Preliminary results on charm production in W decays

The L3 Collaboration

Abstract

A direct measurement of charm quark production in W decays is reported. Jet pairs coming from Ws (in both semileptonic and hadronic events) are studied to search for the presence of charm quarks in any of the jets. Since b-quark contamination is very small, the heavy quark characteristics of the charm production, fragmentation and decay are exploited, combining them with neural networks. The charm fraction herein determined represents a test of the unitarity of the CKM matrix, and using the measured values for the other elements can be converted in a direct determination of the matrix element $|V_{cs}|$.

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1 Introduction

Due to the large top quark mass, the decay $W \rightarrow tb$, in principle favoured by the quark mixing, does not occur for on-shell W bosons. b-quarks can be produced via the Cabibbo-suppressed decay $W \rightarrow bc$, but only a handful of events are foreseen in the whole LEP2 run. The heaviest quark copiously produced in WW events is then the charm; its production (in association with s, d and b in decreasing order of branching ratio) constitutes about half of the W hadronic decays. [1]

Even if with much lower purity than for the case of beauty, a charm tag is possible, thus allowing a measurement of the charm fraction in W hadronic decays $R_W^c$. This measurement is a test of the unitarity of the CKM matrix, since for three quark families it implies $|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 1$, fixing the charm ratio. Assuming the values of $|V_{cd}|$ and $|V_{cb}|$ measured with other techniques and without the need of imposing unitarity, it is possible to convert $R_W^c$ into a measurement of $|V_{cs}|$. This is particularly interesting, since this quantity is experimentally badly known [2], and only imposing the unitarity of the CKM matrix with three families some precise bounds can be found [1].

2 Tagging charm jets

Charm jets exhibit slight differences with respect to uds jets:

- charm decay proceeds through weak interaction, so, although it is Cabibbo-allowed, the average decay length of charm quarks is longer than for uds

- about 20% of charm decays are semileptonic, i.e. electrons or muons with small transverse momentum with respect to the jet axis are produced

- in about 30% of charm decays, a $D^{*\pm}$ meson is produced, which in 70% of the cases undergoes the characteristic decay $D^{*\pm} \rightarrow D^0 \pi^\pm$. In the $D^{*\pm}$ rest frame, the charged pion has a momentum of 39 MeV, only; in the lab frame this pion is usually the one with smallest $p_T$ with respect to the jet axis

- the heavy charm mass produces a harder fragmentation than for uds, resulting in differences in the distributions of some jet-shape variables

The way these differences are exploited in the analysis is described in the following sections.

2.1 Inclusive leptons

Electrons and muons originated from charm decay have a quite broad energy spectrum in the lab frame and small $p_T$ with respect to the jet axes. To keep high identification efficiency, leptons must be accepted even at low energy. The identification is then complicated by the presence of punch-through pions appearing as fake muons, and electromagnetic bumps that inside a jet can easily be associated to nearby tracks, appearing as fake electrons.

One advantage is indeed present in W decays with respect to Z induced processes, namely the possibility of knowing the lepton charge once the sign of the W is known. For instance, a $W^+$ will always decay into $c\bar{s}$ pair, and the subsequent charm semileptonic decay $c \rightarrow \bar{s}e^+\nu_e$ will always produce positive electrons or muons. Unfortunately the sign of the W can only
be known in semileptonic W decays; in this case the inclusive lepton is only searched between tracks or muons with opposite charge with respect to the lepton coming from the other W.

The following cuts are used to identify muons:

- good AMUI (punch-trough bit not set) with momentum $2 < P_{\mu} < 1000$ GeV
- $|DCA_R| < \min(100mm, 3 \times \sigma(DCA_R))$

The efficiency for identifying muons coming from charm decays is about 35%. The purity, defined as the ratio of muons found in charm jets and in all jets, is about 50%. The main background arises from punch-trough pions, as well from true muons originated mainly by kaon decay.

