CDF/PUB/EXOTIC/PUBLIC/8643

Inclusive Search for New Physics with Like-Sign Dilepton Events in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

The CDF Collaboration

February 27, 2007

The CDF Collaboration

Abstract

We present a search for anomalous production of events with two high-momentum leptons (electron or muon) of the same electric charge in $p\bar{p}$ collisions at a center-of-mass energy of 1.96 TeV. We use a data sample corresponding to 1 fb^{-1} of integrated luminosity recorded by the CDF II detector. We perform an inclusive selection with one lepton with transverse momentum above 20 GeV/c and a second one above 10 GeV/c. The standard model backgrounds for this signature are small. Many extensions to the standard model, such as Supersymmetry and models with heavy Majorana particles decaying into leptons, predict the production of two leptons of the same electric charge. This search has better acceptance and examines between a factor of three and ten more integrated luminosity compared to earlier searches in the same channel, resulting in a significant increase in sensitivity. We predict 33.2 ± 4.7 events in our data sample and observe 44; the probability to observe an excess this large or larger is 9%. We also examine a second scenario with increased sensitivity for SUSY-like physics scenario in which a stable neutral particle escapes detection. In that case, we predict 7.8 ± 1.1 events and observe 13. The probability to observe an excess this large or larger is 7%.

The standard model of particle physics (SM) successfully describes all experimental data taken in high energy collisions so far. Despite its successes, there are strong indications that this theory is only an effective low-energy model and new physics must be present at a higher energy scale. An excellent signature to search for deviations from the SM is production of two leptons with both leptons of the same electric charge. This signature occurs naturally in many extensions to the SM and occurs rather rarely in SM interactions.

An example of a model predicting like-sign dileptons is one with a Majorana particle that decays through SM-like bosons into leptons. Heavy Majorana neutrinos (ν_{M}) can be produced in $\mathrm{p\bar{p}}$ collisions in association with a lepton through a virtual W boson ($\mathrm{p\bar{p}} \rightarrow \nu_{\mathrm{M}}\ell^{\pm}\mathrm{X}$) [1]. This new particle can subsequently decay to a W and another lepton ($\nu_{\mathrm{M}} \rightarrow \mathrm{W}^{\pm}\ell^{\mp}$). Given the Majorana nature of this neutrino, *i.e.*, that it is its own antiparticle, more than half of such events will contain like-sign dileptons in the final state.

Another example is the class of models that predict new heavy analogs to the W and Z bosons. For instance, in supersymmetric extensions of the SM, a chargino-neutralino pair can be produced ($\mathrm{p\bar{p}} \rightarrow \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\mathrm{X}$) and decay into final states with three charged leptons ($\tilde{\chi}_1^{\pm} \rightarrow \ell^{\pm}\nu\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0 \rightarrow \ell^{\pm}\ell^{\mp}\tilde{\chi}_1^0$) [2]. Two of those three leptons will have the same charge. These are just two examples of new models which predict an excess in the same-charge lepton channels at hadron colliders.

The CDF and DØ Collaborations have previously investigated events with two same-charge leptons [3, 4]. In this Letter, we present a more general search using data collected with the CDF II detector during the Tevatron's Run II data-taking phase at a center-of-mass energy of 1.96 TeV. We select events as inclusively as possible without optimizing for any particular new physics scenario. To avoid bias, we fix the final event selection criteria before examining the event yield in the signal region. The selection produces a relatively small sample that we investigate for deviations from SM predictions, both in the total number of events and in the shape of kinematic distributions. We use a data sample corresponding to 1 fb^{-1} of integrated luminosity collected between March 2002 and February 2006. This search has better acceptance and examines between factor of three and a factor of ten more integrated luminosity compared to earlier searches in the same channel, resulting in roughly a factor of three increase in the sensitivity to new physics.

The CDF II detector [5] is an azimuthally and forward-backward symmetric apparatus designed to study $\mathrm{p\bar{p}}$ interactions at the Tevatron. The detector has a charged particle tracking system in a 1.4 T solenoidal magnetic field, aligned coaxially with the p and $\bar{\text{p}}$ beams. A silicon microstrip detector provides tracking over the radial range 1.5 to 28 cm [6]. A 3.1 m long open-cell drift chamber covers the radial range from 40 to 137 cm [7]. The fiducial region of the silicon detector extends to $|\eta| \sim 2$ [8], while the drift chamber provides tracking for $|\eta| \lesssim 1$. The curvature resolution of the chamber is $\sigma_C = 3.6 \times 10^{-6}\,\text{cm}^{-1}$ [9]. The curvature corresponding to a track with momentum of $100\,\text{GeV}/c$ is $2.1 \times 10^{-5}\,\text{cm}^{-1}$. The sign of the curvature of a track with 100 GeV/c of transverse momentum, and hence the charge of such a particle, is thus typically determined with a significance of better than five standard deviations.

Segmented electromagnetic and hadronic sampling calorimeters surround the tracking system and measure the energy of interacting particles in the pseudorapidity range $|\eta| \lesssim 3.6$ [10, 11]. A set of drift chambers located outside the central hadron calorimeters and another set behind a 60 cm iron shield detect muon candidates with $|\eta| \lesssim 0.6$ [12]. Additional drift chambers and scintillation counters detect muon candidates in the region $0.6 \lesssim |\eta| \lesssim 1.0$. Gas Cherenkov counters located in the $3.7 \lesssim |\eta| \lesssim 4.7$ region [13] measure the average number of inelastic $\text{p}\bar{\text{p}}$ collisions per bunch crossing and thereby determine the beam luminosity.

