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EVIDENCE FOR MULTIPLE PARTON INTERACTIONS
FROM THE OBSERVATION OF MUTI-MUON EVENTS
IN DRELL-YAN EXPERIMENTS

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A B S T R A C T

We calculate the production of two lepton pairs via the Drell-Yan mechanism. To establish the existence of multiple parton interactions in a single hadron collision lepton pair production is superior to jet production from the theoretical, phenomenological and experimental points of view. The calculated rate agrees with the previously unexplained four-muon events observed in πp and pp interactions. We confirm a recent analysis of ISR four-jet events and discuss some implications of this study.

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The question of multiple parton interactions in a single hadronic collision has rapidly moved from a theoretical curiosity to a critical issue,¹ related to the study of higher order QCD processes, to the general problem of very high energy minimum-bias interactions and to the study of nucleus-nucleus interactions where such events become abundant. Multiple production of weak bosons via multiple parton interactions is also a potential background for new physics searches such as $H \rightarrow WW$ decay with future hadron colliders.

There is now evidence that with increasing energy a growing fraction of hadron collisions produce final states containing jets, which are calculable in perturbative QCD.² It has even been conjectured that all non-scaling features of hadronic interactions are dictated by hard scattering.³ This is an important issue as, by extrapolation, all very high energy interactions are expected to be rich in jet structure. This would certainly affect the procedures proposed to extract new physics from future large hadron colliders, such as the SSC, where the detectors view a pile-up of minimum-bias events at 10^{33}cm^{-2} luminosity. The hard scattering cross-section above some small fixed momentum fraction $x_{\min}$ violates unitarity in the high energy unit.⁴ This is not, however, a problem since with decreasing x more and more partons are stacked inside the colliding hadrons and multiple partonic interactions become increasingly important. They presumably restore unitarity and will, of course, influence the event structure.

Recently the AFS experiment at the CERN ISR claimed evidence for double parton interaction in very high transverse energy four-jet events.⁵ Such events apparently could not be accounted for by the standard QCD $2 \rightarrow 4$ hard scattering subprocesses. On the other hand, the UA2 collaboration failed to observe multiple parton interactions at $\sqrt{s} = 630 \text{ GeV}$.⁶ It has further been argued that

these contrasting results are not necessarily in contradiction,⁵ see also M. Jacob.¹

To help resolve this issue we propose a study of the multiple production of Drell-Yan lepton pairs. In this case the theory is well-understood, the phenomenology under control and the experiments relatively clean. In principle, therefore, this is a superior laboratory for the study of multiple parton interactions. For a previous discussion see Goebel, *et al.*¹ Suprisingly, the relevant data exist in the literature.

The cross-section for the production of two Drell-Yan pairs with invariant masses m_a, m_b and rapidities y_a, y_b is given by

$$\frac{d\sigma^{(2)}}{dm_a^2 dy_a dm_b^2 dy_b} = \frac{\sigma_0(m_a^2)\sigma_0(m_b^2)}{\pi R^2} q(x_{a_1}, x_{b_1}) q(x_{a_2}, x_{b_2}) \quad (1)$$

with

$$\begin{aligned} m_a^2 &= x_{a_1} x_{a_2}, \quad x_{F_a} = x_{a_1} - x_{a_2} = \frac{2m_a}{\sqrt{s}} \sinh y_a \\ m_b^2 &= x_{b_1} x_{b_2}, \quad x_{F_b} = x_{b_1} - x_{b_2} = \frac{2m_b}{\sqrt{s}} \sinh y_b \\ \sigma_0(m^2) &= \frac{4\pi\alpha^2}{9m^2 s} e_q^2. \end{aligned} \quad (2)$$

The kinematics are illustrated in Fig. 1. In Eq. (1), $q(x_i, x_j)$ is the joint probability to find quarks with momentum fractions x_i, x_j inside the hadron. We will argue later that $q(x_i, x_j)$ can be adequately represented by

$$q(x_i, x_j) = q(x_i)q(x_j)(1 - x_i - x_j). \quad (3)$$

Note that Eq. (1) implies a summation over all pairs of quarks and antiquarks in both hadrons (weighted by appropriate charges) which can give rise to a 4-lepton

final state. The joint probabilities in, for example, a proton are thus

$$\begin{aligned}
 q_{uu}^p(x_i, x_j) &= \left[\frac{1}{4} u_v(x_i) u_v(x_j) + u_v(x_i) s(x_j) \right. \\
 &\quad \left. + s(x_i) u_v(x_j) + s(x_i) s(x_j) \right] (1 - x_i - x_j) \\
 q_{dd}^p(x_i, x_j) &= \left[d_v(x_i) d_v(x_j) + d_v(x_i) s(x_j) \right. \\
 &\quad \left. + s(x_i) d_v(x_j) + s(x_i) s(x_j) \right] (1 - x_i - x_j) \\
 &\vdots
 \end{aligned} \tag{4}$$

On the right-hand-side of Eq. (4) appear standard quark structure functions with a sea $s(x)$ common to u, d, s quarks and antiquarks. There are a total of 21 such quark pairs to be considered in each hadron.

