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ANGULAR DISTRIBUTION OF μ PAIRS FROM HADRONIC T PRODUCTION

J. Cleymans and M. Kuroda^{*}
Department of Theoretical Physics
University of Bielefeld

G.J. Gounaris⁺
CERN - Geneva

ABSTRACT

We calculate the angular distribution of muons coming from the decay of the T resonance produced in proton-proton interactions. Similar results are also valid for $\bar{p}p$ and πp interactions at sufficiently high energies.

* On leave from: Department of Physics, University of Thessaloniki, Greece.

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Recently, interesting data have been presented on the angular distribution of muons produced in π -N collisions by the NA3 Collaboration at CERN¹⁾. It has been shown that these data can be understood in the Drell-Yan annihilation framework, provided one takes into account QCD corrections and the motion of the constituents inside the hadrons²⁾. It is known from experiment that the angular distribution in the J/ψ region is strikingly different from that of the background³⁾. It is furthermore to be hoped that information on the azimuthal angle distribution for both the J/ψ and T resonances will also become available in the near future. This will provide very useful information on the hadronic production mechanism of these heavy resonances. This mechanism has not yet been understood in full detail and further measurements are necessary.

A class of suggested models for the production of heavy resonances involved the QCD subprocesses⁴⁾ $q\bar{q} \rightarrow Q\bar{Q}$ and $gg \rightarrow Q\bar{Q}$, as well as⁵⁾ $gg \rightarrow Q\bar{Q}g$ and $q\bar{q} \rightarrow Q\bar{Q}g$ for large transverse momenta. In these models semi-local duality arguments are used to calculate the production cross-sections for heavy resonances. Since the spin of the resonance is not explicitly considered, no information on the density matrix is given.

In this article we direct our considerations to the production mechanism described by the subprocess of Fig. 1a. It has been recently shown by Baier and Rückl⁶⁾ that this diagram completely dominates the cross-section for production of T resonances in pp collisions at $\sqrt{s} \geq 27$ GeV and transverse momentum larger than 2 GeV. They find that contributions from 3P_J states are important only at smaller transverse momenta. This is contrary to the situation appearing in J/ψ production where there is a substantial contribution from χ states, even at large⁶⁾ Q_T .

When considering T production in processes where antiquarks are abundant, like $\bar{p}p$ and π^+p , we should, of course, have important contributions also from diagrams involving $q\bar{q}$ fusion. It has been shown, however, that even though these contributions are important at low energies, their influence disappears completely at higher energies⁶⁾. Especially at CERN collider energies ($\sqrt{s} \sim 500$ GeV) there should be no difference between pp and $\bar{p}p$ production rates for heavy resonances^{*)}.

We conclude, therefore, that according to Ref. 6) the hadron production cross-section of T should be dominated at sufficiently high energies and transverse momenta by the subprocess of Fig. 1a. Since this mechanism seems to

*) Notice that already at $\sqrt{s} \approx 19$ GeV (beam energy 200 GeV) $\sigma(\bar{p}p \rightarrow \psi \dots) / \sigma(pp \rightarrow \psi \dots) = 1.4 \pm 0.4$ indicating that the gg fusion contribution may be dominant for $\bar{p}p$, even for lower energies [see Ref. 7)].

be simple we decided to study the expected angular distribution of the μ pairs produced at the rest frame of T . We believe that an experimental study of this angular distribution will provide a test of the above model which is more stringent than the magnitude and Q_T dependence of the production cross-section⁶⁾.

Before giving details we present the general parametrization for the angular distribution of μ^- in the rest frame of the μ pair. Since T has spin 1 we have, in terms of its density matrix elements⁸⁾

$$W(\theta, \phi) = \frac{3}{8\pi} \left\{ \rho_{11} (1 + \cos^2 \theta) + (1 - 2\rho_{11}) \sin^2 \theta + \right. \\ \left. \rho_{1,-1} \sin^2 \theta \cos 2\phi + \sqrt{2} \operatorname{Re} \rho_{10} \sin 2\theta \cos \phi \right\}. \quad (1)$$

In the study of the angular distribution of the Drell-Yan muon pairs, it is customary to use the equivalent parametrization first introduced by Collins and Soper⁹⁾

$$W(\theta, \phi) = \frac{3}{16\pi} \left\{ 1 + \cos^2 \theta + A_0 \left(\frac{1}{2} - \frac{3}{2} \cos^2 \theta \right) \right. \\ \left. + A_1 \sin 2\theta \cos \phi + \frac{A_2}{2} \sin^2 \theta \cos 2\phi \right\}. \quad (2)$$

The advantage of this parametrization is that the naive Drell-Yan mechanism gives $A_0 = A_1 = A_2 = 0$ so that the coefficients A_i are expected a priori to be small. Since in our discussion we will also take into account the background, we chose to adhere to the parametrization given in (2).

