EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN–EP/2000–117
DSF–26–2000
August 4, 2000

A search for Z' in muon neutrino associated charm production

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Abstract

In many extensions of the Standard Model the presence of an extra neutral boson, Z', is invoked. A precision study of weak neutral-current exchange processes involving only second generation fermions is still missing. We propose a search for Z' in muon neutrino associated charm production. This process only involves Z' couplings with fermions from the second generation. An experimental method is thoroughly described using an *ideal detector*. As an application, the accuracy reachable with present and future experiments has been estimated.

(Submitted to *Physics Letters B*)

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[1] On leave of absence from INFN, Sezione di Napoli, Italy.

[2] Partially supported by the "Fondo Sociale Europeo".

1 Physics motivation

Since its experimental confirmation, the Standard Model of electroweak interactions (SM) has been challenged in all possible directions (see Ref. [1] and references therein) with the aim of finding the signature of new fundamental physics. Although at present there is no clear evidence of any departure from it, sometimes unexpected deviations show up in experiments, for instance the anomalies seen at LEP in R_b [2], at HERA at high Q^2 [3] and at Tevatron [4]. Consequently ad hoc models are built. However, none of these discrepancies has survived to further experimental investigations. Recently, in Atomic Parity Violating experiments, a discrepancy from the SM prediction has been observed [5]. This could be explained in terms of extra Z bosons [6].

The existence of Z' boson is foreseen in many extensions of the SM and is associated with extra $U(1)$ gauge symmetries. For instance, in the symmetry breaking pattern of E_6 or $SO(10)$ the Z' boson is contained in the low energy extension of the SM-like $SU(2)_R \times SU(2)_L \times U(1)_{B-L}$ or $SU(2)_L \times U(1) \times U(1)$, see Ref. [7] and references therein.

ALEPH and OPAL experiments have put limits on the presence of Z' by studying the contribution of new contact interactions in the processes $e^+e^- \rightarrow f\overline{f}$ [8]. The CHARM II experiment derived constraints on additional Z bosons from $\nu_\mu e \rightarrow \nu_\mu e$ scattering measurements [9]. These searches assume a family independent scheme for the Z' couplings to leptons and quarks. Moreover, there exist severe constraints in the first two generations on FCNC Z' from $K_L - K_S$ mass splitting and on lepton family violating Z' from $B(\mu \rightarrow 3e)$. A diagonal Z' strongly coupled to the second family could be limited by $J/\psi \rightarrow \mu^+\mu^-$. However, the pure electro-magnetic contribution and the hadronic uncertainties weaken this limit. Constraints on a Z' which couples differently only to the third generation are somewhat weaker [1].

The large mass difference between the top quark and the remaining ones has recently suggested a new class of models based on $SU(N) \times SU(N)$. In this framework the large mass difference can be naturally accommodated as well as the well-known phenomenology of weak interactions. Moreover, due to the extended gauge interaction the Z' presence in all processes involving the third family could be enhanced [10].

A precision study of weak neutral-current exchange processes involving only second generation fermions is still missing. Therefore, it is mandatory to test the SM predictions in this sector.

In this letter we propose a search for Z' through the measurement of associated charm production induced by ν_μ neutral-current interactions ($\nu_\mu + N \to \nu_\mu + X + c\bar{c}$). An ideal detector is exploited to perform this measurement. The importance of such a search is twofold since on one hand this performs a further test of SM family universality and on the other hand one can check the presence of possible Z' mainly coupled to the second and/or third families. It is worthwhile stressing that the proposed search is model independent.

We shall show that present neutrino experiments already constrain extensions of the Standard Model. Nevertheless, since neutrino factories could become a real perspective for the future, it is conceivable that the new generation of ν–experiments will be able to probe new physics with higher sensitivity.

