Methodology for Measuring Gluon Jet Fraction and Characteristics of Quark and Gluon Jets in Hadron–Hadron Collisions

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Received October 29, 2020; revised November 17, 2020; accepted November 18, 2020

Abstract—The difference in properties of jets initiated by quarks and gluons as a result of hadron–hadron collisions, opens up the possibility of their recognition. Special quark-gluon discriminators of jets are built for this purpose. This paper discusses methods for measuring the fractions of quark and gluon jets in jet sample using the quark-gluon jet discriminator. This opens up the possibility of measuring various characteristics of quark and gluon jets. The technique of such measurements for modern hadron colliders is discussed.

DOI: 10.1134/S1547477121020187

INTRODUCTION

The gluon- and quark-initiated jets (g- and q-jets) have essentially different physical parameters: charged particle multiplicity is larger inside g-jets than inside q-jets, g-jets are less collimated than q-jets, energy of g-jet is more smooth distributed between hadrons, while most of the q-jet energy is concentrated in several leading hadrons. The properties of q/g-jets were first studied in $e^+e^-$ processes which have small number of jets per event, thus it is possible to separate q- and g-jets using information about the whole event \cite{1}. In hadron-hadron collisions, multijet events occur more frequently. Therefore, to recognize jets with a given flavor, sensitive jet parameters (q/g-discriminators, $D$) are built based on the physical jet properties listed above.

The most popular is the likelihood q/g-discriminator. To construct it, the Monte Carlo (MC) distribution functions of q/g-jets over several physical parameters of the jet ($p_1$, $p_2$, ...) are constructed: $f_1^{q/g}(p_1), f_2^{q/g}(p_1), ...$. After that, a q/g-jet likelihood function is defined as a product of the distributions for quark jets, $Q(p_1, p_2, ...)$ = $f_1^q(p_1)f_2^q(p_1)...$, and for gluon jets, $G(p_1, p_2, ...)$ = $f_1^g(p_1)f_2^g(p_1)...$. The likelihood q/g-discriminator is the value $D = Q / (Q + G)$, which varies within [0,1] so a big difference is achieved between q- and g-jets $D$-distributions: the q-jet $D$-distribution has a peak around point $D = 0$. Examples of likelihood $q/g$-discriminators one can find in articles \cite{2, 3}. Further discussion in this paper does not use the explicit form of the $q/g$-discriminator.

Discriminators of $q/g$-jets are mainly used to select channels involving jets. Choosing jets that are above a certain working point $D > D_0$, one can select true or false $q/g$-jets with the required efficiency. The quality of the $q/g$-discriminator, which is defined by the difference of the $D$-distributions between the q- and g-jets, strongly affects the purity of the channel selection and the number of selected events.

To find fraction of q/g-jets in a jet sample ($\alpha^{q/g}$), it is not necessary to recognize the flavour of each jet. For an arbitrary operating point, $D_0$, the $D$-distribution of jets allows finding the probabilities of true and wrong identification of jet flavour. By combining these probabilities, it is possible to calculate the $q/g$-jet fractions in the sample that are independent of the $D_0$ for an ideal experiment. However, in a real experiment, the $D$-distributions have uncertainties, the propagation of which to the $q/g$-jet fractions found by this method depend on the choice of the working point $D_0$.

More promising is the method without using a working point: the method of fitting the measured $D$-distribution by a linear combination of q/g-jet $D$-distributions in the whole $D$-region. In such
method, a sufficiently high measurement accuracy can be achieved without imposing stringent requirements on the quality of the $D$-discriminator, if the sample of jets is sufficiently large. The hadron collider provides the ability to produce a large number of jets, which allows to perform precision measurements of $\alpha^g$.

The high accuracy of measurement of the $q/g$-jet fractions, in turn, imposes new requirements to the methods of measuring the characteristics of $q/g$-jets. The characteristic of a jet sample is understood as a distribution of jets over the physical jet parameter, or raw moments of this distribution. Since the characteristics of $q$- and $g$-jets differ, the characteristics of jet sample are mainly determined by the ratio of $q/g$-jet fractions. However, there is another factor that also affects characteristics of jet sample and which must be taken into account in precision measurement, which is the dependence of the properties of $q/g$-jets on jet sample, i.e. on kinematics and environment in which the selected jets are formed and collected.

