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Measurements of jet rates with the anti-k_t and SISCone algorithms at LEP with the OPAL detector

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Abstract. We study jet production in e^+e^- annihilation to hadrons with data recorded by the OPAL experiment at LEP at centre-of-mass energies between 90 GeV and 207 GeV. The jet production rates were measured for the first time with the anti-k_t and SISCone jet clustering algorithms. We compare the data with predictions by modern Monte Carlo event generators.

1 Introduction

Hadronic final states in high energy particle collisions are characterised by the so-called jets, which describe the phenomenon that final state particles appear in collimated groups. These jets are quantified by defining jet clustering algorithms, which assign particles to groups in order to identify the jet structure of the events. Local parton hadron duality [1, 2] establishes the close correspondence between the hadronic final state jets and the partons as objects of the theory of strong interactions, Quantum Chromo Dynamics (QCD). The production of hadronic final states is described by QCD together with a model for the transition from partons to hadrons.

At the LHC the understanding of the properties of jets and their connection to the partons produced in the hard interactions is essential for the success of its physics program. Before LHC jets were studied in electron-proton ($e^{\pm}p$) collisions by the HERA experiments [3] and in electron-positron (e^+e^-) collisions at LEP and earlier colliders [4, 5], and in $p\bar{p}$ collisions, see e.g. [6].

The introduction of new jet algorithms for LHC [7, 8] raises the question how these algorithms perform in e^+e^- or $e^{\pm}p$ collisions in comparison to established algorithms. A cone jet algorithm for e^+e^- was introduced and studied by OPAL previously [9]. Two studies by ZEUS [10, 11] compared the k_t, anti-k_t and SISCone algorithms in $e^{\pm}p$ DIS and photoproduction.

We report here on studies of the anti-k_t and SISCone algorithms with e^+e^- data from the OPAL experiment at LEP. In e^+e^- collisions a color singlet is produced in the decay of the virtual Z^0 boson or photon to quarks thus providing a very clean environment to study jet physics. The anti-k_t and SISCone algorithms have not yet been tested in e^+e^- collisions.

2 LEP and OPAL

The large electron-positron collider LEP operated at CERN from 1989 to 2000 at centre-of-mass energies from around 91.2 GeV to a maximum of 209 GeV. The OPAL[1] experiment was one of the

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four large detectors at LEP. The OPAL detector [12] had almost complete coverage of the solid angle around the collision point, good momentum (energy) resolution for charged (neutral) particles.

We use data from OPAL recorded during the so-called LEP 2 phase, where LEP was operated at the highest possible energies. A sample in total of about 400,000 hadronic Z^0 decays was recorded to calibrate the detector together with the high energy samples of a few hundred to several thousand high energy hadronic events, for details see [13].

The analysis uses large samples of simulated signal events produced on the Z^0 peak with JETSET 7.4 [14] or HERWIG 6.2 [15] and at higher energies with the KK2f generator [16] coupled with PYTHIA 6 [17] or HERWIG 6 for parton shower and hadronisation. Background events from production of W-boson pairs are simulated with grc4f 2.1 [18] and KORALW [19]. Other backgrounds from two-photon interactions and τ-pair production are negligible after the event selection.

3 Event selection and jet reconstruction

In order to select hadronic final states produced at high energies above the Z^0 peak the event selection has to suppress so-called radiative return events as well as production of W-boson pairs for $\sqrt{s} >$ 161 GeV. Radiative return is a process where radiation of a high energy photon from the initial state (ISR) causes the production of a hadronic final state at reduced effective centre-of-mass (cm) energy $\sqrt{s'}$. At energies above the Z^0 peak the cross section for this process is enhanced when the remaining effective cm energy $\sqrt{s'} \approx m_Z$.

Briefly, in OPAL an algorithm searches for isolated high energy photons in the detector and reconstructs up to four jets in the hadronic final state. Then kinematic fits are performed for the energy of zero, one or two photons emitted parallel to the beam and constrained to the nominal cm energy. The fit with the lowest number of photons and an acceptable χ^2 is chosen and the effective cm energy $\sqrt{s'}$ is calculated. High energy hadronic events are required to have $\sqrt{s'}$ within 10 GeV of the nominal value. Any remaining background is accounted for in the experimental correction procedure.

