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μ PAIR PRODUCTION IN ASSOCIATION WITH A LARGE MOMENTUM HADRON

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A B S T R A C T

Using the recombination model we analyze massive μ pair production in association with a low p_t (almost leading) $\pi^\pm$, $K^\pm$ meson in the target fragmentation region. The cross-section size of the Drell-Yan and ψ production processes (DY/ ψ) for proton and nuclear targets is evaluated, and their kinematical distributions are discussed. The π^+/π^- ratio of the μ pair associated π mesons offers immediate tests. We point out the feasibility of such studies in the backward region of high statistics fixed-target DY experiments.

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The production of low p_t (soft) hadrons in the fragmentation region is successfully described by the recombination model ¹⁾ and its further developments ²⁾. Although a deeper understanding of its input assumptions - the multiparton momentum distributions and the recombination function - would be desirable, its predictive power and simple form allow for a series of successful phenomenological analyses of the soft hadronic multiparticle processes ³⁾.

Massive lepton-pair production has in the recent past been extensively analyzed in the framework of perturbative QCD, and the quark momentum distributions were determined in the timelike region ⁴⁾.

In this paper we study massive lepton-pair production in association with a soft hadron in the target fragmentation region. This allows for a combined analysis of these two production mechanisms whereby one of them may be considered as a disturbance to the other. Accepting undisputedly the recombination model, the cross-section size of the process

$$B + T \longrightarrow \gamma^*/\psi (\rightarrow \mu^+\mu^-) + h + X \quad (1)$$

and its kinematical distributions can be determined. $B \equiv (\pi^\pm, K^\pm, p, \bar{p})$ stands for the hadron beam, T for the nuclear target with atomic numbers (A, Z) , and $h \equiv (\pi^\pm, K^\pm)$ represents the associated meson in the target fragmentation region. $\gamma^*(\psi)$ is the off-shell photon (ψ resonance) generating the final state μ pair. With the recombination parameters fixed in purely hadronic processes this model is tested in a new environment. Furthermore, the kinematical distributions of massive μ pair production can be compared in the presence, or absence, of an associated fast momentum meson.

Most important of all, by such processes one gains insight into the multiparton momentum distributions $f(x_1, x_2, \dots)$ where direct experimental information is sparse. This paper aims to renew interest in the experimental and theoretical study of the semi-inclusive DY type processes, Eq. (1), by extending earlier studies ⁵⁾.

In the following we introduce the model, present the cross-section size of reaction (1) with the characteristics of its kinematical distributions, and point to the high-statistics fixed-target DY experiments which might be particularly suitable for such experimental analyses.

The semi-inclusive cross-section for reaction (1), as presented in Fig. 1, is given by

$$x_M \frac{d^3\sigma}{dx_M dM dy} = \left(\frac{2x_1 x_2}{M} \right) \sum_q e_q^2 [u_{\bar{q}}(x_1) V_q(x_2, x_h) + 1 \leftrightarrow] d\hat{\sigma} \quad (2)$$

where

$$V_q(x_2, x_h) = \int_0^{x_h} dx_a dx_b f(x_2, x_a, x_b) R(x_h, x_a, x_b) \quad (3)$$

and

$$x_1 = \sqrt{\tau} e^y, \quad x_2 = \sqrt{\tau} e^{-y}, \quad \tau = \frac{M^2}{s} \quad (4)$$

The $u_q(x_1)$ is the single parton momentum distribution in the beam hadron. The $V_q(x_2, x_h)$ describes the production of the fast momentum meson (h) in the target fragmentation region. $d\hat{\sigma}$ is the cross-section for the parton subprocess. R is the recombination function¹⁾. $M(\equiv \sqrt{Q^2})$ is the invariant mass of the μ pair. $x_h (\equiv -2p_L/\sqrt{s})$ is the longitudinal momentum fraction of the final state meson h (which in the target fragmentation region is emitted in the negative beam direction). s is the squared over-all centre-of-mass energy, and e_q is the quark charge in units of e .

