EXPERIMENTAL STUDY OF PARTON-PARTON SCATTERING AMPLITUDES
- THE SPIN OF THE GLUON

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ABSTRACT

The rapidity distribution of fast fragments of scattered partons has been measured in events triggered on a π^+ of large transverse momentum, $p_T > 4$ GeV/c. The energy was $\sqrt{s} = 63$ GeV. The data are compared to model calculations assuming spin 0 or spin 1 for the quantum exchanged in the underlying parton-parton scattering process. While the exchange of a spin 0 gluon is excluded by the data, a spin 1 gluon is found in agreement with the observations.

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1. INTRODUCTION

The Quantum Chromo Dynamics (QCD) theory of strong interactions requires the forces between quarks to be mediated by eight spin-1 gauge fields carrying colour: the gluons [1]. Both the non-Abelian nature and the vector character of these fields are essential ingredients of the theory [2], and, consequently, have been subjected to detailed experimental investigations.

Scaling violations have been observed in deep-inelastic lepton-nucleon scattering which, when interpreted as gluon bremsstrahlung, favour the non-Abelian vector hypothesis [3]. Similarly, "3-jet" events in e^+e^- annihilations, viewed as a manifestation of hard gluon radiation, favour the spin-1 assignment [4]. Finally, the study of the τ , when assumed to decay via 3 gluons, excludes Abelian gluon [5] and scalar gluons [6], and is compatible with spin-1 gluons [7].

Here we study another QCD test, originally proposed in 1971 [8], involving large momentum transfers in deep-inelastic hadron-hadron collisions. The idea is to measure the angular distribution of the parton-parton scattering, which evidently exhibits characteristics of the exchanged quantum, that is of the gluon. It should be stressed that, in contrast to the 3 classes of experiments mentioned above, the gluon self-coupling enters here as a first order process [9].

2. EXPERIMENTAL INFORMATION

The experiment was performed with the upgraded Split Field Magnet detector (SFM) at the CERN Intersecting Storage Rings (ISR). As a standard procedure in this detector [10], charged particles are momentum analysed in 4π steradians using multiwire proportional chambers. Complementary information is available in a reduced solid angle from a set of time-of-flight counters and from two wire chambers which measure ionisation. Specific to this experiment [11], a trigger was set up at a polar angle close to 50° demanding a single particle of transverse momentum larger than 4 GeV/c. Mass information for this particle was inferred from threshold Cerenkov counters.

The ISR were operated at an energy of 63 GeV. A sample of 65 000 events was collected where the triggering particle was an identified pion. We use for this analysis events with a π^+ trigger (31 000 events). In

the proton-proton CMS, the average rapidity of the triggering particle was 0.80 (cms polar angle 49°). The transverse momentum spectrum starts at 4 GeV/c and extends up to 12 GeV/c.

We utilize for this study the rapidity distribution of particles opposite in azimuth to the triggering particle ($\Delta\phi$ within $180^\circ \pm 40^\circ$) and of transverse momentum larger than 2 GeV/c. Under these conditions, the precision on the rapidity measurement is better than 0.02 and the corrections which were applied for hardware and software inefficiencies are smaller than 15%.

3. THE GLUON PROBE

We use the quark-parton model [12] and QCD to bridge the gap between the observations and the gluon which is a theoretical concept. The following sequence is assumed to constitute a reasonable description of the data: partons emerge from hadrons (structure), parton-parton scattering occurs, then partons hadronize (fragmentation).

The distribution of the parton-parton scattering angle θ^* reflects the spin of the exchanged quantum: in the spin 0 case one expects a uniform distribution, whereas spin 1 corresponds to a strong forward peaking (basically like $\sin^{-2} \theta^*/2$). A complete description of the process requires detailed calculations (see the appendix), however one can grasp the basic idea if one uses some simplification.

Let θ_T and θ_A represent the angles with respect to the beams, in the proton-proton CMS, of the "trigger parton" and the "away parton", respectively. Let q_T stand for the transverse momentum of the trigger parton. If one neglects the transverse momenta of the partons prior to the scattering, then the 3 variables θ_T , θ_A , q_T define completely the kinematics. In particular they define θ^* . This can be most easily seen using y_T and y_A , the rapidities of the "trigger" and "away" partons, to derive the approximate relation $y_A = y_T + 2 \ln |\tan \theta^*/2|$.