The production of W-boson pairs decaying into hadronic final states is identified and rejected with the well-developed event selection algorithms used by OPAL analyses of W-boson production and properties [20]. Any remaining background is subtracted using simulated samples of W-boson production.

The number of selected events at energies above m_Z ranges from less than 300 at $\sqrt{s} = 130$ and 136 GeV to more than 3000 at $\sqrt{s} = 189$ GeV. At the highest energy of $\sqrt{s} = 207$ GeV about 1700 events were selected.

Jets are reconstructed from all hits in the electromagentic calorimeter and all tracks found in tracking chambers passing basic quality criteria. A so-called matching algorithm identifies hits in the calorimeter connected with tracks and subtracts the estimated energy contributed by the charged particle from the reconstructed energy in the calorimeter [21].

The anti-k_t algorithm [8] in its variant for e^+e^- collisions defines as distance measure between two particles i and j with energies E_i and E_j

$$d_{ij} = \min(E_i^{-2}, E_j^{-2})(1 - \cos\theta_{ij})/(1 - \cos R); \quad d_{iB} = E_i^{-2} \tag{1}$$

where $\cos\theta_{ij}$ is the angle between the two particles, R is a parameter and d_{iB} is the analogue of the distance between a particle i and the beam direction

If d_{ij} is the smallest of all phase space distances the two particles are combined into a pseudo-particle by adding their 4-vectors and removed from the list while the pseudo-particle is added to the list. If d_{iB} is the smallest distance particle i is removed from the list. This procedure continues until the list of (pseudo-) particles is exhausted. The anti-k_t algorithm clusters particles beginning from the most energetic ones usually at the centre of jets and effectively excludes particles at an angle larger than R from the jet axis. The result are jets with a well defined cone-like shape with opening half-angle R.

In the SISCone algorithm [7] all final state particles are used as seeds to center a cone of opening half-angle R. For all particles in the cone the sum of their momenta is calculated and the polar and azimuth angles θ and ϕ of the momentum sum vector are compared with the angles θ_C and ϕ_C of the cone axis. The cone directions are changed until the directions of the momentum sum vector and the cone match. The resulting stable cones are merged if their shared momentum sum is larger than a predefined threshold. For the presentation of the SISCone algorithm results the transformation $y = 1 - \cos R$ is used.

For both algorithms a cut on the minimum jet energy $E_{cut}/E_{vis.} > \epsilon = 0.077$ is applied when R is varied or a fixed value of $R = 0.36$ is chosen when ϵ is varied.

4 Experimental correction procedure

The experimental correction is performed using a novel procedure [22]. The simulated events from a generator like PYTHIA 6 (Py6) or HERWIG 6 (He6) at "particle level", i.e. after hard interaction, parton shower, hadronisation and decays of unstable particles[2], are passed through a full simulation of the OPAL experiment [23]. The hard interaction in the simulation is required to have effective cm energy $\sqrt{s'}$ within 1 GeV of the nominal value in order to suppress ISR. In this way the experimental correction also accounts for ISR effects.

The simulated detector response data are then reconstructed with the same software as the real data to obtain simulated events at "detector level". Events are labeled by the numbers of reconstructed jets at the values of y or ϵ of a given distribution. For example, with four increasing values of y an event could have the sequence $\{4322\}$, i.e. at y_1 4 jets, at y_2 3 jets and at y_3 and y_4 2 jets are found. The ratio of the numbers of events for each label at particle and detector level defines the correction factor. The advantage over the established method of comparing numbers of reconstructed jets directly is that with labeling events are essentially sorted by similarity in topology and the corresponding correction factors are applied to similar events.

Background is subtracted for each label using the predicted contribution from samples of simulated background events. Background is dominated by W-boson pair production with hadronic decays of both Ws. Therefore labels containing events with 4-jet topology for larger values of y or ϵ receive most of the background.

After subtraction of background and application of experimental correction factors the jet fractions are calculated by summing over appropriate labels. For example the 3-jet fraction for y_2 is

$$R_3(y_2) = 1/N \sum_{\{ijkl\},j=3} n_{ijkl} \tag{2}$$

where N is the total number of events and n_{ijkl} is the number of events with label $\{ijkl\}$. The statistical covariances between y or ϵ points can be computed directly based on equ. (2).

