A Sensitive Test of QCD from Parton-Parton Scattering at the ISR

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Abstract

Production of jets with fast leading fragments has been studied in deep inelastic proton proton interactions using the Split Field Magnet detector at the CERN ISR. The kinematics of the underlying parton processes is determined on an event by event basis. Parton scattering amplitudes are extracted for scattering angles, Θ^* , in the interval $-0.4 < \cos\Theta^* < 0.9$. The data, which are known to be dominated by quark gluon scattering, agree with predictions from lowest order QCD, while e.g. an abelian theory can be excluded.

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I. INTRODUCTION

The mechanisms responsible for the production of single particles and jets with large transverse momenta in proton proton interactions have been studied extensively over the last decade, both experimentally [1] and theoretically [2]. It is well established that these rare processes are dominated by scattering of constituents of the protons, mostly quarks and gluons. Model calculations based on lowest order QCD [3] have been successful in reproducing event structures in full phase space [4]. A dedicated experimental investigation of the scattering dynamics is, however, complicated as partons are not directly observed, but rather the emerging jets of hadrons. Therefore, the scattered partons are usually not identified. In this paper this difficulty is overcome by determining the kinematics of flavor-tagged partons, and by selecting appropriate kinematic configurations.

In a typical hard scattering process two partons (quarks or gluons) undergo an 'elastic' interaction with large momentum transfer leading to two sideways jets with large transverse momenta, p_T . These events can be selected experimentally by the presence of a 'trigger' hadron with large transverse momentum, p_T^{tr} , which is the leading fragment of one of the side-ways jets (called 'trigger' jet). The recoiling jet (called 'away' jet) is generally only subject to energy-momentum conservation. Finally, two spectator jets along the directions of the incoming protons originate from the proton remnants which did not participate in the hard parton interaction.

The analysis of parton parton scattering presented in the following is based upon an experiment which was performed with the Split Field Magnet (SFM) detector at the CERN-ISR. The experimental setup is described elsewhere [5]. The analysis is based on 76.000 events with identified π^+ , π^- or K^+ triggers with $p_T^{\text{tr}} > 4 \text{ GeV}/c$ at polar angles $\theta_{\text{CM}} \approx 40^\circ \dots 60^\circ$ in the proton proton rest system, recorded at an invariant proton proton energy $\sqrt{s} = 62 \text{ GeV}$. All data are corrected for detector acceptance.

The event structure and the flavors of the scattered partons are well defined for these events :

- i) The trigger particle is the leading fragment in the trigger jet. It carries on the average a fraction $z_{\text{tr}} \approx 0.7 \div 0.8$ [6] of the jet momentum. In a fragmentation chain picture [7] the trigger particle contains therefore in most cases the scattered parton. This is supported by data on current jets from νN interactions [8]. Contributions from decays of resonances are small [9]. The quantum numbers of the trigger particle reflect thus the flavor of the 'trigger' parton [10]. Positive (negative) pions come

mainly from scattered up-quarks (down-quarks). Triggers from gluon jets are suppressed in the p_T^{tr} range under consideration [10,11]. Hence, the toward parton is generally a quark. The average angle between the momenta of the 'trigger' parton and of the trigger particle was measured to be negligible [12].

- ii) Measured charge and longitudinal momentum structures of away jets imply a dominantly gluonic origin [13], as expected for these kinematic configuration from lowest order QCD [4a]. A quantitative description of away jet properties is achieved by including gluon radiation in the initial and final state [4b,c].
- iii) The quantum numbers of the spectator jets are correlated with those of the sideways jets [10]. This correlation supports the flavor identification of the trigger parton; it shows that the trigger parton originates in most cases from the incident proton moving towards the longitudinal hemisphere of the trigger as a consequence of the asymmetric trigger condition ($\theta_{\text{CM}} < 90^\circ$).
- iv) When a particle is required to carry more than 50% of the away jet momentum, also this jet direction is well approximated by the momentum of this 'pseudotrigger' [14].

