JET PHYSICS AT LEP AND QCD

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Abstract

With the advent of LEP we discovered jets and at its last years we learned a lot about intermediate vector bosons. All that strongly supports our belief in QCD. Jet physics is briefly described in this talk. Experimental results are compared with QCD predictions. It is shown that the perturbative QCD has been able not only to describe the existing data but also to predict many bright phenomena.

The main process of $e^+e^-$-annihilation at LEP looks like two jets moving in the opposite directions. These jets are considered in QCD as (initiated by quarks and collimated) cascades of consecutive emissions of partons each of which produces observed hadrons due to soft confinement.

1. Early days.

Jets were discovered in 1975. Their angular collimation was demonstrated in studies of such kinematical properties as sphericity, spherocity, thrust etc. They show that the transverse momenta are small compared to the total momenta if the proper coordinate axes are chosen. The collimation increases with energy increase.

The jet axes were defined from these characteristics. It has been shown that the angular ($\theta$) distribution of jet axes in $e^+e^-$-annihilation follows the dependence $\propto (1 + \cos^2 \theta)$ expected for spin 1/2 objects.

The quark origin of jets was proven in studies of the ratio of $e^+e^-$-annihilation cross sections to hadrons and to $\mu^+\mu^-$-pairs. QCD predicts that this ratio should be equal to the sum of squared charges of the objects initiating jets. In experiment, this ratio equals just its value for quarks and increases with energy at the thresholds for heavier quarks.

Thus, these early findings assured us that QCD is on the right way. Later, numerous data supported this conclusion as is shown in what follows in brief. To shorten the presentation, only some of most impressive results have been chosen and no Figures are presented. More complete list with a detailed survey and Figures demonstrating comparison with experiment can be found in the books [1, 2] and in recent review papers [3, 4, 5, 6, 7].

2. Theory.

According to QCD, the primary quarks emit gluons which, in their turn, can emit $e^+e^-$-pairs and gluons. Thus the branching process of jet evolution appears. The gluons with high enough transverse momenta can create gluon jets. QCD pretends to describe jets of both quark and gluon origin. Many hadrons are created when partons become confined.
Analytical QCD pretends to start with asymptotical values and proceed to lower energies accounting for conservation laws, higher order perturbative and non-perturbative effects. The perturbative approach is justified at high transferred momenta due to the asymptotic freedom property of QCD which states that the coupling strength becomes smaller with increase of transferred momenta. The perturbative evolution is terminated at some low scale $Q_0 \sim 1$ GeV for transverse momenta or virtualities of partons. Here, the transition between partonic degrees of freedom at short distances to hadronic degrees of freedom at long distances (i.e., from weak to strong coupling) begins. Every experiment encodes this transition. To deal with it in practice, the local parton-hadron duality (LPHD) is assumed which declares that the distributions at the parton level describe the hadron observables up to some constant factor. This concept originates from the preconfinement property of quarks and gluons to form colorless clusters. In this framework, the perturbative QCD has demonstrated its very high predictive power. It works surprisingly well when applied for comparison with experiment.

The most general approach starts from the equation for the generating functional. The generating functional contains complete information about any multiparticle process. It is defined as

$$ G(\{u\}, \kappa_0) = \sum_n \int d^3 k_1 \ldots d^3 k_n u(k_1) \ldots u(k_n) P_n(k_1, \ldots, k_n; \kappa_0), \quad (1) $$

where $P_n(k_1, \ldots, k_n; \kappa_0)$ is the probability density for exclusive production of particles with momenta $k_1, \ldots, k_n$ at the initial virtuality (energy) $\kappa_0$, and $u(k)$ is an auxiliary function. For $u(k) = \text{const}$, one gets the generating function of the multiplicity distribution $P_n(\kappa_0)$. The variations of $G(\{u\})$ over $u(k)$ (or differentials for constant $u$) provide any inclusive distributions and correlations of arbitrary order, i.e. complete information about the process. The general structure of the equation for the generating functional describing the jet evolution for a single species partons can be written symbolically as

$$ G' \sim \int \alpha_S K[G \otimes G - G]d\Omega. \quad (2) $$

It shows that the evolution of $G$ indicated by its variation (derivative) $G'$ is determined by the cascade process of the production of two partons by a highly virtual time-like parton (the term $G \otimes G$) and by the escape of a single parton ($G$) from a given phase space region $d\Omega$. The weights are determined by the coupling strength $\alpha_S$ and the splitting function $K$ defined by the interaction Lagrangian. The integral runs over all internal variables, and the symbol $\otimes$ shows that the two partons share the momentum of their parent. This is a non-linear integrodifferential probabilistic equation with shifted arguments in the $G \otimes G$ term under the integral sign.