Figure 1 shows examples of comparisons of corrected data to simulation produced by the OPAL collaboration as explained in section 2. The simulations provide an excellent description of the data at $\sqrt{s} = 91$ GeV where they were tuned and a reasonable description of the 207 GeV data. We conclude that the experimental corrections derived from these simulations are reliable. Differences between the experimental corrections derived from PYTHIA 6 or HERWIG 6 are included in the experimental systematic uncertainties.

[2] All particles with lifetimes greater than 300 ps are treated as stable.

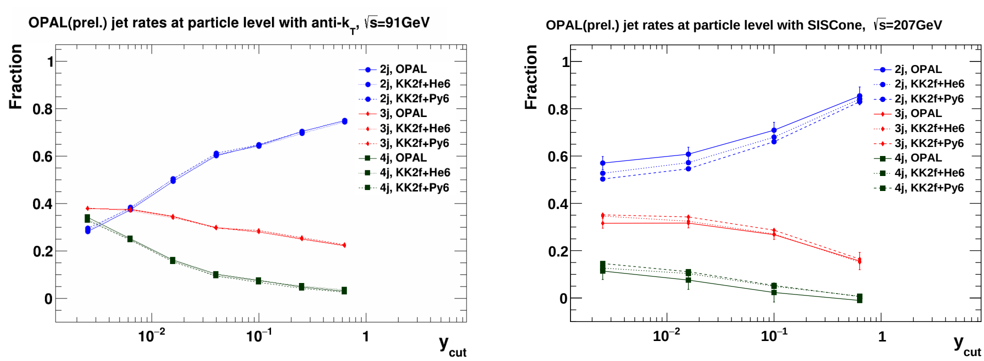

Figure 1. (left) Jet rates at particle level with anti-k_t at $\sqrt{s} = 91$ GeV compared with old simulation tuned by OPAL. The first y point corresponds to $R = 0.07$ and the last to $R = 1.19$. (right) The same for SISCone at $\sqrt{s} = 207$ GeV.

5 Results

We present measurements of the anti-k_t and SISCone jetrates corrected to the particle level at different LEP energy points and compare with predictions by the modern Monte Carlo generator programs Pythia8 (Py8) and Herwig++ (H++). In recent years significant progress in understanding and implementation of event generators has been made and we have taken Pythia8 and Herwig++ as representative examples [24]. The generator programs were used with their default parameter settings. Figure 2 shows results for anti-k_t at $\sqrt{s} = 91$ and 207 GeV as a function of y and for SISCone at $\sqrt{s} = 91$ and 207 GeV as function of $\epsilon = E_{cut}/E_{vis.}$.

We observe a good description of the jet rate data at all energy points by the simulation predictions. The description of the high energy data at 207 GeV is somewhat improved compared to the old OPAL programs shown in figure 1. This might be a result of improved treatment of perturbative QCD in the new simulations responsible for predicting effects evolving with the cm energy $\sqrt{s}$. We note that the general behaviour of the anti-k_t and SISCone algorithms is very similar for the same values of y and ϵ and thus their behaviour is dominated by their parameter settings and not by algorithm details.

In figure 3 we study predictions for hadronisation corrections for the jet rates measured with the new algorithms. The corrections are defined as the ratio of predictions at the parton and the particle level from the Monte Carlo generators. Parton level is defined as the final state consisting of quarks and gluons of simulated events after hard interaction and parton shower before the hadronisation model is applied. The displays in figure 3 show the hadronisation corrections calculated at several points of ϵ for a fixed value of opening half-angle $R = 0.36$ for the SISCone (left) and anti-k_t (right) algorithms.

The corrections for SISCone from KK2f+Py6 (old OPAL tuned MC) and Pythia8 agree well while Herwig++ tends to predict smaller corrections. For the SISCone 3-jet rate the corrections are about 10% with a trend to decrease with decreasing ϵ. For the SISCone 2-jet rate the corrections are about 10-20% while the SISCone 4-jet rate has corrections ranging from 90% to 10-20% at small ϵ. The corrections for the 2-jet rate and the other jet rates are below and above one, respectively. This effect can be explained with the well-known general broadening of jets due to hadronisation reducing the 2-jet and increasing the >2 jet rates.