The above discussion is relevant for single hadron-single hadron collisions. For hadron-nucleus collisions, the discussion is rather different. It is known that for nuclear targets the single Drell-Yan cross-section scales as A^1 , indicating that the incoming hadron scatters incoherently off all the nucleons in the target. For the double Drell-Yan process of Fig. 1 we analogously expect the two quarks in the incoming hadron to annihilate with quarks belonging to *different nucleons* of the nucleus. Hence the "parton beam cross-section" πR^2 in Eq. (1) becomes the nuclear size and the overall nuclear scaling factor is $A^2/A^{\frac{2}{3}} = A^{\frac{4}{3}}$. Moreover the target structure functions $q(x_i, x_j)$ are simple products of nucleon structure functions, i.e., for the nucleus Eq. (4) is replaced by

$$\begin{aligned}
 q_{uu}^A(x_i, x_j) &= [u_v(x_i) + s(x_i)] [u_v(x_j) + s(x_j)] \\
 q_{dd}^A(x_i, x_j) &= [d_v(x_i) + s(x_i)] [d_v(x_j) + s(x_j)] \\
 &\vdots
 \end{aligned} \tag{5}$$

Note that there is no phase space factor $(1 - x_i - x_j)$ in Eq. (5) for nuclear targets.

We have evaluated the double Drell-Yan cross-section $\sigma^{(2)}$ at $\sqrt{s} = 27$ GeV using the structure functions of Ref. 7. Since they require a $K = 2$ factor to obtain agreement between calculated and measured single lepton-pair cross-section, we include a $K^2 = 4$ enhancement factor in Eq. (1). The lepton pair masses m_a, m_b were chosen as the relevant scales in the QCD-evolved structure functions. The results agree well with the observed 4-muon rate in the NA3 experiment;⁸ see Table 1. This agreement is achieved for $R = 0.7$ fm, the usual value for the proton radius. This is consistent with the value of 0.6 fm obtained from the study of 4-jet events.⁵ (Note that the ISR data was analysed using a cross-section parametrized as $\pi(2R^2)$ in the denominator of Eq. (1). Hence their quoted value of 0.3 fm for R corresponds to 0.6 fm in our normalization.) In comparing the calculated and measured event rates we have included the appropriate experimental cuts on the decay muons, as listed in Table 1. The effect of the muon p_T cut is shown explicitly.

This agreement is not fortuitous. We have repeated the calculation for $\pi^- p$ collisions and again find agreement with the measured event rate (Table 2). Note that we have used the pion structure functions from the same experiment with $K = 2$. Table 2 also shows the corresponding cross-section for $p_{\text{lab}} = 800$ GeV/c.

Returning to the double quark distribution functions, our ansatz (Eq. (3)) is well-motivated for sea quarks since one expects factorization to hold in the $x_i, x_j \rightarrow 0$ limit and phase space requires the $(1 - x_i - x_j)$ factor. Similarly, factorization dictates the form of the valence-sea distributions, such as q_{dd}^p in Eq. (4). The argument is, however, less convincing for valence-valence distributions which are important at intermediate x_i, x_j and for which the effects of momentum conservation are important. Therefore to motivate the factorizing form, Eq. (3),

for valence quarks also we consider the explicit distributions proposed in Ref. 9, which satisfy the sum rule constraints exactly. The valence-valence distribution in a proton is taken to be

$$q_{vv}(x_1, x_2) = \frac{7}{2\pi} \frac{(1 - x_1 - x_2)^{\frac{5}{2}}}{(x_1 x_2)^{\frac{1}{2}}} \quad (6)$$

where $q_{uu} = q_{vv}$ and $q_{ud} = 2q_{vv}$. The single valence quark distribution is then

$$q_v(x_1) = \int_0^{1-x_1} dx_2 q_{vv}(x_1, x_2) = \frac{35}{32} \frac{(1 - x_1)^3}{x_1^{1/2}}, \quad (7)$$

consistent with the usual counting rules for $x \rightarrow 1$ and Regge behavior when $x \rightarrow 0$. Now $q_u = 2q_v$ and $q_d = q_v$. Comparing the expression in Eq. (6) with its factorized form obtained from Eq. (7) we have

$$\frac{q_{vv}(x_1, x_2)}{q_v(x_1)q_v(x_2)(1 - x_1 - x_2)} = 0.93 \frac{(1 - x_1 - x_2)^{\frac{5}{2}}}{(1 - x_1)^3(1 - x_2)^3}. \quad (8)$$

In the region $x = 0.1 - 0.2$ where valence quarks are important the above ratio is 1.2 - 1.5. Hence the factorization prescription somewhat underestimates the true distribution, but the margin of error is within the uncertainties caused by our ignorance of other dynamic effects. In practice, it is preferable to use the factorized form since realistic valence distributions are then available, which incorporate scaling violations and distinguish u and d quarks.