The parton cross-section is in the DY process given by the usual electromagnetic $q\bar{q}$ annihilation. The ψ production is described by the model of Ref. 6). In the framework of perturbative QCD the production of $c\bar{c}$ pairs is assumed, which to a large amount subsequently converts to intermediate η_c and χ states; by emitting electromagnetic radiation they decay into ψ 's. The rate is estimated by the lowest order $q\bar{q}$ and gg annihilation graphs⁶⁾, and, as suggested by arguments from semi-local duality^{6a)}, by an M^2 average over the mass region of the intermediate states.

The recombination function¹⁾

$$R(x, x_a, x_b) = \alpha_\pi \left(\frac{x_a}{x} \right) \left(\frac{x_b}{x} \right) \delta \left(1 - \frac{x_a}{x} - \frac{x_b}{x} \right) \quad (5)$$

with $\alpha_\pi \approx 4$ from the soft hadronic processes, is the same for all mesons.

The multi-parton distributions are given by the generalized Kutli-Weisskopf model ⁷⁾ which assumes no parton correlations apart from a strict observation of energy momentum conservation among the infinity of partons in a hadron. We follow the simple ansatz

$$f(x_1 \dots x_N) = \frac{N}{\pi} \frac{f_q(x_j)}{x_j} (1-X)^{\gamma-1+\frac{n_s}{2}} \cdot C_v(X) \quad (6)$$

where $X = x_1 + \dots + x_N$. The primitive structure functions $f_q(x_j)$ are parametrized in a simple manner, and the factor $C_v(X)$ ensures strict momentum conservation. The open parameters were chosen such as to reproduce closest the valence and sea single quark momentum distributions of Ref. 1), and the meson momentum distributions were chosen from Ref. 4). The counting rule powers of the nucleon (meson) gluon distributions are $n_G = 5(3)$. Different parameter sets do not significantly affect the subsequent results unless discussed in the text. Nuclear targets such as W, Fe, etc., are approximated by the appropriate linear combination of neutron and proton cross-sections whereby all nuclear effects are ignored ; this is a good approximation if the momenta are large. The experimental verification of Eq. (6) is not straightforward, and forms part of our present research efforts.

The above model allows for an estimation of the cross-sections. In Fig. 2a we show the rapidity distributions of the DY process initiated by a π^- beam on a proton target (dashed curves) and on a tungsten target (solid curves). The simple DY cross-sections are marked 'DY' whereas those with an additional meson are indicated by its symbol π^+ , π^- , etc. The curves are evaluated for $M = 4$ and $s = 752 \text{ GeV}^2$ corresponding to $E_{\text{lab}} = 400 \text{ GeV}$.

The simple DY cross-section reveals the usual plateau of the rapidity distribution centred around $y = 0$ which on a tungsten target is roughly two orders of magnitude above the cross-section with a proton target. At the lower (upper) end of the y distribution we are in the target (beam) fragmentation region with x_1 small (large) and x_2 large (small). Due to the softer valence and sea distributions of the pion as compared to the nucleon the curves are somewhat asymmetric and extend further into the pion x_1 range. The y distributions decrease with growing M and become more narrow. Increasing s instead widens the rapidity range and lifts the central plateau heights.

Measuring, in addition, a fast momentum meson at $x_h = 0.5$ (as a supplementary constraint on the μ pair data), one reduces the cross-section by one or two orders of magnitude depending on the particular meson. $\pi^\pm$ mesons

occur more frequently in coincidence with a DY lepton pair than the $K^\pm$ mesons. The presented results bare an uncertainty due to the less well-known nucleon sea distributions which, in the chosen parametrization, are not SU(3) symmetric. The $s = \bar{s}$ distributions are in particular suppressed leading to low K rates. For a proton target the associated π rate follows $\pi^+ > \pi^-$ whereas for a tungsten target $\pi^- > \pi^+$ since the amount of u and d quarks in the target is significantly changed. Similarly the K - as compared to the π - rates are modified.