Until now, measurements of the characteristics of $q/g$-jets at hadron colliders were performed using MC generator values of the $q/g$-jet fractions in jet sample [4, 5]. Precision measurements of $q/g$-jet fractions open up new possibilities in measurement of $q/g$-jets characteristics.

**MEASUREMENT OF GLUON JET FRACTION**

The fraction of $g$-jets in jet sample can be determined by fitting the measured normalized $D$-distribution of jets, $H_{\text{DAT}}^D(D)$, with a one-parameter function:

$$H_{\text{DAT}}^D(D) \sim \alpha^g H_{\text{MC}}^g(D) + (1 - \alpha^g) H_{\text{MC}}^g(D). \quad (1)$$

The symbol $\sim$ means fitting of the measured distribution $H_{\text{DAT}}^D(D)$ with a linear combination of the MC distributions of $q/g$-jets, $H_{\text{MC}}^q(D)$. Fraction of $g$-jets, $\alpha^g$, is a fitting parameter in Eq. (1). Model-dependent distributions $H_{\text{MC}}^g(D)$ are determined from MC sample of reconstructed jets with full simulation of detector response. Jet flavour ($q$-jet or $g$-jet) is found by matching the reconstructed jets and generator partons. In Eq. (1) $q$-jets are jets with all possible quark flavors, including reconstructed jets with mis-identified flavour.

Stable result of fit procedure Eq. (1) can be obtained using the method of weighted least squares, in which the following value is a subject for minimization:

$$V = \sum_D \left[ \frac{Y(D)}{w(D)} \right]^2 = \min, \quad (2)$$

where

$$Y(D) = H_{\text{DAT}}^D(D) - \alpha^g H_{\text{MC}}^g(D) - (1 - \alpha^g) H_{\text{MC}}^g(D). \quad (3)$$

In Eq. (2), the summation is performed over the bins of $Y(D)$ histogram. Weight, $w(D)$, can be chosen as a sum in quadratures the standard deviations of the content of the bin $D$ for the involved histograms.

**MEASUREMENT OF CHARACTERISTICS OF QUARK AND GLUON JETS**

Suppose there are two jet samples with the measured characteristics $X_k$ ($k = 1, 2$). In this section, the characteristic of the jet sample $X_k$ stands for the normalized distribution of jets over some jet parameter $y$: $X_k \equiv X_k(y)$. Generalization of conclusions and formulas presented below to the case of raw moments of the distribution over $y$ as a jet sample characteristic $X_k$ can be performed trivially.

Let $\alpha^q_k$ be $q$-jet fraction in $k$th jet sample, which is measured according to Eq. (1). Then there is a system of two equations for unknown characteristics of $q/g$-jet subsamples, $X^{q/g}$:

$$X_1 = \alpha^g X^g + (1 - \alpha^g) X^q,$$
$$X_2 = \alpha^g X^g + (1 - \alpha^g) X^q. \quad (4)$$

The solution of system of Eqs. (4) has the form:

$$X^q = \frac{\alpha^g X_1 - \alpha^g X_2}{\alpha^g - \alpha^g},$$
$$X^g = \frac{(1 - \alpha^g) X_2 - (1 - \alpha^g) X_1}{\alpha^g - \alpha^g}. \quad (5)$$

It is assumed in Eqs. (4), (5) that $q$- and $g$-jet subsamples have universal characteristics, i.e. $q/g$-jet characteristics $y$ and $X \equiv X(y)$ are independent on the jet sample they belong to. Actually, it is satisfied only approximately. Deviation of characteristic of jets with a specific flavor between different jet samples is defined here as “jet flavour non-universality” (JFNU). Given JFNU, Eqs. (4) take the form:

$$X_1 = \alpha^g X^g + (1 - \alpha^g) X^q,$$
$$X_2 = \alpha^g X^g + (1 - \alpha^g) X^q. \quad (6)$$