In summary, triggering on identified high transverse momentum particles at $\theta_{\text{CM}} \approx 40^\circ \dots 60^\circ$ and requiring a particle with moderate transverse momentum in the away jet fixes the momenta of scattered partons essentially on an event-by-event basis. The dominant hard process is quark gluon scattering for the considered kinematic configurations.

II. KINEMATICS AND DYNAMICS OF PARTON PARTON SCATTERING

Parton scattering processes are schematically shown in fig. 1 in the center of mass frame of the partons for three scattering angles Θ^* , and also in the proton proton rest frame in which the trigger parton's scattering angle θ_{CM} is fixed by the trigger particle. In fig. 1 it is explicitly assumed that the incident parton, which gives rise to a trigger particle, is moving towards the longitudinal trigger hemisphere; this is suggested by the observed spectator correlations (see above, [10]). The rapidities $y_1 = \ln \tan \theta_{\text{CM}}/2$ and y_2 of massless trigger and away partons are used to distinguish between forward scattering ($\Theta^* < 90^\circ$) and backward scattering ($\Theta^* > 90^\circ$), as $\cos \Theta^* \approx \tanh \left(\frac{y_1 - y_2}{2} \right)$.

It follows that measurements of the differential cross section for parton scattering as function of y_1 and y_2 yield information on its dependence on $\cos \Theta^*$. The differential cross section is given by [2] :

$$\frac{d^3 \sigma}{dy_1 dy_2 dp_T^2} = \frac{\pi \alpha_s^2}{\hat{s}^2} G_1(x_1) G_2(x_2) |\Gamma(\cos \Theta^*)|^2 \quad (1)$$

In this relation, $\sqrt{\hat{s}}$ is the invariant parton parton energy; $G_i(x_i)$, $i = 1, 2$, denote the structure functions of the relevant partons i as functions of Bjorken x_i , and α_s is the strong coupling constant. Some relevant squared matrix elements $|\Gamma(\cos \Theta^*)|^2$ from lowest order QCD are displayed in fig. 2.

Most important is the fact that the kinematic variable $\cos \Theta^*$ depends only on the difference $(y_1 - y_2)$ (see above), whereas x_i depend, for a fixed value of $\sqrt{\hat{s}}$, on the sum $(y_1 + y_2)$ (see Appendix). Consequently, the crucial observation is that the shape of $|\Gamma(\cos \Theta^*)|^2$ can be derived (see Appendix) from ratios of differential cross sections for different kinematical parton parton configurations (denoted by kinematic variables with(out) tilda), provided $\sqrt{\hat{s}}$ and $(y_1 + y_2)$ are kept constant (i.e. $y_1 + y_2 = \tilde{y}_1 + \tilde{y}_2$), while the difference $y_1 - y_2$ varies ($y_1 - y_2 \neq \tilde{y}_1 - \tilde{y}_2$):

$$\begin{aligned} F &= \frac{d^3 \sigma}{d\tilde{y}_1 d\tilde{y}_2 d \cos \tilde{\Theta}^*} \bigg/ \frac{d^3 \sigma}{dy_1 dy_2 d \cos \Theta^*} = \frac{|\Gamma(\cos \tilde{\Theta}^*)|^2}{|\Gamma(\cos \Theta^*)|^2} \\ &= 1 - \frac{\sin^2 \Theta^*}{\Delta} \frac{d}{d \cos \Theta^*} \ln |\Gamma(\cos \Theta^*)|^2 + O\left(\frac{1}{\Delta^2}\right), \end{aligned} \quad (2)$$

where $\Delta = \coth(y_1 - \tilde{y}_1)$.

Keeping the sum of rapidities constant implies that $x_{1,2} = \tilde{x}_{1,2}$ such that the structure functions cancel in relation (2). In this limit the ratio $F = F(\cos \Theta^*)$ is a direct measure of the slope of $\ln |\Gamma(\cos \Theta^*)|^2$.