Electrons are defined as the most energetic of the tracks with $p > 2 GeV$ in the jet, having an associated calorimetric bump satisfying the following requirements:

- $E_{H\text{CAL}} = 0$
- $E_{H\text{CAL}}^{\text{ideg}} < 20 GeV$
- electromagnetic NN output $> 0.55$
- $p_t < 2$ Gev
- $|\Delta \phi| < 4 \times \sigma(\Delta \phi)$
- $\left| \frac{\phi - \phi_t}{\sqrt{\sigma^2(\phi) + \sigma^2(\phi_t)}} \right| < 10$

Here, $E_{H\text{CAL}}^{\text{ideg}}$ means the energy in the hadronic calorimeter in a 7 degree cone around the cluster position; the electromagnetic neural network output is used instead of the more traditional cut on $\Sigma 9/\Sigma 25$ since it is more effective then the latter for low energy bumps. $|\Delta \phi|$ is defined as the difference in polar angle between the track and the centre of gravity of the bump, after corrections for the track curvature and the centre of gravity displacements due to the magnetic field. The efficiency of this selection on electrons from charm jets is about 40%, while the purity is about 35%, and due to the high background it drops quickly to 25% (i.e. flavour-blindness of the selection) when looser cuts are applied.

2.2 Inclusive $D^{*\pm} \rightarrow D^0 \pi^{\pm}$ reconstruction

The search for exclusive charm decays is very difficult and leads to unsatisfactory results even with the much higher statistics available on the Z peak. Some enhancement of charm production can be however obtained searching for a sort of “inclusive” $D^{*\pm}$ production.

For each jet, all clusters (tracks, calorimetric bumps and muons) are ordered according to increasing angular distance with respect to the jet axis; those clusters are added up to a sort of “supercluster” until the invariant mass of the latter is smaller than 2.5 GeV (slightly above the $D^*$ mass), assuming it to contain the $D^*$ decay products. Only superclusters with more than 3 charged tracks are accepted.

The “slow” pion, characteristic of the dominant decay $D^{*\pm} \rightarrow D^0 \pi^{\pm}$, is then looked for. To this aim, a loop on all the tracks belonging to the superclusters with momentum higher than 1 GeV (and the right charge in semileptonic W decays) is performed, in order to find the one
with minimum $p_t$. If the selected track has $p_t < 150$ MeV, it is considered as a possible slow pion candidate; a Lorentz boost is applied in this track along the supercluster direction and using its mass, and the supercluster without this track is assumed to contain the $D^0$ decay products. The track is then accepted as a slow pion if it satisfies the following cuts:

- $P^* < 300$ MeV
- $M_{D^+} - M_{D^0} < 200$ MeV.

The above-described procedure finds the right slow pion in more than 20% of the cases, and produces a charm-enriched sample where the charm ratio is about 35%.

### 2.3 Impact parameter

Some information can be extracted from the longer lifetime of the charm with respect to uds quarks. To this purpose, the impact parameter-based tagging routine developed by the UCSD group has been used [4]. This routine performs a three-dimensional tag, based on the weighted average of the impact parameter of the tracks of the jet satisfying some quality criteria, with respect to the jet direction. The output of this routine is the significance that the jet does not come directly from the primary vertex.

The good agreement of this variable between data and MC has been tested on a sample of hadrons after a loose 4-jet preselection, leaving about 50% of W and 50% of Z events. The distribution of this variable for the four jets ordered in energy is shown in figure 1.

### 2.4 Jet characteristics

The differences in fragmentation between charm and uds quarks are reflected in some characteristics of the jets. Furthermore, since charm mesons have short lifetime and decay in the detector into multiple tracks, the energy of the leading particle is on average softer for them. So, the boosted sphericity (i.e. the sphericity computed in the jet reference frame) and the energy of the leading particle and calorimetric cluster are used as discriminating variables.

### 2.5 W polarisation

W bosons can be produced at tree level in Lep2 with mainly two kinds of diagrams: $Z/ \gamma$ decay in the s-channel or $\nu_e$ exchange in the t-channel. Only left-handed electrons and right-handed positrons can contribute to this channel, and this originates some degree of polarisation in the W boson produced; some further W polarisation also arises from the annihilation diagram with an intermediate Z boson.