2 Four fermions contact terms and extra neutral bosons

At $Q^2 \ll M_Z^2$ the neutral-current effective Lagrangian ruling the associated charm production induced by ν_μ is given by (see for example Ref. [1] and references therein for notation)

$$\mathcal{L}_W^{\nu c\bar{c}} = -\frac{G_F}{\sqrt{2}}\,\overline{\nu}_\mu \gamma^\alpha (1-\gamma_5)\nu_\mu \left[\epsilon_L(u)\;\overline{c}\gamma_\alpha(1-\gamma_5)c + \epsilon_R(u)\;\overline{c}\gamma_\alpha(1+\gamma_5)c\right], \tag{1}$$

where the parameters $\epsilon_L(u)$ and $\epsilon_R(u)$ account for the different coupling of left-handed and right-handed *up*-kind quarks to neutral-current respectively. Theoretically these two parameters are very precisely predicted [1], namely

$$\epsilon_L^{th}(u) = 0.3459 \pm 0.0002 \quad , \qquad \epsilon_R^{th}(u) = -0.1550 \pm 0.0001 \quad . \tag{2}$$

Since in the SM the matter-gauge coupling is family independent, the experimental determinations of the above parameters (2) are obtained by looking at processes where the four fermions involved come from first generation only or from two different families, as for instance in the ratio $R_q = \sigma(e^- e^+ \to q\overline{q})/\sigma(e^- e^+ \to \mu^- \mu^+)$. This experimental knowledge, which has not yet reached the accuracy of the theoretical predictions, gives [1]

$$\epsilon_L^{ex}(u) = 0.330 \pm 0.016 \quad , \qquad \epsilon_R^{ex}(u) = -0.176^{+0.014}_{-0.006} \quad , \tag{3}$$

which are in 1 σ agreement with theoretical values. Nevertheless pure measurements of these parameters, with a comparable level of precision, in processes involving only the second family are still missing.

The Z' boson presence in the process $\nu_\mu + N \to \nu_\mu + X + c\bar{c}$ can be introduced in a model independent way by the effect of four fermion contact interactions with new couplings [11].

Muon neutrinos produced in weak meson decays are left-handed. Therefore, the most general SM-like term describing the additional interaction is

$$\mathcal{L}_{NP}^{\nu c\bar{c}} = -\frac{G_F}{\sqrt{2}}\left(\frac{M_Z^2}{M_{Z'}^2}\right)\overline{\nu}_\mu\gamma^\alpha(1-\gamma_5)\nu_\mu\left[\eta_L\ \overline{c}\gamma_\alpha(1-\gamma_5)c + \eta_R\ \overline{c}\gamma_\alpha(1+\gamma_5)c\right]. \tag{4}$$

where NP stands for New Physics, η_R and η_L are the $\nu_\mu - c$ new couplings and $M_{Z'}$ is the extra boson mass.

Given the additional contribution, the total effective Lagrangian, $\mathcal{L}_T^{\nu c\bar{c}}$, takes the form

$$\mathcal{L}_T^{\nu c\bar{c}} = -\frac{G_F}{\sqrt{2}}\overline{\nu}_\mu\gamma^\alpha(1-\gamma_5)\nu_\mu\ \overline{c}\gamma_\alpha\left[\epsilon_V(c) - \epsilon_A(c)\gamma_5\right]c \quad , \tag{5}$$

where

$$\begin{aligned}
\epsilon_V(c) &= \epsilon_L(u) + \epsilon_R(u) + \left(\frac{M_Z^2}{M_{Z'}^2}\right)(\eta_L + \eta_R) \\
&\equiv \epsilon_V(u) + \left(\frac{M_Z^2}{M_{Z'}^2}\right)\eta_V = \left[1 + \left(\frac{M_Z^2}{M_{Z'}^2}\right)x\right]\epsilon_V(u) \quad , \qquad (6) \\
\epsilon_A(c) &= \epsilon_L(u) - \epsilon_R(u) + \left(\frac{M_Z^2}{M_{Z'}^2}\right)(\eta_L - \eta_R) \\
&\equiv \epsilon_A(u) + \left(\frac{M_Z^2}{M_{Z'}^2}\right)\eta_A = \left[1 + \left(\frac{M_Z^2}{M_{Z'}^2}\right)y\right]\epsilon_A(u) \quad , \qquad (7)
\end{aligned}$$

and the parameters x and y give the departure from SM predictions.