To describe JFNU quantitatively, one can introduce the JFNU measure for $f$-jets, $\Delta X^f$, and the “universal” characteristics of $f$-jets, $X^f$, for which values averaged over two jet samples can be chosen:

$$\Delta X^f \equiv X^f_2 - X^f_1,$$
$$X^f \equiv \rho^f X^f_1 + \rho^f X^f_2. \quad (7)$$
The JFNU measure, \( \Delta X_f \), is found by MC simulation, and it characterizes physical and kinematic differences between the two jet samples. The following notation is used in Eqs. (7):
\[
X_f' \equiv \frac{n^f_f \psi^f_f}{N_f'}, \quad N_f' \equiv (N_{f_1}^f + N_{f_2}^f),
\]
\[
N_k^f \equiv \sum_y n_k^f(y), k = 1, 2, \tag{8}
\]
\[
X_k^f \equiv \frac{n_k^f(y)}{N_k^f}, \quad \rho_k^f \equiv \frac{N_f^f}{N_f'}, \quad \rho_k^f + \rho_k^f = 1,
\]
\[
f \equiv q, g; \quad q = u, d, s, c, b, x.
\]
Here \( n_k^f(y) \) is the \( y \)-distribution of \( N_k^f \) jets with the flavor \( f \), collected in the \( k \)th jet sample. Recall that the dependence of the characteristics on the \( y \) is omitted:
\[
X_f' \equiv X_f(y), \quad X_k^f \equiv X_k^f(y).
\]

From Eqs. (7) one can find “non-universal” characteristics for two jet samples:
\[
X_1^f = X_f - \rho_2^f \Delta X_f', \quad X_2^f = X_f' + \rho_1^f \Delta X_f'. \tag{9}
\]

Substituting Eqs. (9) into Eqs. (6), a system of equations for the “universal” \( q/g \)-jet characteristics \( X^q/g \) can be written:
\[
\tilde{X}_1 = \alpha_q^f X^q + (1 - \alpha_g^f) X^g,
\]
\[
\tilde{X}_2 = \alpha_g^f X^q + (1 - \alpha_g^f) X^g. \tag{10}
\]

The left parts are the JFNU-corrected measured characteristics, which have the form:
\[
\tilde{X}_1 \equiv X_1 + \gamma^\text{DAT} \Delta X^{\text{JFNU}}, \quad \tilde{X}_2 \equiv X_2 - \Delta X^{\text{JFNU}}. \tag{11}
\]

Here the following notation is used:
\[
\Delta X^{\text{JFNU}} \equiv \beta_q^\psi \Delta X^q + \beta_g^\psi \Delta X^g,
\]
\[
\beta_f' \equiv \frac{\alpha_f^\psi \alpha_f^\psi}{\alpha_f^\psi + \gamma^\text{DAT} \alpha_f^\psi}, \tag{12}
\]
\[
\gamma^\text{DAT} \equiv \frac{N_2^g}{N_1^q}, \quad f = q, g, \quad \alpha_g^q = 1 - \alpha_g^g,
\]
where \( N_k \equiv N_k^q + N_k^g \) is the number of jets in \( k \)th jet sample. Thus, the JFNU corrections for the measured characteristics are expressed through measured \( g \)-jet fractions, \( \alpha_f^q \), ratio of numbers of jets in the two jet samples, \( \gamma^\text{DAT} \), and JFNU measures, \( \Delta X_f \).

Solving the system of Eqs. (10), one can obtain the “universal” characteristics of \( q/g \)-jets in terms of the measured values \( \tilde{X}_1 \) and \( \alpha_g^q \):
\[
X^q = \frac{\alpha_q^q \tilde{X}_1 - \alpha_g^q \tilde{X}_2}{\alpha_q^g - \alpha_g^g},
\]
\[
X^g = \frac{(1 - \alpha_q^q) \tilde{X}_2 - (1 - \alpha_g^g) \tilde{X}_1}{\alpha_q^g - \alpha_g^g}. \tag{13}
\]

These characteristics refer to the combined jet sample. Decomposition of the characteristic \( X \) of the combined jet sample into \( q \)- and \( g \)-jet components has the usual form:
\[
X = \delta_1 X_1 + \delta_2 X_2 = \alpha^q X^q + (1 - \alpha^q) X^g, \tag{14}
\]
where \( \delta_k = \frac{N_k}{N_1 + N_2} \) is fraction of jets of the \( k \)th jet sample in the combined one. The \( g \)-jet fraction in the combined jet sample is expressed in terms of \( g \)-jet fractions in subsamples:
\[
\alpha^q = \delta_2 \alpha_1^q + \delta_2 \alpha_2^q. \tag{15}
\]