The above discussion assumes that double quark-antiquark annihilation is the dominant source of 4-muon events. There are, however, at least two other mechanisms which can give the same final state. The most copious is of course $\psi\psi$ production which has been removed by the lepton pair cuts in the analysis

presented here. Higher order QED diagrams can also contribute, in particular, $q\bar{q} \rightarrow \gamma^*\gamma^* \rightarrow \mu^+\mu^-\mu^+\mu^-$.⁹ We have calculated this cross-section—using the same cuts as before—and obtained a result about a factor 5–6 smaller than the multiple scattering results in Tables 1,2. This can be understood in terms of a nuclear suppression factor $A^{\frac{1}{3}}$ (≈ 6 for $A = 195$) relative to the multiple parton collisions. Notice, however, that the broader transverse momentum distribution of the lepton pairs produced via $qq \rightarrow \gamma^*\gamma^*$ makes it easier for the muons to pass the p_T cuts. (The average p_T of each pair is calculated to be 1.5 GeV/c.) Since we have neglected the virtual photon transverse in each of our $q\bar{q} \rightarrow \gamma^*$ interactions, we have certainly underestimated the multiple interaction events passing the p_T cuts, with respect to the $q\bar{q} \rightarrow \gamma^*\gamma^*$ events. We conclude that the rate from $q\bar{q} \rightarrow \gamma^*\gamma^*$ is about an order of magnitude smaller than the double Drell-Yan rate, and cannot therefore account for the measured rate.

In conclusion, the agreement we have obtained with the data on double Drell-Yan production off a Platinum target shows that several quarks in a hadron can indeed experience independent hard collisions. The joint probability for finding two quarks with momentum fractions x_i, x_j appears to be adequately described by the simple factorized form of Eq. (3) with the $(1 - x_i - x_j)$ factors removed as the target is a nucleus. The two quarks can penetrate the Platinum nucleus and scatter incoherently off any two of the nuclear quarks, which usually belong to different nucleons.

We note that because of the nuclear effects, our results for the radius R (≈ 0.7 fm) appearing in the double Drell-Yan cross-section (Eq. (1)) cannot be directly compared to that obtained in the ISR pp experiment. In our case $A^{\frac{2}{3}}\pi R^2$ must be the well-known nuclear cross-section. In contrast, it is the effective

transverse spread of valence quarks in a single photon which is measured in the ISR experiment.

Multiple scattering processes may become quite important in nucleus-nucleus collisions. If the partons scatter incoherently the single hard scattering process should scale as A^2 , whereas the double scattering scales as $A^4/A^{\frac{2}{3}} = A^{\frac{10}{3}}$. Hence compared to pp collisions, the double/single scattering cross-section rate is enhanced by a factor $A^{\frac{4}{3}} \sim 10^3$ in collisions of heavy nuclei.

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p_{T_a} (GeV/c)	p_{T_b} (GeV/c)	σ (pb)	Events	
			Theory	Expt. ⁸
0.5	0.5	.90	3600	
0.5	1.0	.12	470	
1.0	1.0	4.0×10^{-3}	16	
1.0	1.5	1.6×10^{-3}	6.5	6 ± 3
1.5	1.5	1.8×10^{-4}	0.7	

Table 1. The cross-section for $pp \rightarrow 2(\mu^+\mu^-) + X$ at $p_{\text{lab}} = 400$ GeV/c when the two positive muons have $p_T(\mu^+) > p_{T_a}$ and $> p_{T_b}$, respectively. Each $\mu^+\mu^-$ pair satisfies $m_{\mu\mu} < 2.6$ GeV/c², and $x_F > -0.2$. Also shown is the expected number of events for the p - Pt experiment, obtained using an $A^{\frac{4}{3}}$ scaling law and the quoted luminosity.

p_{lab} (GeV/c)	σ (pb)	Events	
		Theory	Expt. ¹⁰
280	0.012	3.3	3
800	0.018		

Table 2. The cross-section for $\pi^-p \rightarrow 2(\mu^+\mu^-) + X$ at two values of p_{lab} . The cuts are as described in Table 1, with $p_{T_a} = 0.4$ GeV/c and $p_{T_b} = 1.0$ GeV/c.

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FIGURE CAPTION

Fig. 1. Kinematics of the double Drell-Yan mechanism.

Fig. 1