The calculation of the diagram in Fig. 1a is done in the rest frame of the heavy resonance¹⁰⁾. Including all the appropriate factors, projecting the $Q\bar{Q}$ state to a 3S_1 state, and eliminating the wave function at the origin in favour of the decay widths $\Gamma(^3S_1 \rightarrow \mu^+ \mu^-)$ and $\Gamma(^3S_1 \rightarrow \text{hadrons})$, one obtains finally

$$\frac{d\sigma(gg \rightarrow {}^3S_1 + g \rightarrow \mu^+ \mu^- g)}{dy dQ_T^2 d\Omega} = \frac{9\pi^2}{64} \frac{B({}^3S_1 \rightarrow \mu^+ \mu^-) B({}^3S_1 \rightarrow \text{hadrons})}{\pi^2 - 9}.$$

(3)

$$\cdot \frac{\Gamma({}^3S_1 \rightarrow \text{all})}{\hat{s} M} \delta(\hat{s} + \hat{t} + \hat{u} - M^2) A \hat{W}(\theta, \phi)$$

where M is the mass of the produced 3S_1 state,

$$A = 1 - \frac{Q_T^2}{(\hat{s} - M^2)^2} (2\hat{s} - Q_T^2 - M^2) \quad (4a)$$

and $\hat{W}(\theta, \phi)$ is given in (2) with

$$\begin{aligned} \hat{A}_0 = \hat{A}_2 = \frac{1}{2A} \left\{ \sin^2 \theta_3 + \frac{1}{\hat{s}^2 (\hat{s} - M^2)^2} \left[\hat{t}^2 (M^2 - \hat{t})^2 \sin^2 \theta_1 + \right. \right. \\ \left. \left. + \hat{u}^2 (M^2 - \hat{u})^2 \sin^2 \theta_2 \right] \right\}, \quad (4b) \end{aligned}$$

$$\begin{aligned} \hat{A}_1 = \frac{1}{4A} \left\{ \sin 2\theta_3 + \frac{1}{\hat{s}^2 (\hat{s} - M^2)^2} \left[\hat{t}^2 (M^2 - \hat{t})^2 \sin 2\theta_1 + \right. \right. \\ \left. \left. + \hat{u}^2 (M^2 - \hat{u})^2 \sin 2\theta_2 \right] \right\} \quad (4c) \end{aligned}$$

In Eqs (3) and (4) quantities with a hat refer to the subprocess of Fig. 1a. In the rest frame of the heavy resonance we take the plane defined by the gluon momenta as the x - z plane (see Fig. 1b). We call k_1 the momentum of the gluon associated with the beam hadron, k_2 the momentum of the gluon associated with the target and k_3 the momentum associated with the recoiling gluon^{*)}. The z and x axes are chosen so that all momenta lie in the positive x half-plane. As is indicated in Fig. 1b, θ_i is the polar angle of gluon i ; θ and ϕ are the polar and azimuthal angles of the μ^- . The various standard frames are fixed by specifying the z axis in Fig. 1b.

These are:

- 1) Beam frame¹¹⁾: $\theta_1^B \equiv 0$
 $\theta_2^B = \theta_2 - \theta_1$
 $\theta_3^B = \theta_3 - \theta_1$
- 2) Target frame: $\theta_2^T \equiv \pi$
 $\theta_1^T = \pi + \theta_1 - \theta_2$
 $\theta_3^T = \pi + \theta_3 - \theta_2$
- 3) Collins-Soper frame⁹⁾: $\theta_1^{CS} = \frac{1}{2}(\pi + \theta_1 - \theta_2)$
 $\theta_2^{CS} = \frac{1}{2}(\pi - \theta_1 + \theta_2)$
 $\theta_3^{CS} = \theta_3 + \frac{1}{2}(\pi - \theta_1 - \theta_2)$

In the rest frame of the 3S_1 state the beam and target axes refer to obviously natural axes in the process. The Collins-Soper axis averages over them and has the advantage that primordial transverse momentum effects can be expressed in a simple way in terms of the transverse momentum of the lepton pair. In the other two frames these effects are expressed in terms of the transverse momentum of the constituents inside the beam and target particles, a variable which is not directly accessible experimentally.