Relation (2) is based upon two approximations:

- i) The dependence of structure functions [15] and of the strong coupling constant [1] on the squared four-momentum transfer $Q^2 = \hat{s} \sin^2(\Theta^*/2)$ is neglected. Such a dependence leads to incomplete cancellation of $G_i(x_i)$ and of $\alpha_s(Q^2)$ in eq. (2). These small higher order distortions are, however, beyond the scope of this analysis.
- ii) The events selected experimentally for the following analysis are dominated by quark-gluon scattering [13], but other processes, e.g. scattering of two quarks or of

two gluons, are nevertheless present. This requires in principle a summation of all subprocesses (properly weighted) in expression (2). Again, cancellation of $G_1(x_1)$ would become incomplete. However, eq. (2) can in this case be interpreted as the description of an effective scattering process, using effective structure functions G_1 and G_2 , and an effective scattering amplitude $\Gamma(\cos \Theta^*)$. The ratio $F(\cos \Theta^*)$ in eq. (2) corresponds thus to a mixture of different processes which is strongly dominated by quark gluon scattering.

III. EXPERIMENTAL EXTRACTION OF PARTON SCATTERING AMPLITUDES

The extraction of scattering amplitudes reduces to an experimental determination of kinematic variables of the interacting partons on an event-by-event basis.

For the following analysis the interval (0.5, 1.) of rapidities of the 'trigger' parton, approximated by the rapidity of the trigger particle, is divided into two equal intervals which contain the same number of events. The average trigger rapidities $\langle y_1 \rangle$, $\langle \tilde{y}_1 \rangle$ in these intervals approximate the parameter Δ used in eq. 2; with $\langle y_1 \rangle - \langle \tilde{y}_1 \rangle = 0.158$ one obtains $\Delta = 6.4$.

The rapidity y_2 of the away jet is approximated by that of an away 'pseudotrigger' with transverse momentum $\vec{p}_T^{aw}$, restricted by the requirement

$$x_E = |\vec{p}_T^{aw} \cdot \vec{p}_T^{tr}| / |\vec{p}_T^{tr}|^2 > 0.4. \quad (3)$$

Only events fulfilling this criterion are retained in the analysis. The scattering angle Θ^* is thus calculable from y_1 and y_2 , or from $\tilde{y}_1$ and $\tilde{y}_2$.

Finally, the parton-parton center of mass energy $\sqrt{s}$ is derived from the invariant mass $\sqrt{s}$ of the system consisting of the trigger and the pseudotrigger particle:

$$\sqrt{s} = \frac{\sqrt{s}}{\sqrt{x_E} \cdot z_{tr}} \quad (4)$$

where $\sqrt{x_E} \cdot z_{tr}$ is the fractional momentum of the away jet carried by the pseudotrigger. The fractional jet momentum carried by the trigger particle, z_{tr} , varies only little from event to event but depends systematically on y_2 as shown by a model calculation. The analysis is not sensitive to this variation.

One arrives thus at a complete description of parton kinematics. This yields distributions of scattering angles for the two intervals of trigger rapidities. Ratios of these distributions have to be converted into the ratio of differential cross-sections (see eq. 2 and A.2). As the differential cross section for hadrons with $p_T^{\text{tr}} > 4 \text{ GeV}/c$ is constant to better than 10% [4a, 16] in the rapidity range investigated here, the ratio of angular distributions for given trigger rapidity y_1 or $\tilde{y}_1$ approximates very well the function $F(\cos\Theta^*)$, which may thus be underestimated by up to 10%.