3 Present available data on ν_μ associated charm production

The available data on neutrino associated charm production are scarce. Only one event consistent with the neutral-current production of a pair of charmed particles has been observed by the E531 Collaboration in an emulsion hybrid experiment [12]. This event allowed the determination of the associated charm production rate with respect to neutral-current production:

$$\frac{\sigma(\nu_\mu N \to c\bar{c}\nu_\mu X)}{\sigma(\nu_\mu N \to \nu_\mu X)} = 0.13^{+0.31}_{-0.11}\%. \tag{8}$$

No event has been found in charged-current production. Under the assumption that the primary muon was not identified, the previous result can be translated into an upper limit at 90%C.L. on associated charm production in the charged-current production of

$$\frac{\sigma(\nu_\mu N \to c\bar{c}\mu X)}{\sigma(\nu_\mu N \to \mu X)} \leq 0.12\%. \tag{9}$$

4 Simulation of the process

The Lagrangian $\mathcal{L}_T^{\nu c\bar{c}}$ defined in equation (5) contributes to the process $\nu_\mu + N \to \nu_\mu + X + c\bar{c}$ where charm quarks adronize through the gluon exchange with the nucleon partons (boson gluon fusion), see figure 1.

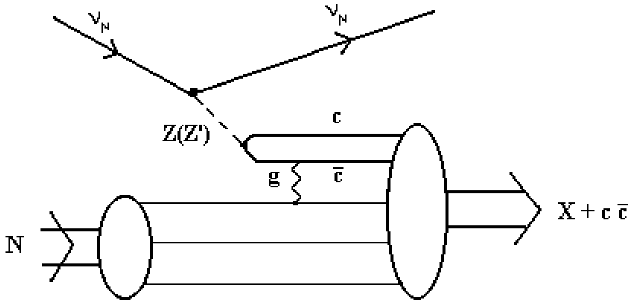

Figure 1: The boson gluon fusion process diagram in ν_μ interactions.

At the relevant Q^2 values ($\leq 20(GeV/c)^2$), the deep inelastic scattering phenomenology is very well described by the three flavour scheme (u, d, and s), see for example Ref. [13]. This implies that the sea charm-parton component is negligible in this Q^2 range. Therefore the only process producing a $c\bar{c}$ pair in the final state is the boson gluon fusion.

In order to simulate the process, we have used the HERWIG event generator [14]. It is based on perturbative QCD calculations and provides a good description of all available data at LEP and Tevatron [15]. All final state particles are generated and the cross-section value is also computed. An associated charm production rate with respect to the neutral-current production of $(0.403 \pm 0.004)\%$ [3] is predicted by HERWIG. It is consistent with the experimental measurement given in Section 3.

5 Description of the method

The search presented in this letter exploits the peculiar topology of the associated charm production in ν_μ neutral-current interactions: two charmed hadrons in the final state. Consequently, there are no other physical processes which may mimic it.

Experimentally we are sensitive to the ratio

$$R = \frac{\sigma^{NC}_{c\bar{c}}}{\sigma^{CC}} \tag{10}$$

which can be written as the product

$$R = \frac{\sigma^{NC}_{c\bar{c}}(Z^0 + Z')}{\sigma^{NC}_{c\bar{c}}(Z^0)} \times \frac{\sigma^{NC}_{c\bar{c}}(Z^0)}{\sigma^{CC}} = r \times f \tag{11}$$

where $\sigma^{NC}_{c\bar{c}}(Z^0)$ is the cross-section of the associated charm production process in ν_μ interactions in absence of the Z' boson, $\sigma^{NC}_{c\bar{c}}(Z^0 + Z')$ includes the contribution of the new neutral boson and σ^{CC} is the ν_μ deep inelastic charged-current cross-section.

