HIGH P_T HADRON CROSS-SECTION AT NEW COLLIDER ENERGIESY. Muraki^{*)}

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Since the discovery of high P_T hadrons at CERN ISR¹⁾, a number of investigations have been made to elucidate this phenomenon. Several remarkable features have been found²⁾. However no theory exists which can explain this phenomenon satisfactorily. The naive gluon exchange model³⁾ cannot predict in the low P_T region ($P_T = 2 - 6$ GeV/c) and the quark interchange model⁴⁾ fails to describe the high P_T region ($P_T = 6 - 14$ GeV/c). Neither model is capable of explaining the heavy particle increase at high transverse momentum.

On the other hand, the Drell-Yan lepton pair production process, induced by hadron-hadron collisions, can be beautifully described by simple parton model predictions⁵⁾ and is one of the best -explained processes in current particle physics.

In 1981, ultra high energy research starts at CERN, in 1983 at Fermilab and in 1984 at BNL (Isabelle). The corresponding laboratory energies are 150, 2000 and 320 TeV respectively. Antiproton-proton collisions at $\sqrt{s}=60$ GeV will also be available in 1981 in the CERN ISR. Again high P_T hadron production cross-sections will be actively studied. Therefore it is important to provide reliable predictions of the differential cross-section

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at these machine energies.

In this paper the high P_T hadron differential cross-section $d\sigma/dP_T$ in the new high energy region is deduced by analogy with the Drell-Yan mechanism.

When one compares the Drell-Yan diagram (Fig. 1a) with the high P_T hadron production diagram (Fig. 1b), one observes a strong similarity between the two processes. The only differences are the coupling constant and the fragmentation process of the quark pair into hadrons. Therefore one can expect that the high P_T jet cross-section will be given by the Drell-Yan cross-section,

$$\left. \frac{d^2\sigma}{dM dy} \right|_{y=0}^{\text{jet}} \approx \left(\frac{g}{\alpha} \right)^2 \cdot \left. \frac{d^2\sigma}{dM dy} \right|_{y=0}^{\text{D-Y}}. \quad (1)$$

Here M and M imply the invariant mass between two jets and the mass of the Drell-Yan photon and g and α are the coupling constants at the vertex.

This idea may be checked by comparing the high P_T inclusive hadron cross-section with the single lepton P_T -distribution from the Drell-Yan particle, $d\sigma/dP_{T_\ell} \big|^{D-Y}$. Since $d\sigma/dP_{T_\ell} \big|^{D-Y}$ has not yet been published, a Monte Carlo calculation has been made to derive $d\sigma/dP_{T_\ell} \big|^{D-Y}$ from the Drell-Yan mass distribution $d\sigma/dM \big|^{D-Y}$. The P_T distribution of the single lepton from the Drell-Yan photon is presented in Fig. 2 where we observe a sharp peak at $P_T \approx M/2$ (i.e. half of the Drell-Yan mass).

It is also known that the high P_T hadron production cross-section is not significantly affected by the processes such as

soft gluon emission or recombination effects. The perturbation effect of soft gluon emission is considered to be about 500 MeV⁶⁾. Therefore, in first approximation, the transverse momentum of the high P_T hadron will be determined by the transverse momentum of the quark pair at the vertex : $P_{T_{had}} \leq P_{T_{quark}}$.

Hence we deduce the following relation between $P_{T_{had}}$ and Drell-Yan mass M^{D-Y} at $m_{jet} \approx M_{D-Y}$,

$$P_{T_{had}} \lesssim P_{T_{quark(jet)}} \approx P_{T_{lepton}} \lesssim M_{D-Y}/2. \quad (2)$$

Using Eqs.(1) and (2), we expect the following relation between the inclusive high P_T hadron production cross-section and the Drell-Yan mass distribution,

$$\left. \frac{d^2\sigma}{dP_{T_{had}} dy} \right|_{y=0}^{had} \approx \left(\frac{g}{\alpha} \right)^2 \cdot \left. \frac{d^2\sigma}{d(M/2) dy} \right|_{y=0}^{D-Y}. \quad (3)$$

