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Evidence for charm production in W decays

The ALEPH Collaboration

Abstract

From the study of kinematic properties of final state particles coming from charm quark in W decays, the inclusive charm production rate is measured. Using the 10.65 pb^{-1} of data collected by ALEPH at 170 GeV and 172 GeV, and studying the two channels $\mathrm{W^+W^-} \rightarrow 4\mathrm{q}$ and $\mathrm{W^+W^-} \rightarrow \ell\nu\mathrm{q}\bar{\mathrm{q}}'$, the fraction of hadronic W decays to c quarks, $\mathrm{R_c^W} = \Gamma(\mathrm{W} \rightarrow \mathrm{cX})/\Gamma(\mathrm{W} \rightarrow \mathrm{hadrons})$, is found to be $0.57 \pm 0.18_{\mathrm{stat}} \pm 0.04_{\mathrm{syst}}$, from which the value $|\mathrm{V_{cs}}| = 1.13 \pm 0.43_{\mathrm{stat}} \pm 0.03_{\mathrm{syst}}$ is derived.

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1 Introduction

In November 1996 ALEPH collected data at 170 and 172 GeV with a luminosity of 10.65 pb^{-1}. Pairs of W bosons were observed and the study of W-production but also of W-decays were therefore possible. The study of charm production in W-decays is of great interest in W-physics, especially in extracting the Triple Gauge Couplings (TGC's) and to study couplings of W bosons to c-quark.

The identification of charm in W deays leads to a direct measurement of the fraction, R_c^W, of hadronic W decays to c quarks defined as $R_c^W = \Gamma(W \to cX)/\Gamma(W \to \text{hadrons})$ (where X stands for $\bar{d}$, $\bar{s}$, or $\bar{b}$) [1]. Within the Standard Model, this branching ratio can be expressed as a function of the different CKM matrix elements through the following relation:

$$R_c^W = \frac{|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2}{|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 + |V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2} \tag{1}$$

Then assuming the unitarity of the CKM matrix, R_c^W is expected to be equal to 0.5. So, a measurement of R_c^W is a direct test of this unitarity.
Furthermore, equation 1 can also be used to extract a value of the least well known CKM matrix element $|V_{cs}|$ which is measured to 1.01 ± 0.18 using $D \to K\ell\nu_\ell$ decays [1].

On the other hand, the accuracy that can be reached in the extraction of the Triple Gauge Couplings is limited by the ambiguities that exist on the different production angles of the quarks in the W center of mass. These ambiguities can be removed if one is able to distinguish between the *up* quark (as the c quark) and the *down* quark in the hadronic decays of the W.

A charm-jet tagger (called NNC in the following) was therefore developped, based on a neural network with 12 variables as input, using mainly charm-lifetime, jet-shape properties, reconstruction of D-mesons and lepton identification. The method of extracting R_c^W and $|V_{cs}|$ from the NNC output is described in this paper.

2 Event selection and charm tag

2.1 Event selection

The first step of this analysis is to select $W^+W^- \to 4q$ and $W^+W^- \to \ell\nu q\bar{q}'$ events [2].

For the semi-leptonic channel, loose lepton identification criteria are applied to charged tracks of the event. For electron candidates the energy is corrected for possible bremsstrahlung photons detected in the electromagnetic calorimeter. The lepton candidate is then chosen as the charged track with the highest energy and momentum among all the candidates. Then a set of cuts based on missing four-momentum ($\not{E}$, $\not{p}$) are used to eliminate non-radiative $q\bar{q}$ background. Finally, the remaining particles of the events are clustered into two jets using the DURHAM [2] algorithm in P-scheme.

[1] Unless explicitly stated, the charged conjugated modes are always implied throughout this paper.

[2] Only the $WW \to e\nu_e q\bar{q}'$ and $WW \to \mu\nu_\mu q\bar{q}'$ final states are considered in this analysis. The $WW \to \tau\nu_\tau q\bar{q}'$ channel is therefore treated as background.