We now vary the kinematical conditions of the massive μ pair and of the jointly produced fast meson h, and analyze the behaviour of the distributions. The μ pair rapidity distributions are no longer centred around $y = 0$ but they are sidewise displaced since μ pair production takes place under conditions which are different from those in the simple DY process. The momentum fractions are in this latter process defined as $x_1 = p_1/E$ where $E (\equiv \sqrt{s}/2)$ is the maximal available centre-of-mass energy per incoming parton. In semi-inclusive μ pair production (as exposed in Fig. 1) the maximal energy for quark 1 is again E. The total energy available for quark 2 is $E^* = E(1-x_h)$ instead. Thus the momentum fraction $x_2^* = p/E^* = x_2/(1-x_h)$ is the true analogue of those used in the simple DY process. If in Eq. (4) x_2 is now fixed via $x_2^* = \sqrt{\tau}e^{-y} \equiv x_2/(1-x_h)$ the rapidity distribution extends over the range of the simple DY process (see dotted curves in Fig. 2a as examples). While increasing x_h the above-noticed shift becomes more and more displaced towards higher values whereas the upper end remains fixed. The maximum point of the y distribution shifts towards larger and larger y values whereas the plateau height is gradually reduced over several orders of magnitude. The larger momenta of the associated meson (around the backward hemisphere) are thus counter-balanced by larger momenta of the off-shell photon emerging in the centre-of-mass forward hemisphere). Typical values are

$$x_h = (0.1, 0.3, 0.5, 0.7, 0.9) \rightarrow x_F = (0.12, 0.12, 0.19, 0.34, 0.55)$$

where x_F is the Feynman scaling variable of the off-shell photon.

Increasing the momentum fraction x_h of the final state meson h, keeping all other parameters fixed, reveals the strong fall-off of the cross-section in the target fragmentation region as familiar already from the purely hadronic soft processes. For a correct comparison we use similar arguments as exposed above. The maximal energy available for semi-inclusive fast meson production is $E^* = E(1-x_2)$ leading to the momentum fraction $x_h^* \equiv p_L/E^* = x_h/(1-x_2)$ as the true analogue of x_h in the hadronic process. Comparing in this way the hadronic with the μ pair associated meson fall-off the curves are on a log plot

simply displaced as long as there is no competition between $q\bar{q}$ annihilation and pion formation for valence quarks. Otherwise the shape of the curves resulting from the two types of processes can be substantially different which, however, now becomes transparent in a consistent manner.

For nuclear targets the fast pion ratios change little, independent of the chosen beam, whereas for a proton target significant changes can, in particular reactions and appropriate kinematical regions, be observed. We come back to this point later.

Increasing M at $y = 0$ leads to a much stronger fall-off than in the simple DY process until the kinematical limit ($M \sim 11$ GeV for the above indicated parameter set) is reached. The y distribution becomes narrower leaving the position of the maximum unchanged with its size, however, substantially reduced.

Increasing M in the simple and the semi-inclusive DY process both at $y = 0$ should not be compared since the kinematical conditions do not match. Using again the earlier arguments on the maximal available energy to define x_1 in μ pair associated fast meson production, the line $x_1 = x_2/(1-x_1) = M/\sqrt{s}$ (in the x_1, x_2 plot) can easily be verified to correspond to $y = 0$ in the simple DY process. On a simple log plot the M dependences of the two types of processes then appear parallel displaced. Taking for the p_t distribution the lowest order QCD graphs as analyzed in Ref. 8), the semi-inclusive rates for a tungsten target are $\sim 4 \cdot 10^{-36}$ cm²/GeV³ at $p_t = 2$ GeV, and $x_h = 0.5$ for a π^+ meson. Thus, looking at the p_t distribution the rates decrease again roughly by two orders of magnitude as compared to the p_t integrated results of Fig. 2a. They fall off exponentially with increasing p_t and the y distribution, in addition, shrinks. Choosing a proton instead of a π^- beam, the above-discussed features and the size of the cross-section remain similar.