The inclusive high P_T pion cross-sections are shown in Fig. 3, together with the Drell-Yan cross-section. According to Eqs. (2) and (3), the horizontal axis of the Drell-Yan mass distribution should be reduced by a factor 2, and the cross-section of the high P_T hadrons should be multiplied by α^2 . In fact good agreement has been obtained for the horizontal reduction factor $\eta \approx 2.5$ and $g=1.0$. Fig. 3a corresponds to Fermilab energies ($\sqrt{s}=27.6$ GeV) and Fig. 3b to CERN ISR energies ($\sqrt{s}=62.4$ GeV). Even if we neglect the influence of quark fragmentation into hadrons, both cross-section agree well in the region of $P_T > 4$ GeV/c or $M_{D-Y} > 9$ GeV (i.e. above upsilon mass).

The original quark P_T distribution can be estimated, by dividing the inclusive hadron cross-section by the fragmentation

function $D(z)=(1-z)^2/z$, $z=2P_{T\text{had}}/P_{\text{quark}}^{7)}$. The original quark P_T distribution corresponds to the jet P_T distribution. As shown in Fig. 4a, the agreement of both cross-sections has been verified over 5 orders of magnitude. Here we have normalized the jet cross-section to the inclusive hadron cross-section at 2 GeV/c. A good fit is obtained for $g = 1.37$ and $\eta = 2.0$.
($z=0.06$)

Since our assumption successfully describes the high P_T hadron production cross-section for $P_T > 2.5$ GeV/c at Fermilab and ISR energies, $d\sigma/dP_{T\text{had}}$ distributions for three ultra high energies have been calculated. The procedure is as follows: the Drell-Yan cross-section of Fig. 4b expressed by curve b or c is considered as the reduced high P_T inclusive hadron production cross-section for the respective new accelerator energy at the P_T value of the lower horizontal axis. The reduction factor of the ordinate α^2 and the real cross-section has been indicated on the right ordinate of Fig. 4b. It is interesting to note that the $d\sigma/dP_{T\text{had}}|_{y=0}$ values are very similar for the three different energies in the P_T range 4 - 100 GeV/c; however the luminosity of Isabelle is expected to be much larger than for the two $\bar{p}p$ colliders. The upper limits for the observation of Drell-Yan particles and high P_T hadrons are presented in Table I.

As shown in Table I, the new accelerators will be powerful probes to study the internal structure of quarks, the quark-anti-quark distribution in nucleons, and the binding force between quark and anti-quark using data of both Drell-Yan and high P_T hadrons.

One interesting experiment will be the study of the ratio of the cross-section for same energy opposite sign particles. The expected ratios of $d\sigma/dP_T$ induced by $\bar{p}p$ and pp collisions at $\sqrt{s} = 60$ GeV have been calculated, assuming valence quark, sea quark and gluon distributions of $(1-x)^3/x$, $(1-x)^8/x$ and $(1-x)^6/x$ respectively. If the standard gluon exchange model⁸⁾ works well, the ratio will be almost 1.0. However if quark-antiquark annihilation into a gluon dominates, the ratio will be 1.4, 1.6, and 2.0 at $P_T = 6.2, 9.4$, and 12.5 GeV/c respectively.

Another interesting feature will be the asymmetry in rapidity of two jets where the mean rapidity of the two jets is non-zero. The particle charge ratios π^+/π^- , K^+/K^- , and $\bar{p}/p$ in any kinematical region will be determined by the structure functions of the u, d quark, the sea quarks ($\bar{u}, \bar{d}, \bar{s}$), and the fragmentation function with the leading hadrons. However if the $\bar{q}q$ annihilation diagram dominates, then the particle composition will be determined by the phase volume defined by the mass of vector boson and quark charge at the vertex. It will be interesting to check whether Morrison's rule⁹⁾ can extend to the colour quantum number exchange process.