For quark and gluon jets, one writes down the system of two coupled equations. Their solutions give all characteristics of quark and gluon jets and allow for the comparison with experiment to be done. Let us write them down explicitly for the
generating functions now.

\[ G'_G = \int_0^1 dx K^G_G(x) \gamma^2_0 [G_G(y + \ln x)G_G(y + \ln(1 - x)) - G_G(y)] \]
\[ + \ n_f \int_0^1 dx K^F_G(x) \gamma^2_0 [G_F(y + \ln x)G_F(y + \ln(1 - x)) - G_G(y)], \tag{3} \]

\[ G'_F = \int_0^1 dx K^G_F(x) \gamma^2_0 [G_G(y + \ln x)G_F(y + \ln(1 - x)) - G_F(y)], \tag{4} \]

where \( G'(y) = dG/dy, y = \ln(p\Theta/Q_0) = \ln(2Q/Q_0), p \) is the initial momentum, \( \Theta \) is the angle of the divergence of the jet (jet opening angle), assumed here to be small, \( Q \) is the jet virtuality, \( Q_0 = \text{const} \), \( n_f \) is the number of active flavors,

\[ \gamma^2_0 = \frac{2N_c \alpha_S}{\pi}, \tag{5} \]

the running coupling constant in the one-loop approximation is

\[ \alpha_S(y) = \frac{6\pi}{(11N_c - 2n_f)y}, \tag{6} \]

the labels \( G \) and \( F \) correspond to gluons and quarks, and the kernels of the equations are

\[ K^G_G(x) = \frac{1}{x} - (1 - x)[2 - x(1 - x)], \tag{7} \]
\[ K^F_G(x) = \frac{1}{4N_c}[x^2 + (1 - x)^2], \tag{8} \]
\[ K^G_F(x) = \frac{C_F}{N_c} \left[ \frac{1}{x} - 1 + \frac{x}{2} \right], \tag{9} \]

where \( N_c = 3 \) is the number of colours, and \( C_F = (N_c^2 - 1)/2N_c = 4/3 \) in QCD. The variable \( u \) has been omitted in the generating functions.

Let us note that these equations can be exactly solved [8] if the coupling strength is assumed fixed, i.e. independent of \( y \). For the running coupling strength, the Taylor series expansion can be used [9] to get the modified perturbative expansion of physically measurable quantities. The asymptotical results are obtained in the so-called double-logarithmic (DLA) or leading order (LO) approximation when the terms \( (\alpha_S \ln^2 s)^n \) are summed. Here \( s \) is the cms energy squared. The emitted gluons are assumed so soft that the energy-momentum conservation is neglected. The corrections accounting for conservation laws in the \( G \otimes G \) term and in limits of the integration as well as the higher order terms in the weight \( \alpha_S K \) (in particular, the non-singular terms of the kernels \( K \)) appear first in the next-to-leading (NLO or MLLA - modified leading logarithm approximation) and then in higher (2NLO,...) orders. Formally, these equations have been proven only for the next-to-leading (NLO) order of the perturbative QCD. However, one can try to consider them as
kinetic equations in higher orders and/or generalize them including the abovementioned effects in a more rigorous way than it is usually implied.

3. QCD predictions and their comparison with experiment.

The theoretical results have been successfully compared with available experimental data. The main bulk of the data is provided by $e^+e^-$-processes at $Z^0$ energy.

The energy dependence of mean multiplicity.