We analyze in complete analogy μ pair production via the ψ resonance. Using semi-local duality its production is described by $c\bar{c}$ production via $q\bar{q}$ annihilation and gg fusion ⁶⁾ whereby the latter process dominates in the central region and the former one in the fragmentation regions. In Fig. 2b we expose the ψ rapidity distribution for a proton (dashed curves) and a tungsten (solid curves) target with the reaction in both cases initiated by a π^- beam. Simple ψ production (ψ) is roughly two orders of magnitude above the analogous DY process, and this feature carries over to the processes involving a fast meson. The slight asymmetry results from the difference in the gluon distributions of the nucleon and the pion. The earlier discussed observations for the DY process apply here

again and, due to the predominance of gg fusion, remain for different beams unchanged. In the $y = 0$ region one verifies the x_h dependence [plotted against $x_h^* \equiv x_h/(1-x_2)$] to be the same as in the analogous purely hadronic processes apart from the over-all factor $\sim 4 \cdot 10^{-13}$ between the two reaction types.

We investigate the ratio of the charged-pion spectra

$$R(\pi^+/\pi^-) \equiv \frac{d\sigma(B+\bar{T} \rightarrow \gamma^*/\mu + \pi^+ + X)}{d\sigma(B+\bar{T} \rightarrow \gamma^*/\mu + \pi^- + X)} = R(x_h^*, y) \quad (7)$$

By exposing in Fig. 3a the x_h^* dependence we focus on the recombination process. In Fig. 3b instead the DY variable y is varied at large x_h^* .

Fast meson production in the target fragmentation region in association with a massive μ pair is influenced by several factors : (i) the amount of valence up/down quarks in the target and their momentum distributions, (ii) the interplay between the different parton-antiparton contributions to μ pair production, (iii) the dynamical behaviour of the three parton distributions involving in particular assumptions on the valence plus sea parametrization, and (iv) the constraints following from the quark quantum numbers.

We analyze Fig. 3a. Hadronic $\pi^\pm$ production (no μ pair) in the proton fragmentation region reveals a strongly rising π^+/π^- ratio due to the $(1-x)$ difference between the $u_v(x)$ and $d_v(x)$ momentum distributions (see curve 1). In the fragmentation region of a neutron target the π^+/π^- ratio decreases from 1 to 0 with increasing x_h values since $\overset{\text{Proton}}{u}(x) = \overset{\text{Neutron}}{d}(x)$ and vice versa. Therefore on a nuclear target with $Z = (A-Z)$, $R(\pi^+/\pi^-)$ remains constant whereas for heavier nuclei with $Z < (A-Z)$ it decreases from 1 to ~ 0.7 .

We now consider fast $\pi^\pm$ production on a proton target in association with a massive μ pair at $x_1 = x_2 = \sqrt{\tau}$.

At small $\sqrt{\tau}$ values (solid curves in Fig. 3a) massive μ pair production is dominated by sea-quarks (or gluons). The π formation process is consequently not disturbed (apart from momentum conservation), and we expect a rising π^+/π^- ratio. ψ production follows almost exactly the hadronic curve 1. The curves 2 represent DY $q\bar{q}$ annihilation with $p, \bar{p}, \pi^\pm, K^\pm$ beams on a proton target. It is dominated by the beam target combinations $u(\bar{u}\pi)$ (20-40%) and $\bar{u}(u\pi)$ (40-60%) where the first symbol stands for the beam parton. In parentheses [e.g. (uh)] we indicate the target parton participating in $\mu^\pm$ pair production and the fast final state meson h .

The relative importance of the various parton combinations, indicated by the percentages, depends on the beam and target hadrons and the final state $\pi^\pm$ meson. The difference in size of the u and $\bar{u}$ factor in the three-parton momentum distribution, Eq. (6), the permutation factors for identical partons, and to a lesser degree the quark charges are at the origin of the discrepancy between the curves 1 and 2. Curve 3 represents the π^+/π^- ratio for semi-inclusive γ^* or ψ production on a nuclear target. Its slight decrease and little dependence on the beam particle follows from the neutron and proton mixture in the target.