MEASUREMENT OF QUARK AND GLUON \( D \)-DISTRIBUTIONS

To measure the fraction of \( g \)-jets in \( k \)th jet sample by the fitting procedure (1), “non-universal” \( D \)-distributions of \( q/g \)-jets are used, which are the distributions found for \( k \)th jet sample, \( H_{q/g}^{k, MC}(D) \). Via combining the two jet samples, one can obtain the “universal” \( D \)-distributions of \( q/g \)-jets, \( H_{q/g}^{\text{DAT}}(D) \), defined by second equation in Eqs. (7). Eqs. (13) allow to obtain the “universal” \( D \)-distributions of \( q/g \)-jets, \( H_{q/g}^{\text{MC}}(D) \), from the data. As model distributions \( H_{q/g}^{k, MC}(D) \) were used to obtain \( \alpha_f^q \), the calculation of \( H_{q/g}^{\text{DAT}}(D) \) by Eqs. (13) can be considered as a data-motivated correction of model “universal” distributions \( H_{q/g}^{\text{MC}}(D) \). From Eqs. (13):
\[
H_{g}^{\text{DAT}}(D) = \frac{\alpha_g^q H_1(D) - \alpha_g^g H_2(D)}{\alpha_g^q - \alpha_g^g}, \tag{16}
\]
\[
H_{g}^{\text{DAT}}(D) = \frac{(1 - \alpha_g^q) H_1(D) - (1 - \alpha_g^g) H_2(D)}{\alpha_g^q - \alpha_g^g},
\]
where the quantities \( H_{1,2}(D) \) are defined by Eqs. (11), (12).

For jet sample, which is a combination of two jet samples, the \( D \)-distribution has the form (14):
\[
H_{q/g}^{\text{DAT}}(D) = \delta_1 H_{q/g}^{1, DAT}(D) + \delta_2 H_{q/g}^{2, DAT}(D) \tag{17}
\]
\[
= \alpha^q H_{q/g}^{\text{DIFF}}(D) + (1 - \alpha^q) H_{q/g}^{\text{DIFF}}(D).
\]

This is an analytical expression for the \( D \)-distribution of the combined jet sample. From it, one can conclude that the \( g \)-jet fraction in the combined jet sample can be found by fitting using corrected \( D \)-distributions of \( q/g \)-jets:
\[
H_{q/g}^{\text{DIFF}}(D) = \alpha^q H_{q/g}^{\text{DIFF}}(D) + (1 - \alpha^q) H_{q/g}^{\text{DIFF}}(D). \tag{18}
\]
On the other hand, according to Eq. (1), the $g$-jet fraction in the combined jet sample can be found by fitting using generator $q/g$-jet $D$-distributions:

$$H^{\text{DAT}}(D) \sim \alpha^g H^{\text{MC}}(D) + (1 - \alpha^g)H^{\text{MC}}(D).$$  \hfill (19)

Although fitting functions in Eqs. (18) and (19) are different, mean $g$-jets fractions in both cases match each other with uncertainties.

In [2, 3] “data-driven reshaping” (DDR) procedure was proposed to correct the model $q/g$-jet $D$-distributions, $H^{q/g\text{MC}}(D)$, using data. DDR also uses two jet samples. In contrast to the procedure described above with the final equations (16), the original equations (Eqs. (4)) were written in method DDR for unnormalized histograms. In this form, the $g$-jet fractions are hidden. However, these equations implicitly contain the generator values $\alpha_{k}^{\text{MC}}$.

To show this, write down the equations that are used in [3] for the DDR procedure. Consider here a general case, which is presented in [3], in which jets with unidentified flavour are separated from $q$-jets. In this case, the original non-normalized $D$-distributions of jets in each MC jet sample have the form (see [3], p. 14):

$$N_{1}^\text{MC}(D) = N_{1}^\text{MC}(D) + N_{1}^\text{MC}(D) + N_{1}^\text{MC}(D),$$  \hfill (20)

$$N_{2}^\text{MC}(D) = N_{2}^\text{MC}(D) + N_{2}^\text{MC}(D) + N_{2}^\text{MC}(D).$$