In the fully hadronic channel, a neural network package is used to select $W^+W^- \to 4q$ events. The event is then forced into four jets using DURHAM in P-scheme, and the pairing is done by using a reference mass method. The selection criteria for the right dijet combination is a χ^2 defined as follows: $\chi^2 = (m_{j1} - m_{ref})^2 + (m_{j2} - m_{ref})^2$ with $m_{ref} = 80.25$ GeV/c^2.

The efficiencies for selecting $W^+W^- \to \ell\nu q\bar{q}'$ and $W^+W^- \to 4q$ events are respectively 78% and 76%, while the purities are 93% and 86%. This corresponds to 31 selected events in the semi-leptonic channel and 54 events in the fully hadronic channel. In the semi-leptonic channel, the main backgrounds are $e^+e^- \to q\bar{q}(\gamma)$ and $W^+W^- \to \tau\nu_\tau q\bar{q}'$ events while the dominant background for the fully hadronic channel is $e^+e^- \to q\bar{q}(\gamma)$.

2.2 Charm-jet tagging

The discrimination of c-jets (signal) and uds-jets (background) in hadronic W decays is based on the following properties:

1. The c-quark is heavier than uds-quarks, the jet-shape properties will therefore be different, particularly the multiplicity of the decay products will be larger for D-mesons. Furthermore these decay products will have specific momentum p and transverse momentum $p_\perp$ distributions (with respect to the jet axis).

2. The semi-leptonic branching ratio for D-mesons, $Br(c \to \ell)$, is of the order 20% (adding electrons and muons), leading to high energetic leptons in the jet.

3. The lifetime of D-mesons being of the order of 1 ps, their decay products will have, on average, large impact parameters.

From these properties, 12 discriminating variables were defined for each jet:

1. **PROBJET**: lifetime probability of a jet being an uds-jet [3],

2. **YMINV1**: the energy of the nucleated system around the leading track of the jet, built with an invariant mass cut at 2.1 GeV/c^2,

3. **NLEPJ**: the number of leptons (electrons or muons) in the jets with $p \geq 1.5$ GeV/c. The criteria used to define leptons are those used for b-physics studies at LEP100 [4].

4. **PDMAX**: the energy of fully reconstructed D-mesons normalised to the beam energy. The D-mesons are reconstructed in the following channels: $D^0 \to K^-\pi^+$, $D^0 \to K^-\pi^+\pi^+\pi^-$ and $D^+ \to K^-\pi^+\pi^+$ [5],

5. **RAPCS**: the sum of the rapidities of the tracks calculated with respect to the jet axis in a 40^o cone around the jet axis,

6. **KKC**: the track multiplicity in a 40^o cone around the jet-axis,

7. **PLUS**: equivalent to PROBJET but calculated only for charged tracks with $\eta_{jet} > 4.9$ [3],

8. **BTAG**: lifetime variable defined as the difference between the χ^2 when all charged tracks are assigned to the primary vertex, and the sum of the primary and secondary vertex χ^2 values when some tracks are transfered from the primary to the secondary vertex,

9. **PISPT**: $p_\perp^2$ of the π_{soft} candidate in D^* decays, defined as the charged track with an energy between 1 and 4 GeV and having the smallest $p_\perp$ with respect to the jet-axis [6].

10. **PMAX**: p of the leading track of the jet,

11. **SDIR1**: the directed sphericity [7] calculated with the 4 most energetic tracks of the jet,

12. **EMINV1**: the sum of the energies of the 4 most energetic tracks of the jet.

These variables are then used as input of a feed forward multi-layered neural network with one hidden layer of 10 neurons, and an output layer consisting of just 1 output node giving the variable used to discriminate between c-jets (output close to +1) and uds-jets (output close to -1). The distribution of some of these variables can be seen in Fig. 1. The output distribution of NNC and the performances of the algorithm are shown in Figs. 2 and 3. Furthermore, Fig. 4 shows a comparison between data and Monte Carlo for the four input variables presented in Fig. 1.