At large $x_1 = x_2 = \sqrt{\tau}$ values (dashed curves in Fig. 3a), electromagnetic μ pair production on a proton target is dominated by valence-valence annihilation (for $\bar{p}p$, π^-p , K^-p scattering) and by valence-sea annihilation (for pp , K^+p scattering). Semi-inclusive $\pi^\pm$ production is influenced by the $\bar{u}(u\pi)$ ($> 95\%$) combination in the first case, and by $u(\bar{u}\pi)$ ($50 \rightarrow 30\%$ with increasing x_h^*) plus $\bar{u}(u\pi)$ ($30 \rightarrow 50\%$) in the second. Less valence u quarks are thus available for $\pi^\pm$ production leading to a much slower rise of the π ratio; the above indicated processes lead to curve 2.

π^+p scattering instead reveals a strongly rising π^+/π^- ratio (curve 4). Indeed, at large x_h^* values semi-inclusive $\gamma^*\pi^+$ production is dominated by the quark combination $\bar{d}(d\pi^+)$ ($> 70\%$) whereas $\gamma^*\pi^-$ production is built up by $u(\bar{u}\pi^-)$ ($\sim 30\%$), $\bar{u}(u\pi^-)$ ($\sim 40\%$), $\bar{d}(d\pi^-)$ ($< 30\%$). Fast π^+ production is therefore not inhibited whereas π^- production is considerably reduced since there is only one valence d quark in a proton.

We analyze Fig. 3b where emphasis is placed on the difference between semi-inclusive DY (solid lines) and ψ (dashed lines) μ pair production. The rapidity y is varied at small and large $\sqrt{\tau}$ with x_h^* fixed, large, and a proton target is used unless otherwise specified. The importance of a specific parton type for μ pair production can therefore be studied.

At small $\sqrt{\tau}$ the π^+/π^- ratio remains almost unchanged since massive μ pair production is dominated by sea-quarks or gluons (see curves 1). If nuclear targets (such as, e.g., tungsten) are used the ratio drops below 1 (curve 2) since the amount of valence u , d quarks as well as their momentum distributions are changed. As $\sqrt{\tau}$ increases the π^+/π^- ratio in semi-inclusive ψ production signals the upcoming of quark annihilation as compared to gluon fusion (curve 3).

At large $\sqrt{s}$ the competition among the valence u quarks sets in, and the π ratio is considerably reduced (curve 4). The strong y variation in π^+p scattering (curve 5) results from the small π^- production rate in the central region where $\bar{d}(d\pi)$ annihilation dominates.

Fixed target DY experiments with high statistics such as, for instance, the NA10 experiment¹⁰⁾ at the CERN-SPS offer in their backward hemisphere the possibility for an analysis of the above-discussed reaction mechanism. In the centre-of-mass system, the fast final state meson h in reaction (1) emerge along the negative beam direction with little transverse momentum. A Lorentz transformation into the lab system projects almost all reaction products in the (lab) forward direction. Only light (or massless) particles with sufficient centre-of-mass momentum can still leave in the lab backward hemisphere which, for $90^\circ \leq \theta_{lab} \leq 180^\circ$ corresponds to $174^\circ \leq \theta_{cm} \leq 180^\circ$, roughly. All hadrons detected in this area are from the target fragmentation region. Thus, the set-up of a hadron detector in this region (in coincidence with a massive μ pair) selects the reaction products we focused upon in the above analysis.