The numbers of jets in jet samples are equal: $N = N_{k}^\text{MCtot} = \sum_{D} N_{k}^\text{MC}(D)$. Instead of the index notation of $D$-discriminant bin $i$, which is used in [3], the functional notation is used here: $X(D) \equiv X_i$. For data, two equations are written for the same number of jets $N$ for two jet samples with unknown weights $w^q(D)$ and $w^g(D)$, which are in [3] are selected independent of jet sample, i.e. “universal” (in the terminology of this work):

$$N_{1}^{\text{DAT}}(D) = w^q(D)N_{1}^\text{MC}(D) + w^g(D)N_{1}^\text{MC}(D),$$  \hfill (21)

$$N_{2}^{\text{DAT}}(D) = w^q(D)N_{2}^\text{MC}(D) + w^g(D)N_{2}^\text{MC}(D).$$

The weights correct the content of MC distributions in the $D$-bin so that the total $D$-distributions in the right sides of Eqs. (21) reproduces the data $D$-distributions in the left sides. From Eqs. (21) follows a system of equations with normalized distributions that explicitly contain the $g$-jet fractions:

$$H_{1}^{\text{DAT}}(D) = w^q(D)\alpha_{1}^{\text{MC}}H^{\text{MC}}(D) + w^g(D)\alpha_{1}^{\text{MC}}H^{\text{MC}}(D),$$

$$H_{2}^{\text{DAT}}(D) = w^q(D)\alpha_{2}^{\text{MC}}H^{\text{MC}}(D) + w^g(D)\alpha_{2}^{\text{MC}}H^{\text{MC}}(D).$$

Here the $f$-jet fraction is determined by the ratio $\alpha_{k}^{\text{MC}} = N_{k}^\text{MCtot}/N$, where $N_{k}^\text{MCtot}$ is the number of $f$-jets in the $k$th MC jet sample $(N_{k}^\text{MCtot} = N_{k}^\text{MCtot} = N_{k}^\text{MC} + N_{k}^{\text{MC}} + N_{k}^{\text{MC}} = 1)$. The JFNU correction is not taken into account in Eqs. (22), i.e. normalized $D$-distributions of $f$-jets are considered independent of the jet sample index $k$. The fact that JFNU correction is not taken into account justifies the assumption used in [3] that the weights $w^q(D)$ in the Eqs. (21) do not depend on index of jet sample $k$.

System of Eqs. (22) contains decompositions of the $D$-distributions for data jet samples into $q$- and $g$-jet $D$-distributions that are normalized by the value:

$$S^f = \sum_{D} w^q(D)H^{\text{MC}}(D).$$  \hfill (23)

One can introduce corrected by DDR procedure normalized $D$-distributions of $f$-jets, $H^{f\text{DAT}}(D)$, and corrected fractions of $f$-jets, $\alpha_{k}^{f}$:

$$H_{1}^{\text{DAT}}(D) = \alpha_{1}^{f}H^{f\text{DAT}}(D),$$

$$H_{2}^{\text{DAT}}(D) = \alpha_{2}^{f}H^{f\text{DAT}}(D),$$

where $\alpha_{k}^{f} = S^f/\alpha_{k}^{f}$, $H^{f}(D) \equiv w^q(D)H^{\text{MC}}(D)/S^f$. It follows from Eqs. (24) that $\alpha_{1}^{f} + \alpha_{2}^{f} + \alpha_{k}^{f} = 1$. Thus, to obtain $q(g)$-jet fraction in $k$th data jet samples it is necessary to multiply MC $q(g)$-jet fraction by the factors $S^q$ and $S^g$ respectively. The same results can be obtained by fit (1) with corrected distributions $H^{f\text{DAT}}(D)$.

Moreover, it follows from Eqs. (24) that $S^q = S^{g} = 1$. To show this, one can sum up the Eqs. (24) by bins and take into account the normalization of histograms:

$$\alpha_{1}^{\text{MC}}S^q + \alpha_{2}^{\text{MC}}S^{g} = \alpha_{1}^{\text{MC}} + \alpha_{2}^{\text{MC}},$$

$$\alpha_{1}^{\text{MC}}S^q + \alpha_{2}^{\text{MC}}S^{g} = \alpha_{1}^{\text{MC}} + \alpha_{2}^{\text{MC}}.$$

The only solution of this system is $S^q = S^{g} = 1$ if the determinant is not zero $\Delta = \alpha_{1}^{\text{MC}}\alpha_{2}^{\text{MC}} - \alpha_{1}^{\text{MC}}\alpha_{2}^{\text{MC}} \neq 0$. 