The W polarisation has important consequences on the energy spectrum of its decay products. Let’s take for instance the decay $W^- \rightarrow e^- \bar{\nu}_e$. Due to the $SU(2)_L$ structure of the gauge group for weak interactions, the W decay products are produced in helicity eigenstates: left-handed fermions and right-handed antifermions. In this case there will be production of right-handed antineutrinos with spin 1/2 and direction parallel to the particle momentum, and left-handed electrons with spin 1/2 antiparallel to the electron direction. The total angular momentum 1 will be parallel to the antineutrino direction. For left-handed $W^-$, it means that to assure angular momentum conservation the direction of flight of the W in the lab frame must be parallel to that of the electron and antiparallel to that of the neutrino; thus the electron energy will be on average higher than that of the antineutrino.
If positive Ws are considered, the same argument can be used to show that electrons have higher energy than neutrinos.

For hadronic W decays, it is easy to show that up-like quarks behave like electrons, and down-like quarks behave like neutrinos.

Even if Ws are not fully polarised, this effect is indeed present also at detector level, as can be seen from the reconstructed energy distributions of u-like and d-like quarks. (fig. 2). Thus the jet energy is used as a discriminating variable.

3 Organisation of the neural networks

In the previous paragraphs, different approaches have been followed to isolate possible differences between charm and uds quarks. These differences can be specific to some charm decay modes (like the presence of leptons or the slow pion) or relative to all charm events (like impact parameter, jet characteristics or energy ordering). To try to exploit most of these differences, a neural network approach has been used, splitting the events into four categories (in increasing order of population):

1. events with an inclusive muon
Figure 2: Reconstructed energy distribution for d-like (full line) and u-like (dashed line) quarks.

2. events with an inclusive electron
3. events with a reconstructed slow pion
4. all other events

For each of these classes, a separate neural network has been set up and trained. The network for events of class 4 has the following input variables:

- impact parameter significance
- boosted sphericity of the jet
- energy of the most energetic SRC in the jet
- momentum of the most energetic track
- number of tracks in a 35° cone around the jet axis
- total jet energy

Jets where inclusive leptons are found have the additional input variable:

- energy of the inclusive lepton

while if a $D^*$ decay is reconstructed, the following variable

- $p_t$ value of the candidate "slow pion"
The WW candidate events used for this study have been selected using a set of dedicated analyses I developed for 183 GeV data; they are quite similar to those used to identify 172 GeV data, described in [5].

Distributions of the input variables described above for charm, uds quarks, non-WW background and data for all jet categories is shown in figures 3, 4, 5, 6.

Each neural network has been independently trained using a large WW Monte Carlo sample, and tested on an independent one. The output of the separate networks is shown in figure 7. These plots don’t look like the usual output of a neural network, where signal and background show clear peaks around the values of 0 and 1. This is a consequence of the fact that even after the application of the neural network the separation between charm and uds is not very strong.

The charm fraction is extracted from these plots. Giving the small signal-background separation, a cut on the NN output doesn’t give the optimal statistical power, so a fit to the shape of the network output is performed.

4 Result from the fit

The relative contribution of charm and uds quarks to the data composition can be extracted from the plots in figure 7, using a likelihood-based fit. In this case, the background is assumed as fixed (1σ variations in the bg cross sections will be considered as a systematic error), while charm and uds jet fractions are constrained by the relation that their sum must equal the total number of jets in data, decreased by the expected number of background jets. The fit is based on a binned log-likelihood fit using Poissonian probabilities for the different jets, and the final likelihood is just the product of the individual likelihoods for the different jet classes. The result of this fit, expressed as the ratio of W bosons decaying to charm over the overall number of hadronic W decays is

$$R_c = \frac{W \rightarrow cX}{W \rightarrow had} = (50.2 \pm 11.0)\%$$

where the error quoted is statistical only.