In the following we assume a 50 GeV mono-energetic ν_μ beam [4]. In the following we assume a 50 GeV mono-energetic ν_μ beam. Under this assumption by using the simulation program described in Section 4 the ratio f results to be $(1.25 \pm 0.01) \times 10^{-4}$. From equation (11) it is then clear that the only relevant contribution is coming from the ratio r.

If we parameterise the ratio r in terms of the x, y and $M^2_{Z'}$ variables defined in Section 2, the most general expression we get is:

$$r(x, y, M^2_{Z'}) = 1 + \left(\frac{500}{M^2_{Z'}}\right)^2 (A_1 y + B_1 x) + \left(\frac{500}{M^2_{Z'}}\right)^4 (A_2 y^2 + B_2 x^2 + C_1 xy). \tag{12}$$

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[3] The error is only statistical.

[4] The results achievable with a real neutrino spectrum of mean energy $<E_\nu>$ are rather well reproduced by using a simple mono-energetic beam with energy equal to $<E_\nu>$.

Fitting the data from the simulation with the previous function, the values of the coefficients we get are: $A_1 = 0.1, A_2 = 0.003, B_1 = 0.02, B_2 = 0.0007$ and $C_1 = -0.0002$. The fit is valid in the $[-30, 30]$ range for both x and y variables.

In Figure 2 the fitted function r for $M_{Z'} = 500$ GeV/c^2 is shown.

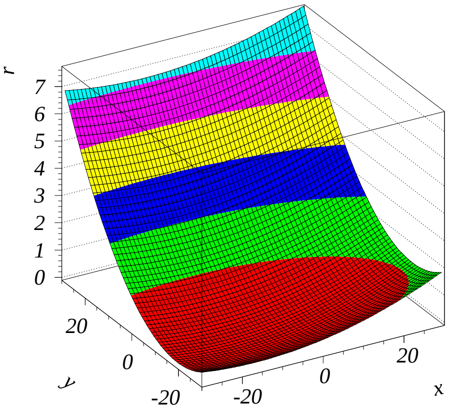

Figure 2: The ratio r is plotted by assuming 50 GeV ν_μ energy and $M_{Z'} = 500$ GeV/c^2.

The number of observed events, N_S, can be written as

$$N_S = N_{c\bar{c}} \cdot \frac{\varepsilon_S}{\varepsilon_B} \cdot r \tag{13}$$

where $N_{c\bar{c}}$ is the number of observed events without the Z' effect, ε_S and ε_B are the reconstruction efficiencies for the events with and without a Z', respectively.

5.1 Measurement accuracy in an ideal detector

We assume an ideal detector designed to identify charmed mesons and baryons which travel on average about 1 mm before decaying if produced by 50 GeV neutrinos. In order to obtain this goal we need a very high 3D resolution tracker. Nuclear emulsions have the required spatial resolution (less then 1 μm). A good hadron spectrometer for additional kinematical analysis and a calorimeter to measure the hadronic shower produced in the interaction are also needed. A muon spectrometer in the down-stream part of the apparatus will allow us to tag charged and neutral-current interactions. It could also be useful to analyse the exclusive semi-leptonic decay channel.

Once the charmed particles have been tagged, the Z' effect would show up as an excess/defect of double charmed events in neutral-current interactions. If no excess/defect is found it will turn into a limit on the coupling parameters.

The detection efficiencies have been calculated with the cuts defined in Table 1. In particular we assume to detect tracks with angles less than 400 mrad. Moreover, in the single prong decays we require the minimum kink angle to be 15 mrad. A minimum flight length cut of 10 μm is also assumed to distinguish between primary and secondary vertices.

Table 1: Reconstruction efficiencies in the emulsion target. Notice that the kink angle cut is only applied for single prong decays.