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In the case \( q = \{u, d, s, c, b, x\} \) (i.e. \( \alpha_i^{\text{MC}} = 0 \) and \( \alpha_k^{\text{MC}} = 1 - \alpha_k^{\text{MC}} \)) condition \( \Delta \neq 0 \) is condition of inequality of \( g \)-jet fractions between two jet samples \( (\alpha_i^g \neq \alpha_k^g) \) and system of Eqs. (24) take the form:

\[
H_{1}^{\text{DAT}}(D) = \alpha_1^{\text{MC}} H_{g}^{\text{DAT}}(D) + \alpha_1^{\text{MC}} H_{g}^{\text{MC}}(D),
\]

\[
H_{2}^{\text{DAT}}(D) = \alpha_2^{\text{MC}} H_{g}^{\text{DAT}}(D) + \alpha_2^{\text{MC}} H_{g}^{\text{MC}}(D),
\]

(26)

The solution of system (26) relative to unknown distributions \( H_{g}^{\text{MC}}(D) \) is equivalent to solution of the system of equations for weights (21) and, after that, calculation of \( H_{g}^{\text{MC}}(D) = w_{g}(D) H_{g}^{\text{MC}}(D) \). The solution of system (26) has the form (16), where it is necessary to replace \( \alpha_k^g \) (\( g \)-jet fraction in \( k \)th data jet sample) with \( \alpha_k^{\text{MC}} \) (\( g \)-jet fraction in \( k \)th MC jet sample) and neglect the JFNU correction. In real analysis, after applying the DDR procedure, one can see some small deviation of the \( g \)-jet fractions between extracted value (data with DDR correction) and MC value within the JFNU correction.

Equations (16) correct the DDR procedure by replacing MC \( g \)-jet fractions \( \alpha_k^{\text{MC}} \) with the measured ones, \( \alpha_k^g \). In addition, the Eqs. (16) contain JFNU correction, which describes universally the differences of \( q/g \)-jet characteristics in different jet samples, and which is important if the fractions of \( g \)-jets are measured with good accuracy.

CONCLUSIONS

The article presents a technique for measuring characteristics of quark and gluon jets, using measured gluon jet fractions in two control jet samples.

The most effective way of measuring the gluon jet fraction is fitting the measured jet \( D \)-distribution with a linear combination of quark and gluon jets \( D \)-distributions \( (D \) is quark/gluon jet discriminator). The fraction of gluon jet is a fitting parameter. Quark and gluon jets \( D \)-distributions are constructed for each jet sample separately using a generator model and with full simulation of detector response. The model defines quark/gluon jet physics parameters, which is used to construct jet \( D \)-value and a rule for identifying the jet type—a rule to match parton initiating jet and jet at hadron level.

Two jet samples characteristics divergence is defined mainly by the quark/gluon jet fractions difference between the jet samples. For precision measurement one should also consider the difference in quark and gluon jet characteristics between the jet samples. This difference arises from jet kinematics and/or from different numbers of accompanying jets, which can affect the operation of jet finder algorithm.

An universal method for taking into account the differences in the quark/gluon jet characteristics between two jet samples is proposed in the article. The method introduces a notion of a “measure of non-universality” of quark/gluon jet characteristic, which is defined as a difference of characteristic between the two jet samples, and a notion of “universal” (averaged) quark/gluon jet characteristic, which is a characteristic of jet sample that combines the two jet samples under study. It is shown that the “universal” characteristic of quark/gluon jets are expressed via the measured characteristics for the two jet samples with some correction. The correction consists of the “measures of non-universality” of quark and gluon jet characteristics (determined in the MC model), the measured gluon jet fractions, and ratio of number of jets in the two jet samples.

The quark-gluon discriminator \( D \), which is used to measure gluon jet fraction, can be considered as an example of the measured jet sample characteristic. Following general formalism, the quark and gluon “universal” \( D \)-distributions, related to the combined jet sample, can be found from the data. These distributions can be compared with the original model quark and gluon \( D \)-distributions, which were used to measure gluon jet fractions. It will allow to determine how well the model of quark and gluon jet formation agrees with the real process.

ACKNOWLEDGMENTS

The authors are grateful to Sergei Shmatov and Maria Savina for careful reading of the paper and valuable suggestions and comments.

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