Before discussing the detailed form of our results we present some of the most striking features. First of all, we consistently found the relation

$$A_0 = A_2 \quad (5)$$

(or, in terms of the density matrix elements $\rho_{00} = 2\rho_{1-1}$) for a wide class of processes. We found this result not only for the diagram of Fig. 1a, but also

^{*)} As usual we call $\hat{s} = (k_1 + k_2)^2$, $\hat{t} = (k_3 - k_2)^2$, $\hat{u} = (k_1 - k_3)^2$.

for the direct production of χ_0 with subsequent decay into a 3S_1 resonance and a photon. Furthermore, the same result is known to be valid¹²⁾ for the QCD diagrams relevant for the Drell-Yan background, namely $qg \rightarrow \mu^+ \mu^- q$ and $q\bar{q} \rightarrow g\mu^+ \mu^-$. It therefore seems that (5) is quite general for these processes.

As a second feature we note that at $y = 0$ for pp scattering, we have

$$A_1 = 0 \quad (6)$$

in the Collins-Soper frame. This result follows from symmetry considerations. In the beam and target axes frames A_1 is equal in magnitude but different in sign. If the beam and target particles are not the same, (6) does not hold. Also, the Drell-Yan background gives $A_1 \neq 0$.

A straightforward comparison of Eq. (3) integrated over angles, with the transverse momentum distributions as measured in Ref. 13), leads to a curve which is about a factor⁶⁾ four below the ISR data¹³⁾. This may be taken care of by⁶⁾ noticing that the Λ value in leading order QCD calculations may be different when considering deep inelastic processes and decays of heavy resonances. Of course, an exact calculation should give the same value for Λ in both processes. It may therefore be reasonable to argue that our lowest order results (3) should be multiplied by a factor like⁶⁾

$$\left\{ \alpha_s(M/\Lambda_{\text{production}}) / \alpha_s(M/\Lambda_{\text{decay}}) \right\}^3$$

which, if $\Lambda_{\text{production}} \sim 500$ MeV and $\Lambda_{\text{decay}} \sim 100$ MeV gives a factor of ~ 3.6 . We should emphasize, though, that the density matrix elements of the produced T , which are the essential results of this work, are independent of the over-all normalization of the differential cross-sections, and consequently of the aforementioned correction factors.

In Fig. 2 the results of the calculations for pp scattering are presented for A_0 and A_1 for two different energies, $\sqrt{s} = 27$ and 63 GeV in the beam frame. Also presented is the value of α as a function of the transverse momentum of the μ pair. The quantity α directly indicates the deviation from isotropy: $1 + \alpha \cos^2\theta$. It is to be noticed that at $Q_T = 0$ α equals 1; it then decreases very rapidly to zero for $Q_T \approx 2$ GeV, and becomes negative afterwards. This is not directly apparent in the Figure because we have included the background due

to Drell-Yan pairs, which tend to have roughly a $1 + \cos^2\theta$ distribution. The two effects together finally produce the curve of Fig. 2, showing that the distribution in the polar angle θ will essentially be isotropic for large values of Q_T . The value of A_1 is also presented in Fig. 2c, and it is always small and positive. Almost identical results are obtained in the Collins-Soper frame.

For the gluon distributions we used $3(1-z)^5/z$ for the proton. The values of α and A_0 are very insensitive to the special choice of gluon distribution. Only the values for A_1 change, however its magnitude is always small.

Our results can be straightforwardly extended to the case of J/ψ and T photoproduction by substituting

$$B(^3S_1 \rightarrow \text{hadrons}) \text{ by } \frac{8}{3} B(^3S_1 \rightarrow \gamma + \text{hadrons}).$$

In this case, the calculations are simplified since we have to make only one convolution integral with a gluon distribution function¹⁴⁾. Furthermore, χ states cannot be produced directly because of colour conservation. So in this case the results are applicable to J/ψ as well as T . We therefore find a similar dependence of α on Q_T . We conclude that this angular dependence would provide one interesting test for the production mechanism of heavy quarkonia.

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FIGURE CAPTIONS

- Fig. 1a: Dominant diagram for large transverse momentum T production in hadronic collisions.
- 1b: Kinematics of the process in the rest frame of the muon pair. 1 (2) refers to the gluon associated with the beam (target), 3 refers to the recoiling gluon.
- Fig. 2 : The angular distribution parameters of the μ^- : α , A_0 and A_1 are shown for the process $pp \rightarrow T...$ at $\sqrt{s} = 27$ and 63 GeV in the beam frame. The curves correspond to a weighted average between the resonance production and the Drell-Yan background.

FIG. 1a

FIG. 1b

Beam frame, $pp \rightarrow \gamma X$

FIG. 2