Cuts	ε_S (%)	ε_B (%)
Angular cut ($\vartheta \leq 0.4$)	87.3 ± 0.3	87.5 ± 0.3
Kink angle cut ($\geq$ 15 mrad)	95.2 ± 0.2	95.0 ± 0.2
Flight length cut ($\geq$ 10 μm)	95.2 ± 0.2	95.4 ± 0.2

The topology of the two samples of events is extremely similar so that the detection efficiencies are the same within the error, as shown in Table 1.

In Table 2 we report the hadronization fractions as predicted by the event generator model. No dependency of the hadronization fractions on the Z' couplings has been observed in this model.

In Figure 2 we see that for “large” Z' couplings, i.e. x and $y > 20$, we can get an enhancement of the associated charm production of about a factor seven.

On the other hand, if we do not observe any excess/defect we can put a limit on the x and y parameters. As an example we report in Figure 3 the sensitivity plot at 90% C.L. for the x and y variables at $M_{Z'} = 500$ GeV/c^2. Different statistics of associated charm production events as well as different systematic errors are assumed. In Table 3 we report the summary of the four different scenarios considered in Figure 3. Each scenario corresponds to a given number of associated charm events, $N_{c\bar{c}}$, namely 10, 50, 100 and

Table 2: The hadronization fractions are reported for associated charm production events induced by 50 GeV ν_μ. The error is only statistical.

$f(\%)$	D^+	D^0	D_s^+	Λ_c^+
D^-	5.3 ± 0.2	7.5 ± 0.3	0.09 ± 0.03	14.8 ± 0.4
$\bar{D}^0$	11.6 ± 0.3	15.5 ± 0.4	0.32 ± 0.06	27.2 ± 0.5
D_s^-	2.2 ± 0.2	2.7 ± 0.2	0.10 ± 0.03	6.2 ± 0.2
$\bar{\Lambda}_c^-$	1.2 ± 0.1	2.3 ± 0.2	0.04 ± 0.02	2.8 ± 0.2

500. For the sake of simplicity we also report the corresponding number of charged current neutrino interactions, N_μ. For each scenario the systematic error has been ranged from 1% to 50%.

The allowed region of parameters is obtained from the formula

$$1 - 1.64 \cdot \frac{\sigma}{N_{c\bar{c}}} \leq \frac{\varepsilon_S}{\varepsilon_B} \cdot r \leq 1 + 1.64 \cdot \frac{\sigma}{N_{c\bar{c}}} \tag{14}$$

where σ is defined as

$$\sigma = (\varepsilon_{stat}^2 + \varepsilon_{sys}^2) \tag{15}$$

and includes the error on the event counting from both a statistical and systematics source. The factor 1.64 takes into account the required confidence level. Therefore in Figure 3 for each plot the two lines bound the region of coupling parameters where no significant excess/defect of associated charm production events is found. In other words, an observation of a number of charm pair events in agreement with SM predictions excludes the regions outside the band.

As expected, in the Scenario A the statistical fluctuation is dominant with respect to the systematic error so that the bounds are rather large and systematics-independent. On the contrary, for a large statistic experiment as predicted in Scenario D the systematic uncertainties would play a crucial role: the smaller the systematic error is, the narrower the allowed parameters band becomes.

6 Measurement accuracy with present and future experiments statistics

Among the neutrino experiments which are currently taking or analysing data, CHORUS[16], which uses nuclear emulsions as a target, has an ade-