3 Results, systematics and checks

3.1 R_c^W and $|V_{cs}|$ measurement

Fig. 5 shows the NNC output for the jet in the pair having the highest NNC value, this is to select mainly c-jets in cX-pairs. In this way, the semi-leptonic channel $W^+W^- \to \ell\nu q\bar{q}'$ contributes for one entry in Fig. 5 and the hadronic channel, $W^+W^- \to 4q$, for two entries. Table 1 summarises the number of entries for each contribution in the Monte Carlo and the total number of entries found in the data. Among the non WW background events (noted "bkg jets" in the table), the $e^+e^- \to c\bar{c}(\gamma)$ events are expected to contribute for 5 entries.

Sources	Nb of entries
Signal jets	57.2
WW bkg jets	56.1
bkg jets	15
Total MC	128.3
Data	122

Table 1: Number of entries in Fig. 5 for the different contributions in the simulation and for the data. The Monte Carlo is normalised to the data by using the $e^+e^- \to W^+W^-$ cross section as measured by ALEPH [5] and the PYTHIA [12] prediction for $\sigma(e^+e^- \to q\bar{q}(\gamma))$.

To extract R_c^W, an unbinned likelihood fit is performed to the shape of the NNC distribution of Fig. 5. The function which is fitted is:

$$\mathcal{L} = \prod_{i=1}^{N_{data}} \mathcal{L}(R_c^W, NNC_i)$$

with

$$\begin{aligned}\mathcal{L}(R_c^W, NNC_i) &= R_c^W \cdot N_W \cdot Prob_c(NNC_i) + (1 - R_c^W) \cdot N_W \cdot Prob_u(NNC_i) + \\ & N_{bkg} \cdot Prob_{bkg}(NNC_i)\end{aligned}$$

The total number of W-events, N_W, is estimated as $N_{data} - N_{bkg}$, in order to be normalised to the data WW cross-section. $Prob_X(NNC_i)$ (with X = c, u, bkg) is the probability, determined from Monte Carlo, for an event i with a NNC output NNC_i to be of type X.

Setting R_c^W as free parameter in the fit, the result obtained is:

$$R_c^W = 0.57 \pm 0.18_{stat}$$

Using the world average values $|V_{ud}| = 0.9736 \pm 0.0010$, $|V_{us}| = 0.2205 \pm 0.0018$, $|V_{ub}| = 0.0033 \pm 0.0008$, $|V_{cd}| = 0.224 \pm 0.016$ and $|V_{cb}| = 0.041 \pm 0.003$ [1], this leads to a value for $|V_{cs}|$ equal to:

$$|V_{cs}| = 1.13 \pm 0.43_{stat}$$

3.2 Systematic errors

The following sources of systematic errors are considered:

1. An uncertainty of 5% is applied to the normalisation of the $q\bar{q}$ background as estimated in Ref. [9].

2. The errors resulting from a particular choice of Monte Carlo generator are estimated by replacing KORALW [10] by EXCALIBUR [11] for WW events and PYTHIA by HERWIG [13] for the $q\bar{q}$ background.

3. The effect of colour reconnection is estimated by comparing the results of the fit obtained with EXCALIBUR with and without its implementation.

4. The effects due to detector miscalibration are studied by varying the response of the electromagnetic and hadronic calorimeters by 1.5% and 4% respectively.

5. m_{ref} is varied by ± 1 GeV/c^2.

6. The JADE [14] algorithm is used to form the jets instead of DURHAM.

7. Since this analysis is based on the properties of the decay products of the charmed hadrons, the effects from charm production (relative production rates of the D^0, D^+, D_s^+, and Λ_c), charm fragmentation and charm decay properties (D-mesons topological branching ratios, inclusive production of K^0, $\bar{K}^0$, $K^\pm$, and π^0) are studied in details following the recommendations of Ref. [15].

The different sources of systematic errors are summarised in Table 2.