For fixed y_T , y_A depends only on θ^* and hence the distribution in y_A will be directly sensitive (up to a Jacobian) to the shape of the θ^* distribution: A study of the ratio of θ^* distributions under the spin 1 hypothesis as compared to the spin 0 hypothesis, translates easily into a similar ratio for y_A distributions. Taking by convention $y_T > 0$, implies that peaking at small θ^* corresponds essentially to an enhancement at $y_A < 0$. Choosing $\theta_T \neq 90^\circ$, we can therefore

expect a shift of the away-side rapidity distribution according to the gluon spin hypothesis, yielding a very simple and clear experimental signature.

The momentum of the trigger particle is close to that of the trigger parton as shown experimentally [13], so it may be used to estimate θ_T and q_T . We approximate θ_A by selecting charged particles opposite in azimuth to the triggering particle, of momentum large enough so that they make a small angle with the away parton. Our trigger conditions finally fix θ_T in a rather small range, so that we can study the distributions in θ_A or y_A for fixed slices in q_T .

Following the preceding discussion, we analyse the rapidity distribution of last charged particles opposite in azimuth to the trigger. The results of the complete calculations are shown in fig. 1. The different curves correspond to variations in the model (see the Appendix). One finds that the distribution for the scalar gluon is in all cases shifted with respect to that of the vector gluon by about 0.3 units of rapidity. The direction of this shift corresponds to our prior expectations.

To summarize, complete calculations confirm our qualitative expectations. Absolute predictions of the rapidity distribution depend slightly on the details of the model. But the two hypothesis under study stay well separated.

4. COMPARISON OF THE DATA WITH THE MODEL

Two experimental distributions of rapidity for the charged particles "away" from the trigger are shown in fig. 2 together with model predictions. We selected transverse momenta of the trigger larger than 4 GeV/c and 6 GeV/c respectively. The "away" particles were restricted to an azimuthal wedge opposite to the trigger within $\pm 40^\circ$, and had a transverse momentum at least as large as half that of the trigger, i.e. $x_E = p_T/p_{T \text{ trigger}} > 0.5$. This momentum cut ensures that the rapidity of a fragment is a good estimate of the parton rapidity; the rms difference between these two quantities is smaller than 0.2. All curves were normalised to unit area. Fig. 3 represents the average rapidity of away particles as a function of the transverse momentum of the trigger.

The data agree well with the vector gluon hypothesis, whereas the scalar one is definitely ruled out. The comparison is made in these

figures with our "standard model" but, as seen in fig. 1, the scalar assumption would be even less acceptable if the model were modified.

5. CONCLUSIONS

From the investigation of the rapidity distribution of fast fragments from the hard-scattered partons in deep-inelastic proton-proton interactions, we conclude that the forces between partons are probably mediated by spin-1 fields; a model with scalar gluons is excluded. This result strongly supports QCD to be the underlying field theory of hadronic interactions.

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APPENDIX

In the quark-parton model [12], the double inclusive cross section for hadron production, m in the trigger-jet and n in the away-jet, may be obtained from eq. (1):

$$d\sigma = \int_{ij \rightarrow k\ell} G_i(x_i, \vec{k}_{Ti}, Q^2) \frac{dx_i}{x_i} d\vec{k}_{Ti} G_j(x_j, \vec{k}_{Tj}, Q^2) \frac{dx_j}{x_j} d\vec{k}_{Tj} \cdot \frac{d\sigma}{dt}^{ij \rightarrow k\ell} \cdot D_k^m(z_m, \vec{q}_{Tm}, Q^2) \frac{dz_m}{z_m} d\vec{q}_{Tm} \cdot D_\ell^n(z_n, \vec{q}_{Tn}, Q^2) \frac{dz_n}{z_n} d\vec{q}_{Tn} \quad (1)$$

The proton structure function G depends on the scaled longitudinal momentum x and on the transverse momentum k_T of the partons. With analogous notations, the fragmentation function D depends on z and q_T of the hadrons. In addition, dependence on a scale Q^2 is accounted for.

The model predictions for the rapidity distribution of "away" particles at fixed rapidity of the triggering particle were obtained by numerical integration of eq. (1) [14]. As input to these calculations, one needs the structure functions, the scattering cross section $d\sigma/dt$ for vector and scalar gluons, and the fragmentation functions.