5 Checks and systematic errors

The charm identification presented exploits tiny differences between the different quark flavours, and can be sensitive to small disagreements in the Monte Carlo modelling of hadronic events, in principle possible in the low energy region. Given the limited statistics, systematic checks cannot be done directly on the sample under study. About 10000 hadronic events have been therefore selected from the Z calibration run, and the same algorithms for jet shape, electron, muon and slow pion identification have been applied. The distributions of jet shape variables used in the networks are shown in figures 8,9,10,11; no significant disagreement is visible in any of them.

The number of electron, muons and pions identified in the hadronic jets is shown in table 5 together with expectations from MC. Those numbers are compatible with expectations, within statistical fluctuations (also considering that the total number of jets is about 10% higher than expected due to the high measured hadronica cross section).

Systematic errors are evaluated varying normalisation of background and the relative population of the different jet classes, as well as changing the shape of some distributions. A
Figure 3: Impact parameter distribution

Figure 4: Jet energy

Figure 5: Energy of leading cluster

Figure 6: Energy of leading track
Figure 7: The output distribution for the four neural network classes for charm (white histogram), uds (single hatch) and non-ww BG (double hatch)
Figure 8: Number of tracks in a 35° cone

Figure 9: Energy of the leading track in the jet

Figure 10: Energy of leading cluster in the jet

Figure 11: Pt of reconstructed slow pion
### Table 1: Jet class population

<table>
<thead>
<tr>
<th>Category</th>
<th>N. expected</th>
<th>N. seen</th>
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<tbody>
<tr>
<td>Muons</td>
<td>18</td>
<td>12</td>
</tr>
<tr>
<td>Electrons</td>
<td>52</td>
<td>64</td>
</tr>
<tr>
<td>$D^*$</td>
<td>154</td>
<td>182</td>
</tr>
<tr>
<td>Others</td>
<td>1899</td>
<td>2006</td>
</tr>
</tbody>
</table>

### Table 2: List of systematic errors

<table>
<thead>
<tr>
<th>Source</th>
<th>Variation (%)</th>
<th>Effect (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background normalization</td>
<td>±5</td>
<td>0.4</td>
</tr>
<tr>
<td>Inclusive muons</td>
<td>±2</td>
<td>0.2</td>
</tr>
<tr>
<td>Inclusive electrons</td>
<td>±5</td>
<td>0.8</td>
</tr>
<tr>
<td>Reconstructed $D^*$</td>
<td>±5</td>
<td>1.6</td>
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<td>Track number</td>
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<tr>
<td>Cluster energy</td>
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<td>2.1</td>
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<tr>
<td>Total</td>
<td></td>
<td>3.5</td>
</tr>
</tbody>
</table>

### 6 $V_{cs}$

The charm production fraction $R(W \rightarrow cX)$ is can be directly derived from the elements of the
CKM mixing matrix:

$$R(W \rightarrow cX) = \frac{|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2}{|V_{cd}|^2 + |V_{cs}|^2 + |V_{cd}|^2 + |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2}$$

The unitarity of the CKM matrix imposes this ratio to be 0.5, in agreement with the measured value quoted above. Since the value of $|V_{cs}|$ is known experimentally with much worse precision than the other matrix elements, it is convenient to interpret the measurement of $R(W \rightarrow cX)$ as a measurement of $|V_{cs}|$. To this purpose, the values of the other matrix elements and their symmetric errors have been taken from the PDG [1]. The result is

$$|V_{cs}| = 0.98 \pm 0.22\,(stat.) \pm 0.08\,(syst.)$$

### 7 Conclusions

An algorithm to determine the fraction of charm quark in WW decays has been developed, based on the heavy-quark characteristics of the charm jets. A system of six neural network is used for different categories of jets, and the charm fraction can be extracted using either a 1-dimensional or a 2-dimensional fit of the output of those networks. The most precise determination comes from the latter, that also accounts for correlations among jets coming
from the same W. The final result is then $R_c = (50 \pm 11 \pm 4)\%$, in good agreement with the prediction from the SEM with unitarity of the CKM matrix. This measurement can be also converted into a determination of $V_{cs}$ using the PDG values for the other matrix elements; the value obtained is $V_{cs} = 0.98 \pm 0.22 \pm 0.08$

8 Acknowledgments

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References