The equations for the average multiplicities in jets are obtained from the system of equations (3), (4) by expanding the generating functions in $u - 1$ and keeping the terms with $q=0$ and 1 according to the definition

$$\left.\frac{dG}{du}\right|_{u=1} = \sum nP_n = \langle n \rangle. \quad \text{(10)}$$

From their solutions one learns about the energy evolution of the ratio of multiplicities in quark and gluon jets $r$ and of the QCD anomalous dimension $\gamma$ (the slope of the logarithm of average multiplicity in a gluon jet) defined as

$$r = \frac{\langle n_G \rangle}{\langle n_F \rangle}, \quad \gamma = \frac{\langle n_G \rangle'}{\langle n_G \rangle} = (\langle \ln \langle n_G \rangle \rangle'). \quad \text{(11)}$$

They have been represented by the perturbative expansion at large $y$ as

$$\gamma = \gamma_0 (1 - a_1 \gamma_0 - a_2 \gamma_0^2 - a_3 \gamma_0^3) + O(\gamma_0^4), \quad \text{(12)}$$

$$r = r_0 (1 - r_1 \gamma_0 - r_2 \gamma_0^2 - r_3 \gamma_0^3) + O(\gamma_0^4). \quad \text{(13)}$$

Using the Taylor series expansion of $\langle n \rangle$ at large $y$ in the corresponding equations with (12), (13) one gets the coefficients $a_i$, $r_i$.

One of the most spectacular predictions of QCD states that in the leading order approximation, where $\gamma = \gamma_0$, average multiplicities should increase with energy [10, 11, 12, 13] like $\exp[c\sqrt{\ln s}]$, i.e., in between the power-like and logarithmic dependences predicted by hydrodynamical and multiperipheral models. Next-to-leading order results account for the term with $a_1$ in Eqn. (12) [14, 15, 16] and contribute the logarithmically decreasing factor to this behavior whereas the higher order terms do not practically change this dependence [17, 18]. The fitted parameters in the final expression are an overall constant normalization factor which is defined by confinement and a scale parameter $Q_0$. The $e^+e^-$-data are well fitted by such an expression. Let us note here that the expansion parameter $\gamma$ is rather large at present energies being about 0.4 - 0.5.

Let us stress here that the perturbative expansion in Eq. (12) leads to the modification of the perturbative expansion for $\langle n \rangle$. Since $\gamma$ exponentiates in $\langle n \rangle$, the so called modified perturbative expansion shows up in $\langle n \rangle$.

Difference between quark and gluon jets

The system of two equations for quark and gluon jets predicts that asymptotically the energy dependence of mean multiplicities in them should be identical.
However, normalization differs, and gluon jets are more "active" so that the ratio $r = \langle n_G \rangle / \langle n_F \rangle$ of average multiplicities in gluon and quark jets should tend at high energies [19] to the ratio of Casimir operators $C_A / C_F = 9/4$. Once again, this prediction shows how far are we now from the true asymptotics because in experiment this ratio is about 1.5 at $Z^0$ energy and even smaller at lower energies. The higher order terms [20, 14, 18](calculated now up to 3NLO) improve the agreement and approach the experimental value with an accuracy about 15%. The higher order terms change slightly also the energy behavior of quark jets compared to gluon jets as observed in experiment. However, the simultaneous fit of quark and gluon jets with the same set of fitted parameters is still not very accurate. This failure is again due to insufficiently precise description of the ratio $r$.

Let us stress here that LO and NLO terms in energy dependence of mean multiplicities cancel in the ratio $r$. Thus, this is the most sensitive measure of higher order corrections which pushes us to work at the limits of our knowledge. Moreover, due to this cancellation the $\gamma_0^3$-terms in $r$-expansion correspond to $\gamma_0^4$-terms in expansion of $\gamma$ itself, i.e. to 4NLO and not to 3NLO-terms there. And they have been calculated analytically [18]. Therefore the slight disagreement with experiment should not surprise us very much when we work at (and, may be, even outside!) the limits of applicability of the whole approach.

Moreover, QCD predicted [18] that the ratio of multiplicities $r$ should be smaller than the ratio of their slopes (first derivatives) which, in turn, is smaller than the ratio of their curvatures (second derivatives), and all of them are smaller than 2.25 and tend to this limit in asymptotics. This has been confirmed by experiment as well.

Oscillations of cumulant moments.

The shape of the multiplicity distribution can be described by its higher moments related to the width, the skewness, the kurtosis etc. The $q$-th derivative of the generating function corresponds to the factorial moment $F_q$, and the derivative of its logarithm defines the so-called cumulant moment $K_q$. The latter ones describe the genuine (irreducible) correlations in the system (it reminds the connected Feynman graphs).

$$ F_q = \frac{\sum_n P_n n(n-1)...(n-q+1)}{(\sum_n P_n n)^q} = \frac{1}{\langle n \rangle^q} \cdot \left. \frac{d^q G(z)}{du^q} \right|_{u=1}, \quad (14) $$

$$ K_q = \frac{1}{\langle n \rangle^q} \cdot \left. \frac{d^q \ln G(z)}{du^q} \right|_{u=1}. \quad (15) $$

These moments are not independent. They are connected by definite relations that can easily be derived from their definitions in terms of the generating function. In that sense, cumulants and factorial moments are equally suitable.

