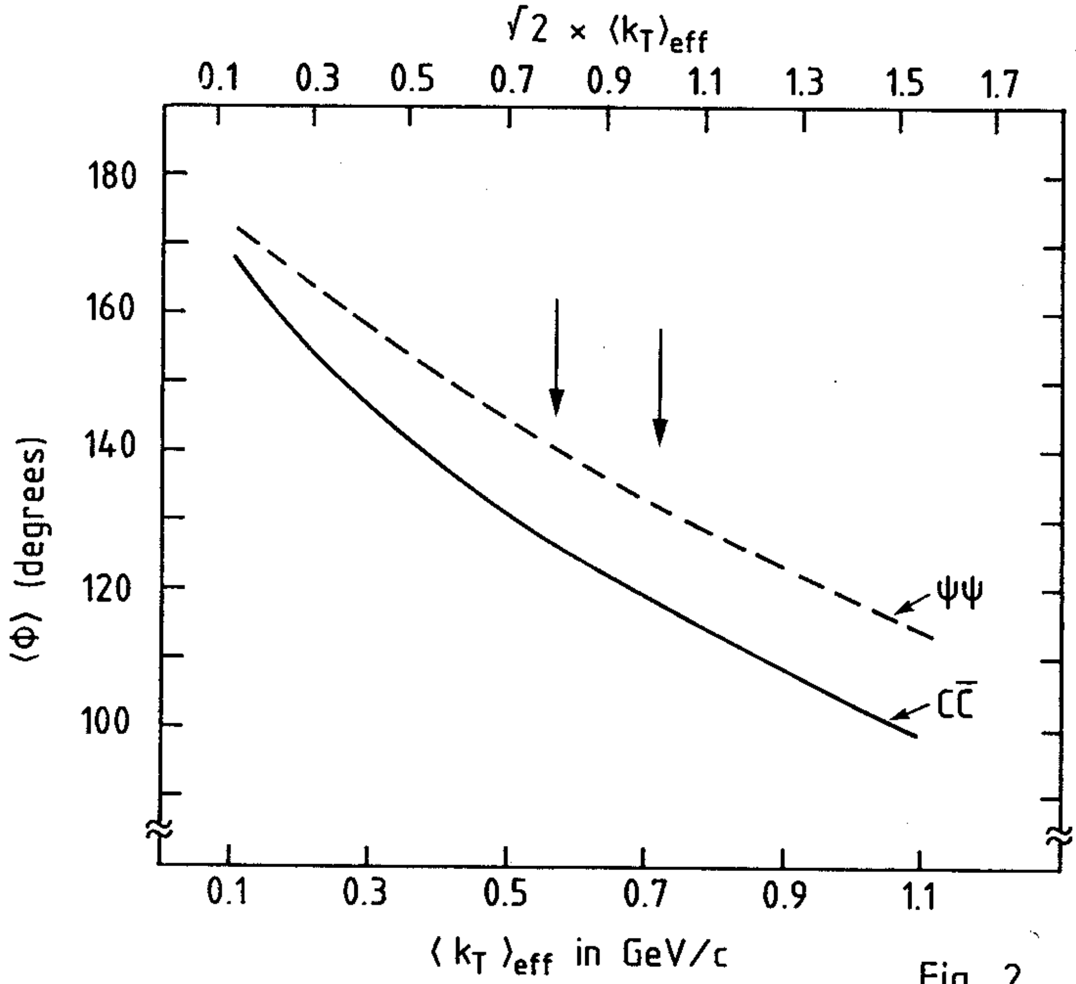
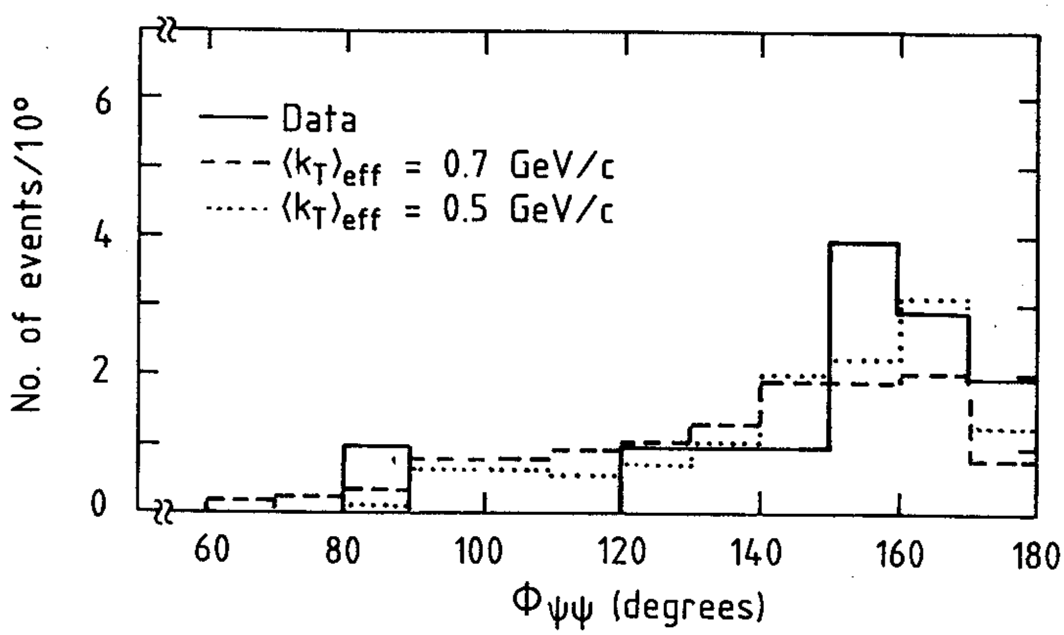

a) $C\bar{C}$ pair ($\sqrt{s}$ = 26 GeV)
curve → $\langle k_T \rangle_{eff}$ = 0.1 GeV (×1/5)
$\langle k_T \rangle_{eff}$ = 0.5 GeV/c
$\langle k_T \rangle_{eff}$ = 0.7 GeV/c
$\langle k_T \rangle_{eff}$ = 0.9 GeV/c
b) ΨΨ pair
(Average of $\sqrt{s}$ = 16.8 & 23 GeV)
0.024
0.020
0.016
0.012
0.008
0.004
0
$\frac{1}{N}$ dN/dΦ
15
35
55
75
95
115
135
155
175
Φ (degrees)

Fig. 1



√2 × ⟨k_T⟩_eff
0.1 0.3 0.5 0.7 0.9 1.1 1.3 1.5 1.7
180
160
140
120
100
⟨Φ⟩ (degrees)
ψψ
cc̄
0.1 0.3 0.5 0.7 0.9 1.1
⟨ k_T ⟩_eff in GeV/c

Fig. 2



Data
⟨k_T⟩_eff = 0.7 GeV/c
⟨k_T⟩_eff = 0.5 GeV/c
No. of events/10°
6
4
2
0
60 80 100 120 140 160 180
Φ_ψψ (degrees)

Fig. 3