Finally we would like to point out two facts. Eq.(3) naturally leads to the constancy of the R-ratio ($\equiv$ single prompt lepton / high P_T hadrons) in the high P_T region. In other words, the experimental fact that the R-ratio ($\equiv \ell/\pi$) is constant in the wide range of P_T , supports the validity of our hypothesis.

Secondly, in the region of lower $\sqrt{s}$ (ex. $\sqrt{s} = 27.4$ GeV), high P_T hadron cross-sections can be described by an exponential form¹⁰⁾, while at ISR energies, a power behaviour works better. This follows from the shape of the Drell-Yan cross-section : $d\sigma/dM^2 \propto 4\pi\alpha^2/3M^4 F(\tau)$, $F(\tau) \propto \exp(-\beta \cdot 2P_T/\sqrt{s})$. In the lower $\sqrt{s}$ region, the exponential term $F(\tau)$ dominates, while in the higher $\sqrt{s}$ region, the power term M^{-4} defines the cross-section. At $\sqrt{s} \rightarrow \infty$, Drell-Yan and high P_T cross-section will be described by power laws, namely M^{-4} and P_T^{-4} respectively.

Our paper is summarized as follows :

- (1) inclusive high P_T hadron cross-sections and jet cross-sections can be described by analogy with the Drell-Yan mass spectrum.
- (2) the Drell-Yan cross-section $d\sigma/dM_{D-Y}$ can therefore be identified with the high P_T hadron (jet) production cross-section :
$$\left. \frac{d^2\sigma}{d(M/2) dy} \right|_{D-Y}^{y=0} \approx \alpha^2 \left. \frac{d^2\sigma}{dP_T dy} \right|_{had}^{y=0}.$$
- (3) the increasing high P_T hadron production cross-section with increasing energy $\sqrt{s}$ has the same explanation as the increasing high mass Drell-Yan photon formation probability with $\sqrt{s}$.
- (4) $d\sigma/dP_T^2 \big|_{had}^{y=0}$ of hadrons at high P_T region induced by hadron-hadron collisions obeys a P_T^{-4} law at $\sqrt{s} \rightarrow \infty$, while at lower energies it follows an exponential shape. Cosmic ray data support P_T^{-4} behaviour¹¹⁾.
- (5) the constancy of the R-ratio ($\approx 10^{-4}$) for a wide range of P_T can be naturally explained by our conjecture.

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Figure Captions

Fig. 1 The Drell-Yan diagram(a) and the quark-antiquark annihilation mechanism for high P_T hadron production(b).
----(photon) and ~~oooo~~ (gluon) lines. The quark pair fragments into two jets.

Fig. 2 Monte Carlo P_T distribution of the single lepton from the Drell-Yan particle with mass $M=10, 40, 80$ GeV.
A sharp peak is found at $P_T \approx M/2$.

Fig. 3 The comparison of the Drell-Yan cross-section with the high P_T inclusive cross-section for (a) Fermilab experiments($\sqrt{s}=27.4$ GeV) and (b) CERN ISR experiments ($\sqrt{s}=62.4$ GeV). The inclusive high P_T pion cross-section is reduced by a factor $1/\alpha^2$ and the horizontal scale is also reduced as factor 2.5.

Fig. 4 (a) the comparison of the Drell-Yan cross-section with the high P_T jet (quark) cross-section for ISR experiments. High P_T jet cross-section is reduced by a factor 10^4 and P_T scale is reduced by factor 2.0.
(b) the prediction of Drell-Yan and high P_T inclusive hadron cross-section for new accelerators: a; $\sqrt{s} \rightarrow \infty$, b; FNAL colliders and c; CERN $\bar{p}p$ colliders.

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Table I

Beam	$\bar{p}p$		pp
	CERN	FNAL	
Maximum High P_T Hadrons (GeV/c)	80	140 (260)	230
Maximum Drell-Yan Mass (GeV)	60	80 (140)	220
for Luminosity	10^{30}	10^{30} (10^{31})	10^{33}

(a)

(b)

Fig. 1

Fig. 2

FIG. 3

(a)

(b)

FIG. 4