The structure functions for quarks and antiquarks were parametrized according to ref. [15]. In their range in x and Q^2 , the CDHS data match well the parton kinematics of our experiment. The gluon distribution quoted in [15] is derived indirectly from the measured quark distribution by integrating the Altarelli-Parisi [16] equations. For the parton transverse momentum k_T , an exponential probability density function in the variable k_T^2 was used, resulting in a mean value $\langle k_T \rangle = 0.85$ GeV/c [17].

The parton-parton scattering cross section for coloured vector gluons [18], coloured scalar gluons and Abelian scalar gluons are listed in table 1. The usual Mandelstam variables s , t , u correspond to the parton-parton sub-system. Results concerning absolute cross sections are based on $\Lambda = 300$ MeV and the coupling constant α_s

$$\alpha_s(Q^2) = \frac{12\pi}{33 - 2N_f \ln(Q^2/G^2)}, \quad N_f = 3 \quad (2)$$

Quark fragmentation functions are taken from the Field-Feynman algorithm for quark jets [19]. In order to account for the measured behaviour at $z \rightarrow 1$ and to include scaling violations [20], the following splitting function for quark $\rightarrow$ quark + meson was used

$$f(z) = (1-z)^N \quad (3)$$

which yields a fragmentation function $zD(z) \rightarrow (1-z)^N$ for $z \rightarrow 1$. Therefore, and since the splitting function is closely related to the flavour non singlet component of quark jets, it seems natural to use the Q^2 dependence of N as derived from the analysis of the scaling violations of non singlet moments, as given by the renormalisation group equations of QCD [21]

$$N = 1 + \lambda \ln \frac{\ln \left(\frac{Q^2}{\Lambda^2} \right)}{\ln \frac{1}{\Lambda^2}}, \quad \lambda = \frac{16}{25} \quad (4)$$

This formula gives a good fit to recent high-energy e^+e^- data [20] for $Q_0^2 = 4 \text{ GeV}^2$.

Gluons are assumed to split into quark-antiquark pairs, which fragment independently. As these quarks may have low virtuality, there is some arbitrariness in choosing their fragmentation function. Based on investigations of the τ decay into 3 gluons [7], [22], we decided to adjust them such that quark and gluon jets are identical at moderate Q^2 (4 GeV^2). Then the pattern of scale breaking is fixed by QCD: at intermediate Q^2 the scaling violations are 9/4 times larger than for quark jets, that is $\lambda = 1.44$ in (4); at asymptotic Q^2 , beyond the range of our experiment, fast quarks form the leading component in gluon jets, and $D_g(z)$ converges towards $-D_q(z) \cdot (1-z)/\ln(1-z)$ [23].

In most theoretical treatments of parton-parton scattering [17], [24], [25], the choice of the scale Q^2 is not uniquely defined. We used a symmetrical definition [17]

$$Q^2 = 2 s t u / (s^2 + t^2 + u^2). \quad (5)$$

The cross section (1) has been calculated by Monte-Carlo techniques and was used successfully to describe inclusive spectra and two-particle correlations [14]: a more detailed description will be given elsewhere.

Of course all Monte-Carlo events have been subjected to the same selection criteria as the real data. Acceptance corrections were applied to the data before comparison with the models.

Fig. 1 gives the results for our "standard model" (full line) as described above for vector and scalar gluon hypotheses. Since some of the assumptions of the model are to some extent arbitrary, we have studied variations, some of which are shown in fig. 1. It turns out that the shape of the rapidity distribution is fairly insensitive to such modifications. The choice of scale Q^2 is more critical as the dotted line of fig. 1 shows (the choice $Q^2 = s/7$ was suggested in [26]). However, vector and scalar hypotheses correspond always to well separated distributions.

The scattering amplitudes for the scalar gluon case are given in table 1. We kept the structure functions as extracted from the data under the vector hypothesis [15]. As shown from the dashed-dotted line in fig. 1, variations of the pattern of scale breaking have negligible effects. The choice of the gluon structure function is however more critical. If one enforces a fit to lepton-nucleon data assuming scalar gluons, the resulting gluon distribution turns out to be extremely soft [27]. Translated into the rapidity distribution of the away-jet, this causes a shift towards "back-to-antiback" configuration, i.e. in the direction of positive rapidity [25], increasing the disagreement with experimental data.