Source	$\Delta R_c^W (\%)$
QCD Normalisation	0.055
QCD Generator	0.97
WW Generator	0.10
Colour Reconnection	0.25
Detector Resolution	0.42
m_{ref}	2.3
Jet algorithm	2.00
Charm Production	0.1
Charm Fragmentation	0.3
Charm Decay	1.2
Total Error	3.5

Table 2: Estimated contributions to the systematic uncertainty on R_c^W.

3.3 Checks of the analysis

Figure 6 shows the log likelihood curve obtained after fit. A value of R_c^W equal to zero is therefore excluded at 3.5 σ.

The compatibility between data and Monte Carlo NNC distributions (with the fitted value of R_c^W) is tested using a Kolmogorov test. This gives a probability of compatibility of 80.1%, while if R_c^W is set to zero, this probability becomes 10.2%.

Furthermore, the number of fully reconstructed D mesons in the data is 4, 1 is expected as combinatorial background from W decays and 0.12 candidates are expected in $e^+e^- \rightarrow c\bar{c}(\gamma)$. Fig 7 shows a four jet event where the jet at 135° has a NNC output of 0.95 with a D-meson candidate. The reconstructed channel is $\bar{D}^0 \rightarrow K^+\pi^-$ where the mass of the $\bar{D}^0$ is found to be 1.863 GeV/c^2. The decay length is 2.5 mm which leads to a value for PROBJET of -1.99 i.e. a probability for the jet to be uds equal to 1%.

Finally, the number of energetic lepton candidates observed in the data is 15, while 14.6 (8.5) are expected in the simulation with (without) $W \rightarrow cX$ transitions.

4 Conclusion

Using an inclusive charm tag based on the kinematics properties of jets produced in W decays, the inclusive charm production rate in W decays is measured for the first time. The analysis of the 170-172 GeV data collected in November 1996 leads to:

$$R_c^W = \Gamma(W \rightarrow cX)/\Gamma(W \rightarrow \text{hadrons}) = 0.57 \pm 0.18_{stat} \pm 0.04_{syst} \quad (2)$$

from which the value $|V_{cs}| = 1.13 \pm 0.43_{stat} \pm 0.03_{syst}$ is derived. The measured value of R_c^W is compatible with the Standard Model expectation of 0.5 assuming the unitarity of the CKM matrix.

Acknowledgement

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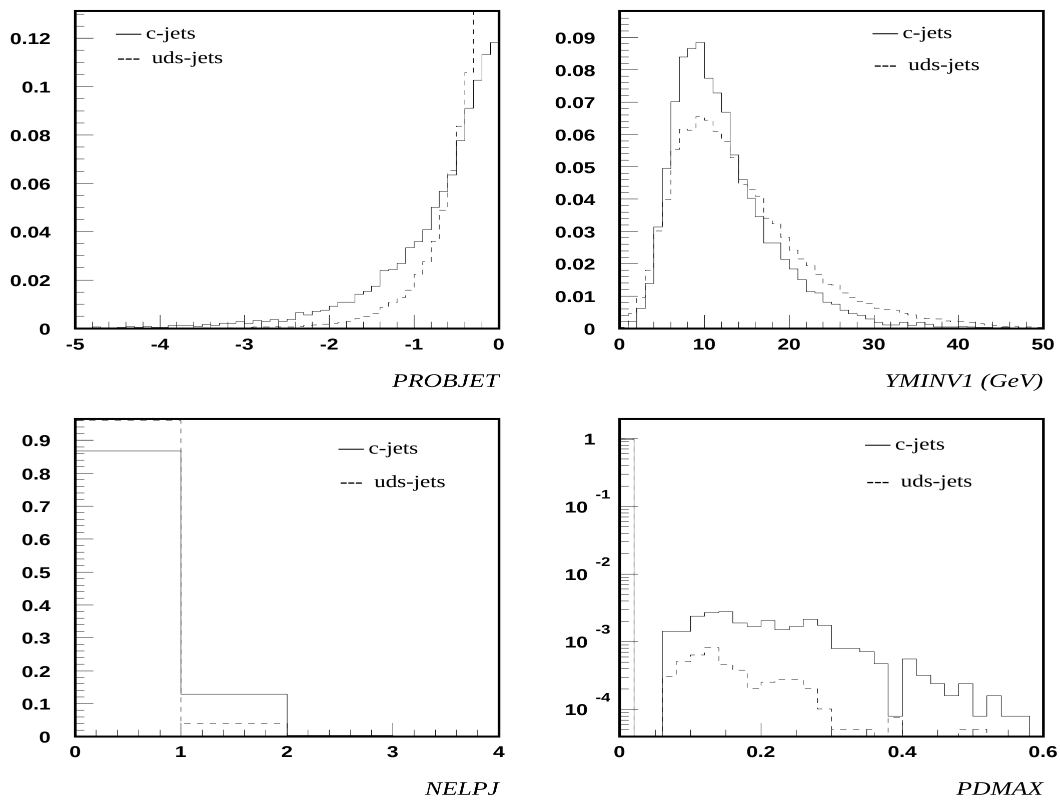