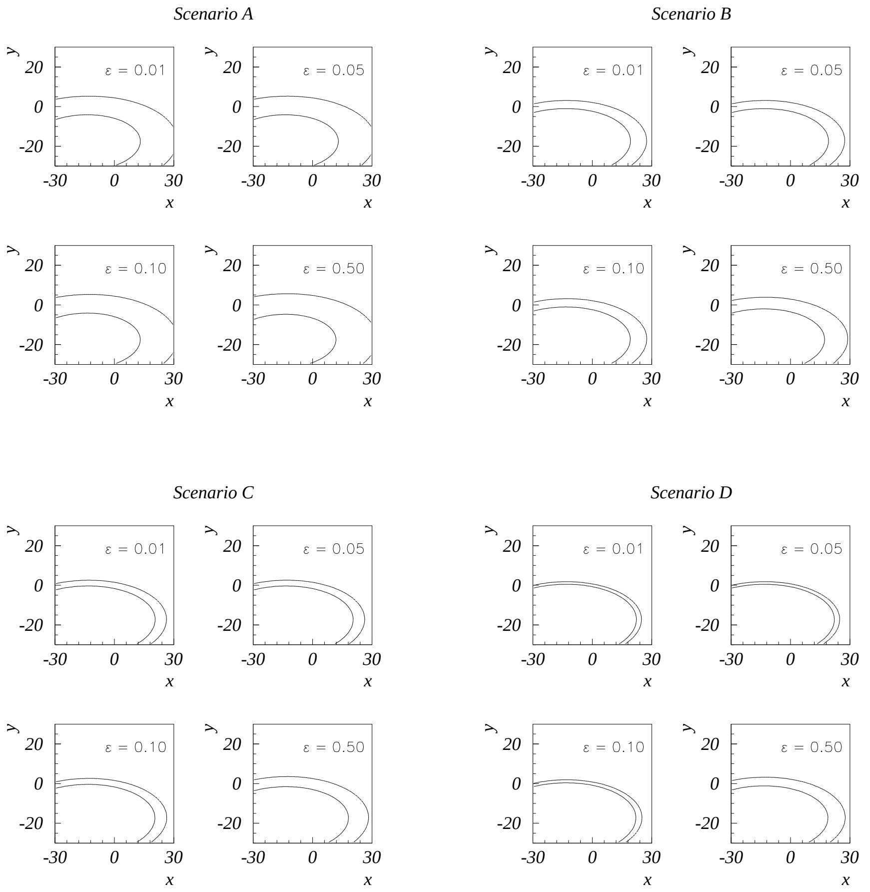

Figure 3: The sensitivity plots for the x and y variables at $M_{Z'} = 500$ GeV$/c^2$ are shown in the four different scenarios described in the text. ε indicates the systematic error.

Table 3: Summary of the statistics used for the different scenarios shown in Figure 3. The set of systematical errors used is also shown.

Scenario	N_μ	$N_{c\bar{c}}$	$\varepsilon_{syst}(\%)$
A	1×10^5	10	$1, 5, 10, 50$
B	5×10^5	50	$1, 5, 10, 50$
C	1×10^6	100	$1, 5, 10, 50$
D	5×10^6	500	$1, 5, 10, 50$

quate spatial resolution to search for associated charm production induced by muon neutrinos. Starting from a sample of approximately 500000 charged-current events, it is estimated that $\sim$ 350000 events will be analysed in the emulsion[17]. Assuming a 50% efficiency to detect the charmed pair, a statistic of about 20 events can be expected. Consequently, the CHORUS experiment can explore the x and y parameter region similar to the one shown in the Scenario A of Figure 3.

A search with higher sensitivity could be performed exposing a dedicated detector, whose feasibility study has not yet been worked out, at the future neutrino beams from muon storage rings[18]. Such beams could provide $\mathcal{O}(10^6)\nu_\mu$ charged-current events/year in a 10 kg fiducial mass detector, 1 km away from the neutrino source. With this statistic the sensitivity reached by Scenarios C and D could be exploited.

It is worthwhile observing that a high sensitivity search for Z', produced e.g. via the processes $gg \rightarrow q\bar{q} \rightarrow Z'$, will be performed at LHC experiments (see for instance [19]) few years before neutrino factories will be operational. Nevertheless, a negative result of such an analysis would not decrease the interest of a high sensitivity search for $c\bar{c}$ production in neutrino interactions. An exotic Z' with stronger coupling to the $I_3 = 1/2$ component of weak isospin doublets could still give measurable effects at neutrino factories, unlike LHC experiments which are only sensitive to the Z' coupling to charged leptons ($I_3 = -1/2$).

