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Average jet-charge density and direct measurement of quark charges

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A new method for the direct measurement of the quark charge is proposed. Instead of a neutrino beam, an electron, photon, or hadron beam can be used so the statistics is much larger in our method. Examples of γ-N and e-N collisions are presented for measuring the u- and d-quark charge.

Model analyses[1-4] show that it is reasonable to expect a stable relation between the average charge of jets produced by partons of type α and the charge of the parent parton. Thus, supposing we can by some means isolate a set of jets produced by parton α, then the quantity $\bar{e}_{J_\alpha}$ reflects the charge of parton α:

$$\bar{e}_{J_\alpha} \equiv \frac{1}{n_\alpha} \sum_{i=1}^{n_\alpha} e_{J_\alpha}(i) \ . \tag{1}$$

Here, n_α is the total number of observed jets from quarks with the same flavor α (say, $\alpha = u$) and $e_{J_\alpha}(i)$ refers to the observed charge of the ith jet in this set of jets. The precise definition of the observed charge of a jet has been discussed in detail in Ref. 3. First, we address the problem, which it is not at all obvious, of how to identify the parent parton of a given jet.

A method of measuring the average jet charge from u quarks was originally proposed by Feynman.[1] He suggested the study of jets produced in ν-p inelastic scattering. This selects u-quark jets, because only d and s quarks in the proton can absorb W^+ bosons and then turn into u quarks (a few charm quarks may be produced, but they also carry charge $\frac{2}{3}$). Similarly, $\bar{\nu}$-p deep-inelastic scattering and some improved schemes[5,6] have been considered. The experiments have been performed[6-10] and the results are in agreement with fractional quark charge. However, because fractional quark charge is such a fundamental concept, it is desirable to find additional tests of this property. It is the purpose of this paper to present several such tests.

In order to increase the probability of jet events and to study harder jets, it is natural to study jets produced by electromagnetic and strong interactions. In contrast with ν-p scattering, however, it is not obvious to select a sample of jets of one particular quark flavor in a process of electromagnetic or strong interactions. In order to tackle this problem, statistical criteria of selection have achieved reasonably successful results[11-13] in collider experiments.

We would, however, like to suggest a new scheme to measure the average jet charges of u and d quarks. Since our method does not require recognizing which jet is produced from which type of quark or gluon, it enables us to deal with electromagnetic and strong interactions without using statistical criteria and, because we deal with the strong and electromagnetic interactions instead of weak ones, the magnitude of cross sections with our method can reach about 4×10^3 times larger than those in Ref. 1. Our scheme is particularly appropriate for the real and virtual photon beams of very high energies which will be available at Fermilab and DESY HERA.

Let us define a new physical quantity $\bar{Q}_J$, the average jet-charge density for a given sample of events in region $d\Omega$ of momentum space for the process $A+B\to\text{jet}+X$,

$$\bar{Q}_J \propto \frac{1}{N}\sum_i^N e_J(i) = \frac{1}{N}\sum_\alpha \sum_{i_\alpha}^{n_\alpha} e_{J_\alpha}(i_\alpha) \ . \tag{2}$$

Here the sum over α goes over quarks, antiquarks, and gluons, $N=\sum_\alpha n_\alpha$ is the total number of jets, and $e_J(i)$ $(i=1,2,\ldots,n)$ refers to the observed charges of any high-P_T jets appearing in the region $d\Omega$ of momentum regardless of which type of quarks (or gluons) they are produced from. In terms of the differential cross section $d\sigma/d\Omega$ for producing a jet from a present parton α and the average jet charge $\bar{e}_{J_\alpha}$ of Eq. (1), we have

$$\bar{Q}_J \propto \sum_\alpha \frac{d\sigma}{d\Omega}(A+B\to\alpha+X)\bar{e}_{J_\alpha} \ . \tag{3}$$

By definition, all jets produced by any type of partons are included in $\bar{Q}_J$, so the random errors of the measurement of observed jet charges will be canceled in each subsummation

$$\sum_{i_\alpha}^{n_\alpha} e_{J_\alpha}(i_\alpha)$$

of Eq. (2).

Since the fragmentation from partons to hadrons is a strong-interaction process, charge-conjugation invariance requires

$$D_\alpha^h(z,Q^2) = D_{\bar{\alpha}}^{\bar{h}}(z,Q^2) \ , \tag{4}$$

where $D_\alpha^h(z,Q^2)=D_{\bar\alpha}^{\bar h}(z,Q^2)$ is a fragmentation function from parton α into hadron h, and $\bar\alpha$, $\bar h$ are the charge-conjugated partners of α and h, respectively. As usual, D_α^h and $D_{\bar\alpha}^{\bar h}$ are functions of z, the fractional momentum of the hadron, and Q^2, the momentum transfer squared in the process. Equation (4) implies the simple relation

$$\bar e_{J_{\bar\alpha}}=-\bar e_{J_\alpha} .$$

We thus derive an important property of the average jet-charge density:

$$\bar Q_J=\sum_\alpha \frac{d\sigma}{d\Omega}(A+B\to\alpha+X)\bar e_{J_\alpha}$$
$$=\sum_\beta \left[\left[\frac{d\sigma}{d\Omega}(A+B\to\beta+X)-\frac{d\sigma}{d\Omega}(A+B\to\bar\beta+\bar X)\right]\bar e_{J_\beta}\right] , \quad (5)$$

where the sum over β goes over quark flavors only, and does not count antiquarks. This means that the contributions to $\bar Q_J$ from the processes $A+B\to\beta+X$ and $A+B\to\bar\beta+\bar X$ will cancel if

$$\frac{d\sigma}{d\Omega}(A+B\to\beta+X)=\frac{d\sigma}{d\Omega}(A+B\to\bar\beta+\bar X) . \quad (6)$$