Figure 1: Distributions of four input variables (among the twelve) to NNC for c-jets from W decays (signal) and uds-jets (background). The two contributions are normalised to the same area.

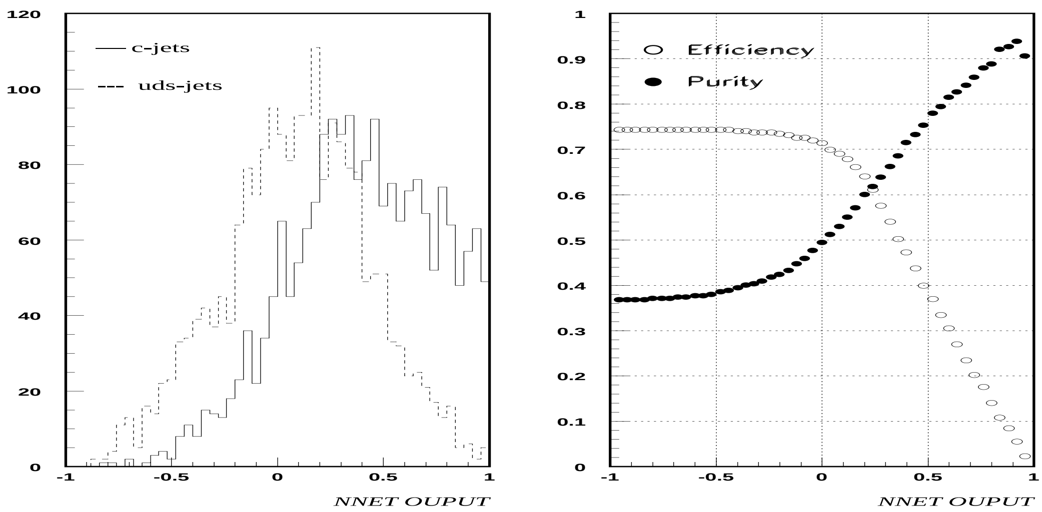

Figure 2: NNC output and its performances for the $W^+W^- \rightarrow \ell\nu q\bar{q}'$ channel. The efficiency is defined as the probability of tagging a c-jet in a cX-pair times the efficiency for a given cut on the NNC output distribution.