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TABLE 1
List of parton-parton cross sections

Process	Vector Gluon	Scalar gluon
$q_i q_j \rightarrow q_i q_j$	$\langle \frac{2}{9} \rangle > 2 \frac{s^2+u^2}{t^2} + \delta_{ij} [\langle \frac{2}{9} \rangle > 2 \frac{t^2+s^2}{u^2} + \langle \frac{-2}{27} \rangle > \frac{4s^2}{ut}]$	$\langle \frac{2}{9} \rangle > + \delta_{ij} [\langle \frac{2}{9} \rangle > - \langle \frac{-2}{27} \rangle]$
$q_i \bar{q}_i \rightarrow q_j \bar{q}_j$	$\langle \frac{2}{9} \rangle > 2 \frac{t^2+u^2}{s^2} + \delta_{ij} [\langle \frac{2}{9} \rangle > 2 \frac{s^2+u^2}{t^2} + \langle \frac{-2}{27} \rangle > \frac{4u^2}{st}]$	$\langle \frac{2}{9} \rangle > + \delta_{ij} [\langle \frac{2}{9} \rangle > - \langle \frac{-2}{27} \rangle]$
$gg \rightarrow q\bar{q}$	$\langle \frac{1}{12} \rangle > 2 \frac{u^2+t^2}{ut} - \langle \frac{3}{16} \rangle > 4 (1 - \frac{ut}{s^2}) + \langle \frac{3}{32} \rangle > 4$	$\langle \frac{1}{12} \rangle > 2 \frac{u^2+t^2}{ut} - \langle \frac{-1}{96} \rangle > 4$
$q\bar{q} \rightarrow gg$	$\langle \frac{16}{27} \rangle > 2 \frac{u^2+t^2}{ut} - \langle \frac{4}{3} \rangle > 4 (1 - \frac{ut}{s^2}) + \langle \frac{2}{3} \rangle > 4$	$\langle \frac{16}{27} \rangle > \frac{1}{2} \frac{u^2+t^2}{ut} - \langle \frac{-2}{27} \rangle >$
$gq \rightarrow gq$	$- \langle \frac{2}{9} \rangle > 2 \frac{u^2+s^2}{us} + \langle \frac{1}{2} \rangle > 4 (1 - \frac{us}{t^2}) - 1$	$- \langle \frac{2}{9} \rangle > \frac{u^2+s^2}{us} + \langle \frac{-1}{36} \rangle > 2$
$gg \rightarrow gg$	$\frac{9}{3} (3 - \frac{tu}{s^2} - \frac{us}{t^2} - \frac{st}{u^2})$	0

We show $s^2/\pi\alpha_s^2 (d\sigma/dt)$ where s, t, u correspond to the sub-system. Colour factors are represented inside angular brackets. The formulas for vector gluon are extracted from [18], which should be consulted for colour factors which we have not explicitly shown.

FIGURE CAPTIONS

- Fig. 1 Rapidity distribution of fast ($x_E > 0.5$) particles in the away jet associated to a π^+ trigger. Full line: "standard model", the horizontal error bars indicate the influence of parton k_T . Dashed-dotted line: gluon fragmentation steepened by $(1-z)$ at the reference Q^2 of 4 GeV^2 . Dotted line: scale Q^2 chosen as $s/7$. All distributions are normalized to unit area.
- (a) Non-abelian vector gluon (QCD);
- (b) Non-abelian scalar gluon. Distributions for abelian scalar gluons are almost identical.
- Fig. 2 Rapidity distribution of particles with $x_E > 0.5$ in the away jet ($\Delta\phi = 180^\circ \pm 40^\circ$). We show data points and predictions of the "standard model" for vector and scalar gluons. Distributions from events with a π^+ trigger, $6 \text{ GeV}/c > p_T > 4 \text{ GeV}/c$ (2-a) and $p_T > 6 \text{ GeV}/c$ (2-b) are displayed.
- Fig. 3 The average rapidity of away particles ($x_E > 0.5$, $\Delta\phi = 180^\circ \pm 40^\circ$) associated to π^+ triggers is shown, curves correspond to
- (a) vector gluon exchange;
- (b) Scalar gluon exchange.

Fig. 1

Fig.2(a)

Fig.2(b)

Fig. 3