This gives us a chance to cancel all of the flavor-singlet contributions. In other words, we may pick up the only contributions of valence quarks as long as we choose the right process, for which the relation of Eq. (6) holds.

In the following, we shall give two specific examples to illustrate how to use average jet-charge density $\bar Q_J$ to determine $\bar e_{J_u}$ and $\bar e_{J_d}$.

First we consider two kinds of high-P_T jet processes

(a) γ+proton$\to$jet+anything ,

(b) γ+neutron$\to$jet+anything ,

which can be performed at Fermilab by a photon beam with the energy of $E_{\rm lab}=600$ GeV. For these reactions, most subprocesses are canceled and the only contributions come from the subprocesses

$$\gamma+u_v(\text{or } d_v)\to u(\text{or } d)+g . \quad (7)$$

Taking $d\Omega=dx\,d\hat t$, where x is the fractional momentum of valence quark in the nucleon and $\hat t$ is a common Mandelstam variable of the subprocess of Eq. (7). We have

$$\bar Q_J^{\gamma p}(x,\hat t)=[u_p^v(x,Q^2)\bar e_{J_u}+\tfrac14 d_p^v(x,Q^2)\bar e_{J_d}]\frac{d\hat\sigma}{d\hat t}(\gamma u\to ug) , \quad (8)$$

$$\bar Q_J^{\gamma n}(x,\hat t)=[u_n^v(x,Q^2)\bar e_{J_u}+\tfrac14 d_n^v(x,Q^2)\bar e_{J_d}]\frac{d\hat\sigma}{d\hat t}(\gamma u\to ug) , \quad (9)$$

where u_N^v (d_N^v) with $N=p$ or n are the up- (down-) valence-quark distribution functions in the nucleon. $\bar Q_J^{\gamma p}$ and $\bar Q_J^{\gamma n}$ can be measured directly in experiment, $d\hat\sigma/d\hat t$ can be calculated in QCD, and u_N^v and d_N^v ($N=p$ or n) have been given by deep-inelastic scattering. We may regard Eqs. (8) and (9) as mixings of $\bar e_{J_u}$ and $\bar e_{J_d}$. If $\bar Q_J^{\gamma p}$ and $\bar Q_J^{\gamma n}$ are measured, we can combine (8) and (9) and find the solutions of $\bar e_{J_u}$ and $\bar e_{J_u}$. In particular, the ratio

$$\frac{\bar e_{J_u}}{\bar e_{J_d}}=-\frac{\frac14(d_n^v\bar Q_J^{\gamma p}-d_p^v\bar Q_J^{\gamma n})}{u_n^v\bar Q_J^{\gamma p}-u_p^v\bar Q_J^{\gamma n}} \quad (10)$$

is independent of any cross section of subprocesses.

The same information can be obtained from jet production in electron-proton and electron-neutron scatterings, which could be realized at high energy at HERA by performing electron-proton and electron-deuteron collisions. Substituting $\bar Q_J^{ep}$, $\bar Q_J^{en}$, and $(d\hat\sigma/d\hat t)(eu\to ue)$ for $\bar Q_J^{\gamma p}$, $\bar Q_J^{\gamma n}$, and $(d\hat\sigma/d\hat t)(\gamma u\to ug)$ in Eqs. (8)–(10), respectively, we can get the average jet-charge densities in e-N collisions and then find $\bar e_{J_u}$, $\bar e_{J_d}$.

Finally, we give the predictions for the $\bar Q_J$'s for the above four reactions in QCD at the Born-approximation level. In the center-of-mass system of the initial particles, we define

$$x_T\equiv\frac{|\mathbf{k}_q|\sin\theta_q}{E} ,\quad x_L\equiv\frac{|\mathbf{k}_q|\cos\theta_q}{E} ,\quad a_L\equiv(x_T^2+x_L^2)^{1/2} ,\quad x\equiv|\mathbf{p}_q|/E , \quad (11)$$

where $\mathbf{p}_q$ is the momentum of a valence quark in the initial nucleon, $\mathbf{k}_q$ the momentum of the final high-P_T quark, and θ_q the scattering angle of the final quark, $2E$ is the total c.m. energy.