Solving the Eqns. (3), (4), one gets quite naturally the predictions [9, 8, 21] for the behavior of the ratio $H_q = K_q / F_q$. At asymptotically high energies, this ratio is predicted to behave as $q^{-2}$. However, the asymptotics is very far from our realm. At present energies, according to QCD, this ratio should reveal the minimum at
$q \approx 5$ and subsequent oscillations. This astonishing qualitative prediction has been confirmed in experiment (for the first time in Ref. [22]). Moreover, the oscillations of the moments with their rank have been observed. The quantitative analytical estimates are not enough accurate but the numerical computer solution [23] reproduces oscillations quite well. These new laws differ from all previously attempted distributions of the probability theory.

*The hump-backed plateau.*

Dealing with inclusive distributions, one should solve the equations for the generating functional. It has been done up to NLO approximation. As predicted by QCD, the momentum (rapidity $y$) spectra of particles inside jets should have the shape of the hump-backed plateau [24, 12, 13, 25]. This striking prediction of the perturbative QCD differs from the previously popular flat plateau advocated by Feynman. It has been found in experiment. The depletion between the two humps is due to angular ordering and color coherence in QCD. The humps are of the approximately Gaussian shape near their maxima if the variable $\xi = -\ln x; \quad x = p/E_j$ is used. Here $p$ is the particle momentum, $E_j$ is the jet energy. This prediction was first obtained in the LO QCD, and more accurate expressions were derived in NLO [26]. Moments of the distributions up to the fourth rank have been calculated. The drop of the spectrum towards small momenta becomes more noticeable in this variable. The comparison with experimental data at different energies has revealed good agreement both on the shape of the spectrum and on the energy dependence of its peak position and width.

*Difference between heavy- and light-quark jets.*

Another spectacular prediction of QCD is the difference between the spectra and multiplicities in jets initiated by heavy and light quarks. Qualitatively, it corresponds to the difference in bremsstrahlung by muons and electrons where the photon emission at small angles is strongly suppressed for muons because of the large mass in the muon propagator. Therefore, the intensity of the radiation is lower in the ratio of masses squared. The coherence of soft gluons also plays an important role in QCD. For heavy quarks the accompanying radiation of gluons should be stronger depleted in the forward direction (dead-cone or ring-like emission). It was predicted [27, 28] that it should result in the energy-independent difference of companion mean multiplicities for heavy- and light-quark jets of equal energy. The naive model of energy rescaling [29, 30, 31] predicts the decreasing difference. The experimental data support this QCD conclusion.

*Color coherence in 3-jet events.*

When three or more partons are involved in hard interaction, one should take into account color-coherence effects. Several of them have been observed. In particular, the multiplicity can not be represented simply as a sum of flows from independent partons. QCD predicts that the particle flows should be enlarged in the directions of emission of partons and suppressed in between them. Especially interesting is the prediction that this suppression is stronger between $q\bar{q}$-pair than between $qq$ and $gq$ in $e^+e^- \rightarrow q\bar{q}g$ event if all angles between partons are large (the ”string” [32] or
"drag" [33] effect). All these predictions have been confirmed by experiment. In $q\bar{q}g$ events the particle population values in the $qg$ valleys are found larger than in the $qq$ valley by a factor $2.23\pm0.37$ compared to the theoretical prediction of 2.4. Moreover, QCD predicts that this shape is energy-independent up to an overall normalization factor.

Let us note that for the process $e^+e^-\rightarrow q\bar{q}\gamma$ the emission of additional photons would be suppressed both in the direction of a primary photon and in the opposite one. In the case of an emitted gluon, we observe the string (drag) effect of enlarged multiplicity in its direction and stronger suppression in the opposite one. This suppression is described by the ratio of the corresponding multiplicities in the $q\bar{q}$ region which is found to be equal $0.58\pm0.06$ in experiment whereas the theoretical prediction is 0.61.