All approximations inherent in this procedure have been studied in model simulations. Parton parton scattering was simulated using simple power laws for structure functions and fragmentation functions. Three different parametrization of $|\Gamma(\cos\Theta^*)|^2$ were used :

$$|\Gamma(\cos\Theta^*)|^2 = 1, \sin^{-4}(\Theta^*/2), \sin^2\Theta^* . \quad (5)$$

Trigger particles were generated in the rapidity range between 0.6 and 1.0 with $p_T^{\text{tr}} > 4 \text{ GeV}/c$. The ratios $F(\cos\Theta^*)$, extracted following the procedure described above, are shown in fig. 3 for all three input distributions and for three intervals of $\sqrt{s}$. The agreement between reconstructed and generated ratios is good in all cases.

The ratios $F(\cos\Theta^*)$ from real data are shown in fig. 4a for positive triggers (π^+, K^+) and negative triggers (π^-) separately, averaged over the range of $10 < \sqrt{s} < 29 \text{ GeV}$. No significant differences are observed between the two trigger charges. The combined data are displayed in fig. 4b. The range of scattering angles extends well into the backward regime ($\Theta^* > 90^\circ$) which is thus explored for the first time.

IV. COMPARISON WITH THEORY

Figure 4b confronts the ratios $F(\cos\Theta^*)$ for quark quark, quark gluon and gluon gluon scattering, as predicted by leading order QCD, with the measurements. Theory for all three processes agrees equally well with the data in the forward scattering region, i. e. $\cos\Theta^* > 0.3$. This is due to the fact that $|\Gamma(\cos\Theta^*)|^2$ is dominated by gluon exchange in the t-channel, and therefore scales asymptotically like $\sin^{-4}\Theta^*/2$ for $\Theta^* \rightarrow 0^\circ$ (fig. 2). This asymptotic behaviour, already observed previously [17a], reflects the gluon spin, and is not very sensitive to more subtle dynamical characteristics of QCD. It can, however, be exploited to exclude experimentally some QCD processes and exotic theories

- i) In scalar gluon theories [17] the scattering amplitudes do not diverge for $\cos \Theta^* \rightarrow 1$. Fig. 4 shows as an example the prediction for quark quark scattering in scalar theories. It is in clear disagreement with the data in the forward scattering range.

The following conclusions depend on the experimental identification of quark gluon scattering

- ii) The backward scattering process $gu \rightarrow ug$, where the incident up-quark, moving into the longitudinal trigger hemisphere, recoils against a gluon yielding the trigger particle, exhibits a pole for $\cos \Theta^* \rightarrow 1$ and is in strong disagreement with the data for $\cos \Theta^* > 0.3$. Hence, it cannot be a dominating process.
- iii) Gluon selfcoupling does not exist in abelian gauge theories. Thus quark gluon scattering proceeds via s or u-channel quark exchange, leading to disagreement with the observed behaviour. Note that the shape of $|\Gamma(\cos \Theta^*)|^2$ for quark quark scattering is similar in abelian and non-abelian theories.

The measurements of $F(\cos \Theta^*)$ extend far into the backward regime, down to $\cos \Theta^* \approx -0.4$, inaccessible to experiments so far. Various QCD subprocesses which all have similar angular shapes for $\cos \Theta^* > 0.2$ show very different patterns for $\cos \Theta^* < 0.2$ (see also fig. 2). While predictions for quark quark and gluon gluon scattering deviate significantly from the data for $\cos \Theta^* < 0$, and can therefore be excluded as dominant contributions, the QCD predictions for quark-gluon scattering remain the only ones compatible with the measurements in the full angular range.

Exploring the backward scattering regime with sufficient precision, one is thus for the first time sensitive to the different shapes of squared matrix elements which allows to test dynamic properties of QCD beyond the exchange propagator.

V. CONCLUSIONS

A new method has been developed, and was applied to extract the shape of parton scattering amplitudes from measurements of high transverse momentum proton proton interactions. The analysis is based upon well defined parton parton kinematics and makes use of flavor identification of the scattered partons. It covered for the first time the parton backward scattering regime. Distinct differences of scattering amplitudes between the various QCD subprocesses are predicted such that a test of dynamics beyond the

existence of a t -channel pole is accessible experimentally. The data presented are sensitive to these differences, and are in full agreement with quark gluon scattering in the framework of QCD. They disfavor appreciable contributions from all other QCD processes, and are inconsistent with abelian theories of strong interactions.