By taking $\bar e_{J_u}=\frac23$, $\bar e_{J_d}=-\frac13$, the average jet-charge densities can be predicted in terms of x_L and x_T:

$$\bar Q_J^{\gamma p}(x_T,x_L)=\frac{8\pi\alpha\alpha_s}{27E^2}\frac{x_T}{a_L(a_L-x_L)x}\times\left[\frac{2-a_L-x_L}{2}+\frac{2}{2-a_L-x_L}\right]\times(\tfrac23-\tfrac1{24})xu_p^v(x,Q^2) , \quad (12)$$

$$\bar Q_J^{ep}(x_T,x_L)=\frac{\pi\alpha^2x_T}{18E^2a_L(a_L-x_L)x}\frac{4+(2-a_L-x_L)^2}{(a_L+x_L)^2}\times(\tfrac23-\tfrac1{24})xu_p^v(x,Q^2) , \quad (13)$$

and

$$\bar Q_J^{\gamma n}(x_T,x_L)=\tfrac25\bar Q_J^{\gamma p}(x_T,x_L) ,\quad \bar Q_J^{en}(x_T,x_L)=\tfrac25\bar Q_J^{ep}(x_T,x_L) , \quad (14)$$

where we have used the isospin relations

$$u_p^v=d_n^v=2d_p^v=u_n^v . \quad (15)$$

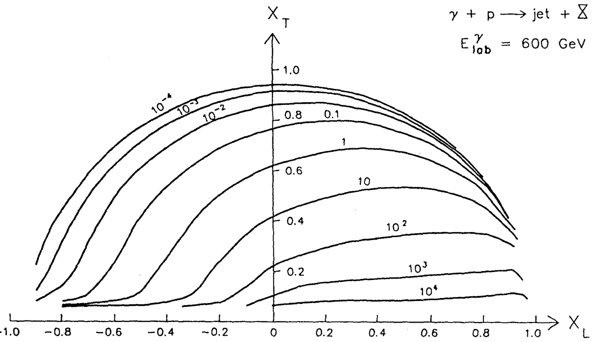

FIG. 1. The calculated average jet-charge density $\bar{Q}\,{}^{\gamma p}_{J}(x_T,x_L)$ distributions in the (x_T,x_L) plane with $\bar{e}_{J_u}=\frac{2}{3}$, $\bar{e}_{J_d}=-\frac{1}{3}$ as the input. $\bar{Q}\,{}^{\gamma n}_{J}(x_T,x_L)=\frac{2}{5}\bar{Q}\,{}^{\gamma p}_{J}(x_T,x_L)$ according to Eqs. (14) and (15). The incident photon beam energy $E^{\gamma}_{\rm lab}=600$ GeV. The numbers by the curves are in units of nb.

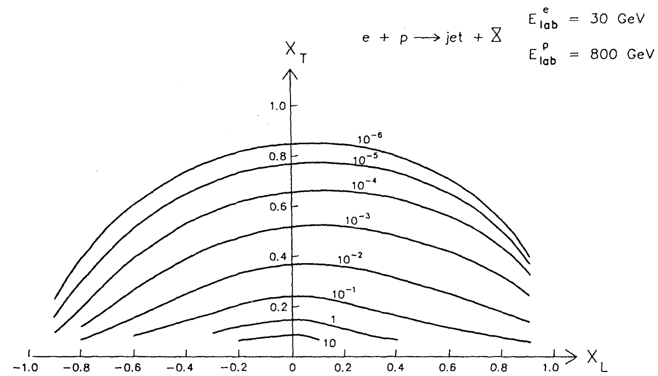

FIG. 2. The calculated average jet-charge density $\bar{Q}\,{}^{ep}_{J}(x_T,x_L)$ distributions in (x_T,x_L) plane with $\bar{e}_{J_u}=\frac{2}{3}$, $\bar{e}_{J_d}=-\frac{1}{3}$ as the input. $\bar{Q}\,{}^{en}_{J}(x_T,x_L)=\frac{2}{5}\bar{Q}\,{}^{ep}_{J}(x_T,x_L)$ according to Eqs. (14) and (15). The incident electron beam energy $E^{e}_{\rm lab}=30$ GeV and the incident proton beam energy $E^{p}_{\rm lab}=800$ GeV. The numbers by the curves are in units of nb.

We shall not consider the higher-order corrections to the cross sections of subprocesses, since the value of $\bar{e}_{J_\alpha}$'s, especially the ratio $\bar{e}_{J_u}/\bar{e}_{J_d}$, should be independent of the cross sections of any subprocess.

For numerical calculations, we take $s=1200$ GeV^2 for γ-N collisions and $s=9600$ GeV^2 for e-N collisions, and use the nucleon structure functions by Buras and Gaemers.[14] We also take $\Lambda=0.218$ GeV, $Q^2=4xE^2$. The results are shown in Figs. 1 and 2. The curves of $\bar{Q}_J$ in these two figures are drawn under the input of $\bar{e}_{J_u}=\frac{2}{3}$, $\bar{e}_{J_d}=-\frac{1}{3}$. Comparing these "theoretical" curves with the corresponding measured, one we can determine the experimental value of $\bar{e}_{J_u}$ and $\bar{e}_{J_d}$.

We should emphasize that our method to measure quark charge does not require identifying the parent-quark flavors of jets. This is an important advantage. We wish this kind of experiment would be performed at Fermilab and HERA in the near future.

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