The color coherence reveals itself as inside jets as in inter-jet regions. It should suppress both the total multiplicity of $q\bar{q}gg$ events and the particle yield in the transverse to the $q\bar{q}g$ plane for decreasing opening angle between the low-energy jets. When hard gluon becomes softer, color coherence determines, e.g., the azimuthal correlations of two gluons in $q\bar{q}gg$ system. In particular, back-to-back configuration ($\varphi \sim 180^0$) is suppressed by a factor $\sim 0.785$ in experiment, 0.8 in HERWIG Monte Carlo and 0.93 in analytical pQCD. In conclusion, color coherence determines topological dependence of jet properties.

Some proposals have been promoted for a special two-scale analysis of 3-jet events when the restriction on the transverse momentum of a gluon jet is imposed [34, 35]. They found also support from experiment.

**Intermittency and fractality.**

The self-similar parton cascade leads to special multiparton correlations. Its structure with "jets inside jets inside jets..." provoked the analogy with turbulence and the ideas of intermittency [36]. Such a structure should result in the fractal distribution in the available phase space [37]. The fractal behavior would display the linear dependence of logarithms of factorial moments on the logarithmic size of phase space windows. The moments are larger in smaller windows, i.e. the fluctuations increase in smaller bins in a power-like manner (see the review paper [38]).

In QCD, the power dependence appears for a fixed coupling regime [8]. The running property of the coupling strength in QCD flattens [39, 40, 41] this dependence at smaller bins, i.e. the multifractal behavior takes over there. The slopes for different ranks $q$ are related to the Renyi dimensions. Both the linear increase at comparatively large but decreasing bins and its flattening for small bins have been observed in experiment. However, only qualitative agreement with analytical predictions can be claimed here. The higher order calculations are rather complicated and mostly the results of LO with some NLO corrections are yet available. In experiment, different cuts have been used which hamper the direct comparison. However, Monte Carlo models where these cuts can be done agree with experiment better. The role of partonic and hadronization stages in this regime is still debatable.
Subjet multiplicities.

A single quark-antiquark pair is initially created in $e^+e^-$ annihilation. With very low angular resolution one observes two jets. A three-jet structure can be observed when a gluon with large transverse momentum is emitted by the quark or antiquark. However such a process is suppressed by an additional factor $\alpha_s$, which is small for large transferred momenta. It can be calculated perturbatively. At relatively low transferred momenta, the jet evolves to angular ordered subjets ("jets inside jets..."). Different algorithms have been proposed to resolve subjets. By increasing the resolution, more and more subjets are observed. For very high resolution, the final hadrons are resolved. The resolution criteria are chosen to provide infrared safe results.

In particular, one can predict the asymptotical ratio of subjet multiplicities in 3- and 2-jet events if one neglects soft gluon coherence:

$$\frac{n_{3j}}{n_{2j}} = \frac{2C_F + C_A}{2C_F} = \frac{17}{8}.$$ 

(16)

Actually, the coherence reduces this value to be below 1.5 in experiment for all acceptable resolution parameters. Theoretical predictions [16] agree only qualitatively with experimental findings.

Subjet multiplicities have also been studied in separated quark and gluon jets. The analytical results [42] represent the data fairly well for large values of the subjet resolution scale $y_0$.

Jet universality.

According to QCD, jets produced in processes initiated by different colliding particles ($ep, pp, AA$ etc) should be universal and depend only on their own parent (gluon, light or heavy quark) if not modified by the secondary interactions. This prediction has been confirmed by many experiments.

4. Conclusions and outlook.

A list of successful analytical and Monte-Carlo QCD predictions can be made longer. In particular, much work was done on the energy dependence of higher moments of multiplicity distributions, on forward-backward multiplicity correlations, on Bose-Einstein correlations, on various shape parameters of jets (and, in general, on event shape distributions), on non-perturbative corrections etc. QCD serves not only as a powerful tool for studies of multiparticle production processes but as a background for new physics as well.

The new era will be opened with the advent of new generations of linear colliders like TESLA.

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We should praise LEP and experimentalists from ALEPH, DELPHI, L3 and OPAL collaborations for numerous results which allowed to enlarge our knowledge of physics of multiparticle production. I regret that the available space for the
written version did not allow me to refer to all these papers and I had to omit Figures and cite mostly the theoretical predictions. In oral presentation, I tried to avoid these shortcomings.

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