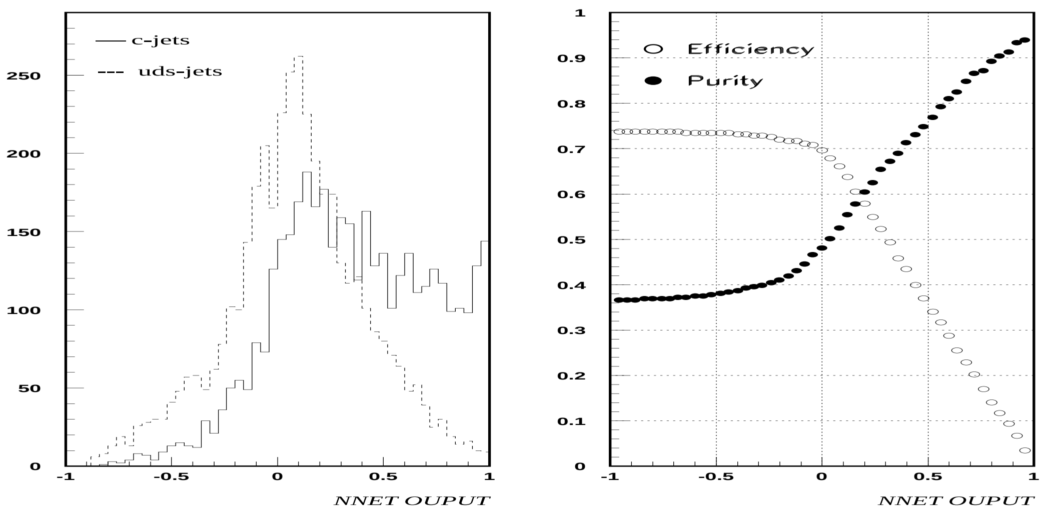

Figure 3: NNC output and its performances for the $W^+W^- \rightarrow 4q$ channel. The efficiency is defined as the probability of tagging a c-jet in a cX-pair times the efficiency for a given cut on the NNC output distribution.

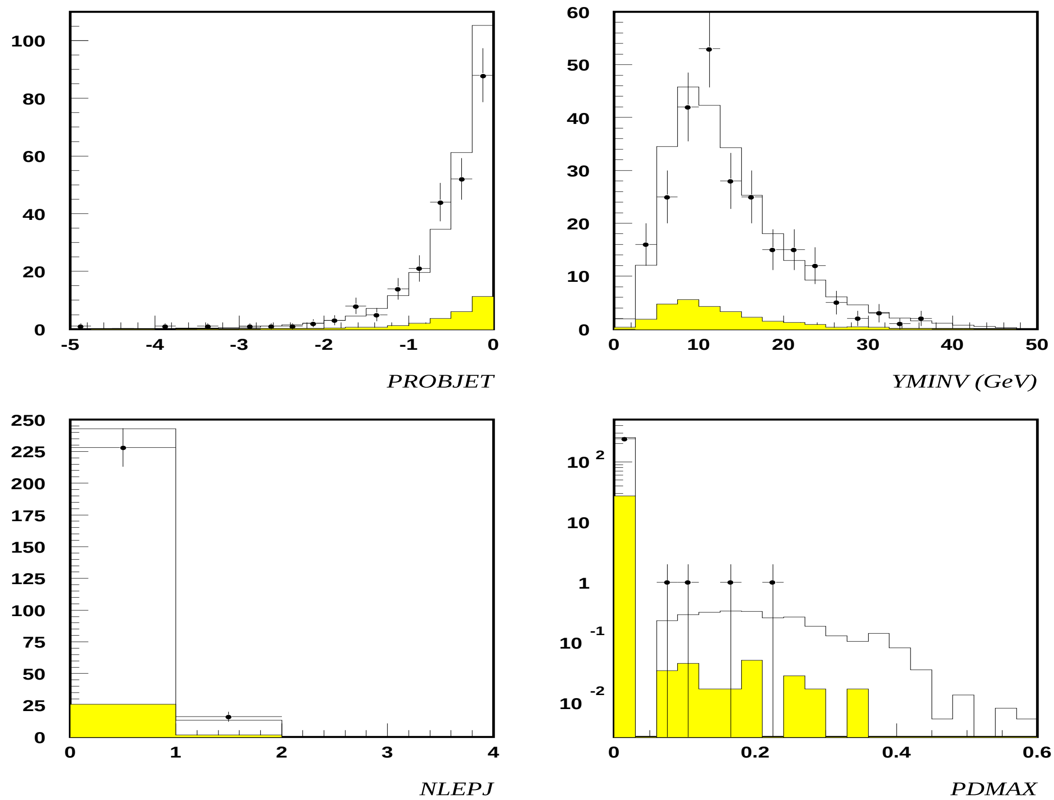

Figure 4: Distribution of four input variables to NNC for: the non WW background events (shaded histogram), the WW events (open histogram), and the data (points).