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APPENDIX

The differential cross section $d^3 \sigma / dy_1 dy_2 d \cos \Theta^*$ is given by equation (1), where $x_{1,2} = \sqrt{\frac{\hat{s}}{s}} \exp(\pm \frac{y_1 + y_2}{2})$; $\hat{s}$ is a function of the transverse momentum p_T of the scattered partons, and of $y_1 - y_2$:

$$\hat{s} = \frac{4 p_T^2}{\sin^2 \Theta^*} = 4 p_T^2 \cosh^2 \left(\frac{y_1 - y_2}{2} \right).$$

It is useful to rewrite this cross section using the Jacobian

$$\left| \frac{\partial (y_L, \sqrt{\hat{s}}, \cos \Theta^*)}{\partial (y_1, y_2, p_T^2)} \right| = \frac{1}{\sqrt{\hat{s}}}. \quad (\text{A.1})$$

This yields the relation :

$$\Sigma (y_L, \sqrt{\hat{s}}, \cos \Theta^*) = \hat{s}^{3/2} \frac{d^3 \sigma}{dy_1 d(\sqrt{\hat{s}}) d \cos \Theta^*} = \pi \alpha_s^2 G_1(x_1) G_2(x_2) \left| \Gamma(\cos \Theta^*) \right|^2. \quad (\text{A.2})$$

For the ratio $F(\cos \Theta^*)$ of differential cross sections determined at fixed $\sqrt{\hat{s}}$, and for $y_1 + y_2 = \tilde{y}_1 + \tilde{y}_2$, one obtains :

$$F(\cos \Theta^*) = \frac{\Sigma(\tilde{y}_L, \sqrt{\hat{s}}, \cos \tilde{\Theta}^*)}{\Sigma(y_L, \sqrt{\hat{s}}, \cos \Theta^*)} = \frac{\left| \Gamma \left(\frac{1 - \Delta \cos \Theta^*}{\cos \Theta^* - \Delta} \right) \right|^2}{\left| \Gamma(\cos \Theta^*) \right|^2}, \quad (\text{A.3})$$

where $\cos \tilde{\Theta}^*$ was replaced by $(1 - \Delta \cos \Theta^*) / (\cos \Theta^* - \Delta)$, and $\Delta = \coth(y_1 - \tilde{y}_1)$.

The structure functions cancel in this ratio, since $x_{1,2} = \tilde{x}_{1,2}$.

By a Taylor expansion one arrives at :

$$F(\cos \Theta^*) = 1 - \frac{\sin^2 \Theta^*}{\Delta} \frac{d}{d(\cos \Theta^*)} \log \left| \Gamma(\cos \Theta^*) \right|^2 + O\left(\frac{1}{\Delta^2}\right). \quad (\text{A.4})$$

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Figure Captions

Fig. 1 : Parton parton scattering configurations in the parton parton and the proton proton center of mass systems.

Fig. 2 : Dependence of various lowest order QCD scattering amplitudes on the scattering angle $\cos \Theta^*$.

Fig. 3 : Reconstruction of simulated parton scattering amplitudes expressed in terms of the ratio F (see text). Data points are results of the reconstruction algorithm. The solid lines represent the input ratio. Shown are three different input shapes and three intervals of $\sqrt{s}$.

Fig. 4 : a) Measurement of the scattering amplitude ratio F (see text) for positive (π^+ , K^+) and negative (π^-) trigger particle.
b) Combined data from all triggers. The lines represent expectations from various QCD subprocesses including u-quark gluon scattering, $gu \rightarrow ug$, where the scattered gluon gives rise to the trigger particle, and from less conventional theories.

Fig. 1

Fig. 2

Fig. 3

Fig. 4b)

Fig. 4a)