Using the p_t distributions of purely hadronic soft particle production as given in Ref. 9), we determine the cross-section of reaction (1) with the kinematical variables for meson h set in the lab frame. The spectrum in Fig. 4 of a hadron trigger at $\theta_{lab} = 90^\circ$ (in coincidence with the μ pair) exposes the rapidly decreasing cross-section as the lab momentum grows. At the earlier defined kinematical conditions the momentum spectrum never exceeds $p_{lab} \sim 1$ GeV/c and further decreases as the centre-of-mass energy grows. Since the Lorentz transformation significantly depends on the mass of the triggered hadron different x_h ranges are selected. The range $0.1 \text{ GeV/c} \leq p_{lab} \leq 0.7 \text{ GeV/c}$ for $\pi^\pm$ (at $\theta_{lab} = 90^\circ$) corresponds to $0.2 \leq x_h \leq 0.8$ with the centre-of-mass longitudinal momentum distribution varying in the range $2.5 \text{ GeV/c} \leq -p_L \leq 11 \text{ GeV/c}$. Similarly the lab momentum of the $K^\pm$ mesons varies in the range $0.1 \text{ GeV/c} \leq p_{lab} \leq 0.5 \text{ GeV/c}$ corresponding to $0.5 \leq x_h \leq 0.9$ with the centre-of-mass longitudinal momentum in the range $7 \text{ GeV/c} \leq -p_L \leq 12 \text{ GeV/c}$. A 90° hadron trigger at a given lab momentum thus selects different x_h values for trigger particles with different masses. Reducing θ_{lab} of the hadron trigger stretches the spectrum to larger momentum values with the lab and centre-of-mass momenta almost linearly related for a given lab angle. The possibility for the detection of particles with masses $m_h \gtrsim 1 \text{ GeV}$ also significantly grows.

With the above study of massive lepton pair production with a hadron trigger we aimed :

- (i) to point anew to the theoretical and experimental interest of the semi-inclusive DY type processes, giving order-of-magnitude estimates for the cross-sections ;
- (ii) to illustrate in a simple phenomenological model the hidden theoretical issues ;
- (iii) to work out the predictions of the recombination model as one of the favoured schemes to describe soft-hadron production ; and
- (iv) to suggest how existing fixed target DY experiments could measure these processes.

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FIGURE CAPTIONS

- Fig. 1 Drell-Yan process with an associated hadron h in the recombination model.
- Fig. 2a Drell-Yan massive lepton pair production : $\pi^- + W/p \rightarrow \gamma^* + (h) + X$. Rapidity distribution without (DY) and with an associated hadron ($\pi^\pm, K^\pm$) on a tungsten (solid lines) and a proton target (dashed lines) at $s = 752 \text{ GeV}^2$, $M = 4 \text{ GeV}$ and $x_h = 0.5$.
- Fig. 2b Drell-Yan-like ψ production : $\pi^- + W/p \rightarrow \psi + (h) + X$. ψ rapidity distribution without (ψ) and with an associated hadron ($\pi^\pm, K^\pm$) on a tungsten (solid lines) and a proton target (dashed lines) at $s = 752 \text{ GeV}$ and $x_h = 0.5$.
- Fig. 3a Ratio of the charged pion spectra $R(x_h^*, y=0)$ [see Eq. (7)] plotted versus $x_h^* = x_h/(1-x_2)$ at small (solid lines) and large (dashed lines) $x_1 = x_2 = \sqrt{\tau}$ values. The proton (curves 1,2,4) and the tungsten (curve 3) targets are analyzed for different beams ; thick lines indicate a set of closed-by curves.
- Fig. 3b Ratio of the charged pion spectra $R(x_h^* = 0.8, y)$ [see Eq. (7)] plotted versus the $\mu^\pm$ pair rapidity y at small and large $\sqrt{\tau}$ for DY (solid lines) and ψ (dashed lines) production. The proton (curves 1, 3,4,5) and the tungsten (curve 2) targets are analyzed for different beams ; thick lines indicate a set of closed-by curves.
- Fig. 4 Associated hadron spectrum for $\pi^- W \rightarrow \psi + h + X$ at 90° in the lab system with fixed ψ rapidity $y = 0$, and $s = 752 \text{ GeV}^2$.

FIG. 1

Fig. 2a

Fig.2b

Fig. 3a

Fig. 3b

Fig. 4