7 Conclusions

We have presented a search for an extra neutral boson, Z', by studying the associated charm production in neutral-current neutrino interactions. The peculiarity of this process is that it involves only second generation fermions. Therefore, it allows the testing of the SM family universality through the measurement of Z' couplings with the second family, a sector where so far there are no experimental limits. We have also shown that, with existing data, for the first time it is possible to constrain the Z' couplings to the second generation.

Acknowledgements

We are indebted to W.K. Tung for useful discussions concerning the sea charm-parton component in the nuclei. We thank M. Mangano for the helpful discussion. We would also like to thank S. Anthony for the careful reading of the manuscript.

References

[1] D.E. Groom et al., *Eur. Phys. J.* **C15** (2000) 1.

[2] R.M. Barnett et al., *Phys. Rev.* **D54** (1996) 1.

[3] Zeus Collaboration, J. Breitweg et al., *Z. Phys.* **C74** (1997) 207.
H1 Collaboration, C. Adloff et al., *Z. Phys.* **C74** (1997) 191.

[4] CDF Collaboration, F. Abe et al., *Phys. Rev. Lett.* **77** (19996) 438.

[5] S.C. Bennett and C.E. Wieman, *Phys. Rev. Lett.* **82** (1999) 2484.

[6] R. Casalbuoni, S. De Curtis, D. Dominici, R. Gatto, *Phys. Lett.* **B460** (1999) 135.
J. Erler and P. Langacker, *Phys. Rev. Lett.* **84** (2000) 212.
J. Rosner, *Phys. Rev.* **D61** (1999) 016006.
G.-C. Cho, hep-ph/0002128.

[7] J. Erler and P. Langacker, *Phys. Lett.* **B456** (1999) 68.

[8] ALEPH Collaboration, R. Barate et al., *Eur. Phys. J.* **C12** (2000) 183.
OPAL Collaboration, G. Abbiendi et al., *Eur. Phys. J.* **C6** (1999) 1.

[9] Charm II Collaboration, P. Vilain et al., *Phys. Lett.* **B332** (1994) 465.

[10] K.R. Lynch et al, hep-ph/0007286.

[11] E.J. Eichten, K.D. Lane and M.E. Peskin, *Phys. Rev. Lett.* **50** (1983) 811.

[12] E531 Collaboration, N. Ushida et al., *Phys. Lett.* **B206** (1998) 375.

[13] J. Amundson, C. Schmidt, W.K. Tung and X.N. Wang, hep-ph/0005221.

A.M. Cooper-Sarkar, R.C.E. Devenish and A. De Roeck, Int. J. Mod. Phys. **A13** (1998) 3385.

[14] G. Marchesini, B. R. Webber, G. Abbiendi, I. G. Knowles, M. H. Seymour and L. Stanco, Computer Phys. Commun. 67 (1992) 465.

HERWIG 6.1 Release Note, hep-ph/9912396.

[15] S. Catani et al., *Proceedings of the workshoop on Standard Model physics (and more) at the LHC* CERN 2000-004.

A. Ballestrero et al., hep-ph/0006259.

[16] CHORUS Collaboration, E. Eskut et al., *Nucl. Instr. Meth.* **A401** (1998) 7.

[17] CHORUS Collaboration, E. Eskut et al., *Phys. Lett.* **B424** (1998) 202.

CHORUS Collaboration, E. Eskut et al., *Phys. Lett.* **B434** (1998) 205.

[18] S. Geer, *Phys. Rev.* **D57** (1998) 1.

[19] A. Henriques, L. Poggioli, ATLAS Internal note PHYS-NO-010, 1 October 1992.

P. Camarri et al., Proceedings of the LHC workshop, VOL. II, pag. 704-708, October 1991.