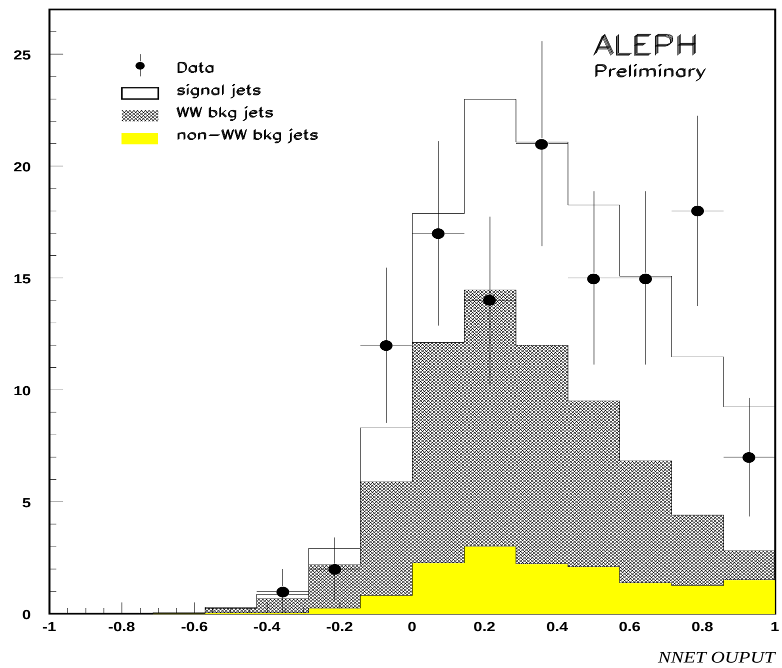

Figure 5: NNC output for the jet in the pair with the highest neural network output.

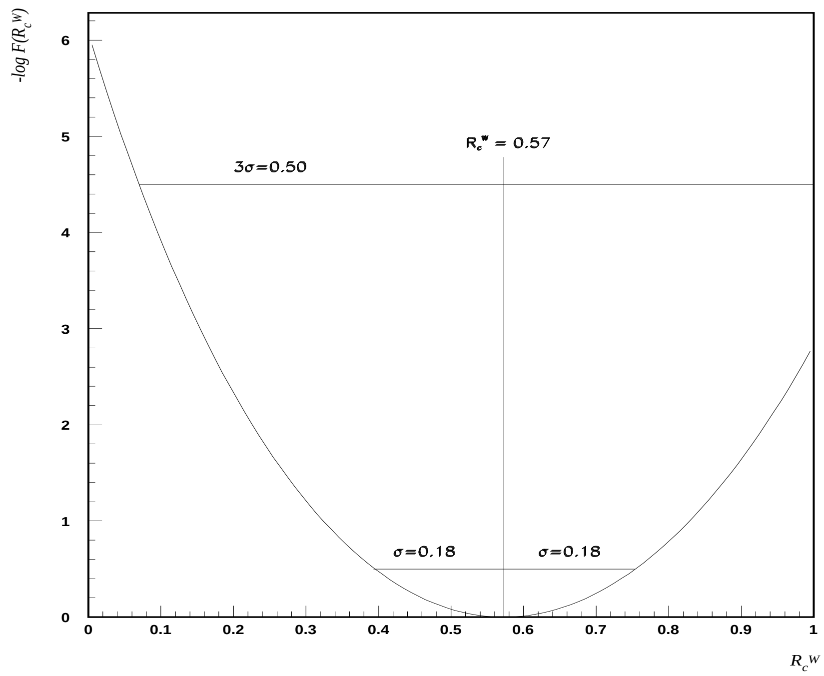

Figure 6: The logarithm of the likelihood fucntion $\mathcal{L}$ as function of $\mathrm{R_c^W}$.