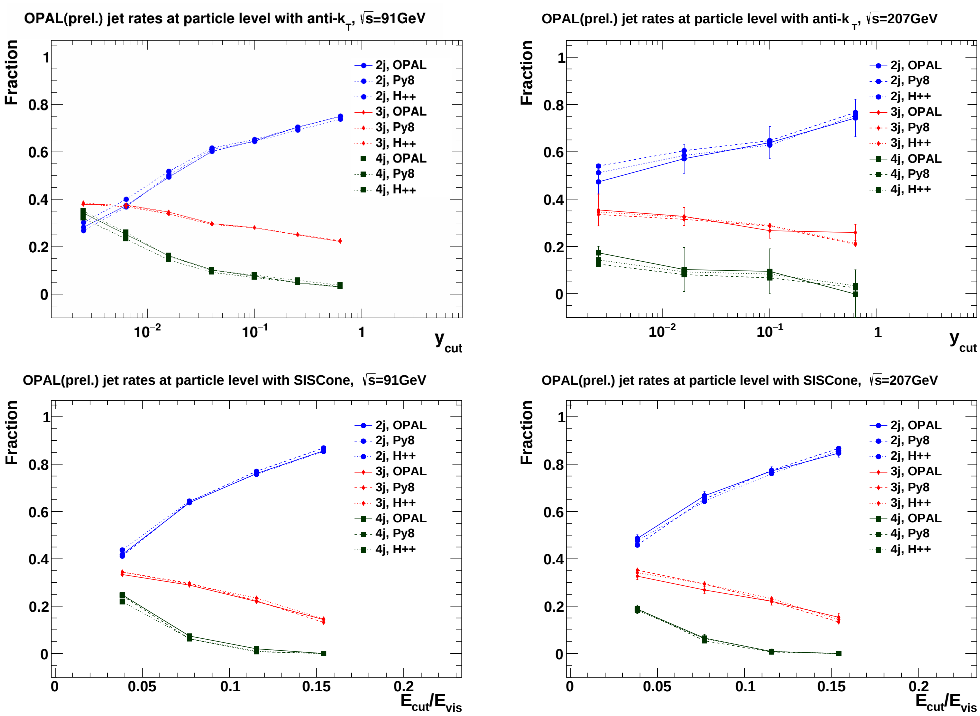

Figure 2. (upper row) Jet rates at particle level with anti-k_t at $\sqrt{s} = 91$ and 207 GeV compared with new Monte Carlo predictions as indicated. (lower row) The same for SISCone as a function of ϵ for $R = 0.36$.

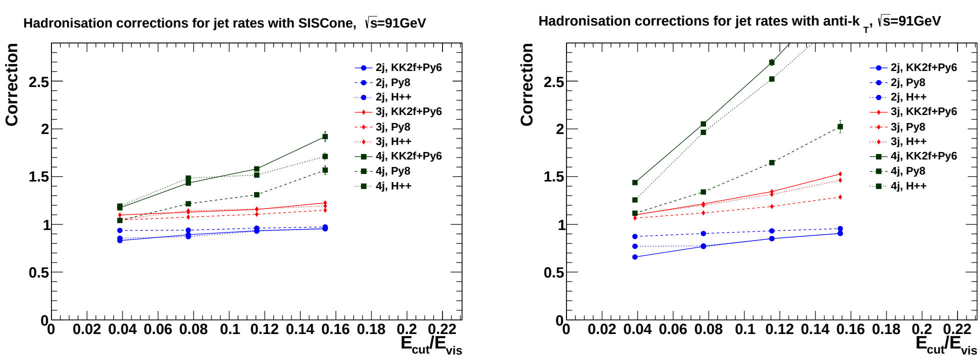

Figure 3. (left) Hadronisation corrections predicted by simulations as indicated for SISCone at $\sqrt{s} = 91$ as a function of ϵ for $R = 0.36$. (right) The same for anti-k_t.

For the anti-k_t algorithm we find a similar pattern of the corrections compared with SISCone, but the values of the correction factors are generally larger. For the Durham algorithm with additional requirement on the jet energies (not shown) we find hadronisation corrections essentially flat in ϵ and significantly smaller w.r.t. both SISCone and anti-k_t.

6 Summary

We have shown results for jet rates reconstructed with the algorithms SISCone and anti-k_t in hadronic final states in e^+e^- annihilation. The jet rates are compared with predictions by Monte Carlo event generators and generally good agreement is found. The hadronisation corrections predicted by the generators show interesting behaviour as a function of $\epsilon = E_{cut}/E_{vis.}$.

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