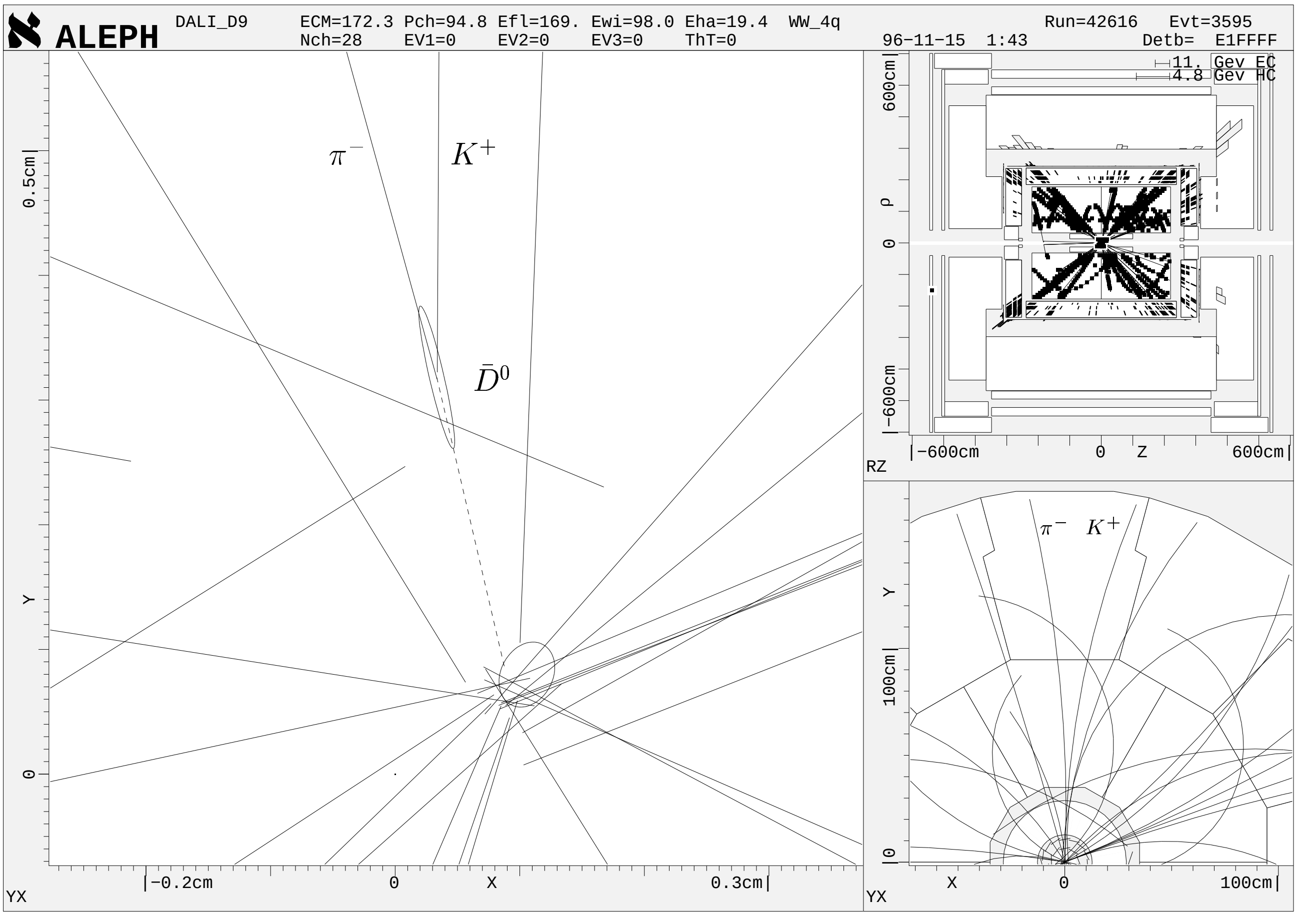

Figure 7: Four jet event with a reconstructed D-meson in the channel $\bar{\mathrm{D}}^0 \rightarrow \mathrm{K}^+\pi^-$.