We use data collected with a high-momentum central lepton trigger, which identifies events with an electron candidate with $E_{\text{T}} > 18$ GeV and $|\eta| \lesssim 1$ or a muon candidate with $p_{\text{T}} > 18$ GeV/c and similar η requirements. We select events with a pair of same-charge leptons (electrons or muons) regardless of other activity in the event. This analysis uses lepton candidates with $|\eta| \lesssim 1$. The tracks associated with the leptons have to share a common vertex, *i.e.*, they come from the same $\text{p}\bar{\text{p}}$ interaction. We define the two highest-momentum charged leptons passing our selections as the leading and sub-leading lepton. We select leading and sub-leading electrons that fulfill the following requirements on the transverse component of the energy: $E_{\text{T}} > 20$ GeV and $E_{\text{T}} > 10$ GeV, respectively. We select muons that pass similar transverse momentum requirements. We remove photon-conversion electrons using a procedure described below. Cosmic-ray muons are identified and removed by looking for a track opposite to the reconstructed muon candidate which has timing information that is consistent with a particle moving toward the beam-line rather than away from it. We also place a minimum requirement on the invariant mass of the lepton pair, $m_{\ell\ell} > 25$ GeV/c^2, to remove the large background from Drell-Yan and heavy quark production at low mass. The leptons must be isolated from other particles in the event, both in the calorimeter and in the tracking chamber. An electron (muon) is considered to be isolated in the calorimeter if the sum of the transverse energy within a cone $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} \leq 0.4$, minus the lepton $E_{\rm T}$, is less than 10% of the lepton $E_{\rm T}(p_{\rm T})$. Similarly, if the total transverse momentum of all other tracks within a cone $\Delta R \leq 0.4$ around the lepton is less than 10% of the candidate track $p_{\rm T}$, the lepton is considered to be isolated in the tracking chamber.

SM backgrounds that produce like-sign dileptons in the final state include Drell-Yan dilepton production with a photon that is radiated off a final-state lepton and converts into an $\rm e^+e^-$ pair which fails our conversion identification algorithm (*i.e.*, is not "tagged") as well as diboson production. The latter includes on- and off-shell ZZ and WZ production followed by decay into leptonic final states, as well as Zγ and Wγ with the photon converting into two electrons inside the detector. In the following, we refer to the above Drell-Yan and Zγ processes as $\ell\ell\gamma$ backgrounds and to the Wγ and WZ processes as WV. Events with W($\rightarrow \ell\nu$) + 1 jet and Z($\rightarrow \ell\ell$) + 1 jet where the jet is falsely identified as a lepton can also result in two lepton candidates with the same charge. Contributions from heavy flavor backgrounds ($\rm t\bar{t}$, $\rm b\bar{b}$) are found to be negligible.

To estimate the background contribution from the $\ell\ell\gamma$ and diboson processes, we determine geometric and kinematic acceptance using Monte Carlo calculations followed by a GEANT-based simulation of the CDF II detector [14]. We use the Monte Carlo generator described in Ref. [15] for the Wγ background, MADEVENT for the WZ background [16], and PYTHIA for the other SM processes [17]. We use the CTEQ5L parton distribution functions to model the momentum distribution of the initial-state partons [18]. The expected number of events for each background component is determined as the product of the cross section, the luminosity of the sample, and the acceptance of the detector. The last is corrected for trigger efficiency and differences in lepton reconstruction efficiency between the data and the simulation. These efficiencies are derived via studies of W($\rightarrow \ell\nu$) and Z($\rightarrow \ell^+\ell^-$) events, and the differences are typically less than 10%.

Events with untagged photon conversions represent the dominant background to this search. To tag photon conversions, we take advantage of the kinematic condition that the trajectories of the electron and the positron from the photon are approximately parallel at the conversion point. We define the following variables: Δs is the distance in the transverse plane between the two tracks at the point that the two tracks are parallel, $\Delta\cot(\theta)$ is the difference in the cotangents of the polar angles between the two tracks, and Δz is the distance in the z dimension between the two points on the tracks used to compute Δs. A track pair is tagged as a photon conversion if $\Delta s < 1.1\,\mathrm{cm}$, $|\Delta\cot(\theta)| < 0.26$ and $\Delta z < 1.2\,\mathrm{cm}$. Conversion tagging will fail due to inefficiencies of the above selection or due to very asymmetric conversions, where the momentum of either the electron or the positron drops below our track selection threshold of $p_{\mathrm{T}} > 500$ MeV/c.

Processes producing opposite-charge leptons, such as Drell-Yan dilepton production, can contribute to our backgrounds if one of the lepton tracks is poorly measured and its charge is incorrectly reconstructed. The charge of a particle is determined from the direction the particle curves in the magnetic field. We test our understanding of the charge misassignment mechanism by examining the modeling of the curvature uncertainty. The uncertainty on the curvature measured in the tracking chamber provides an estimate of the probability of incorrectly measuring the sign of a track's curvature. For this purpose, we select electrons from events with two electrons where one electron is identified based solely on its energy deposits in the calorimeter and examine the curvature uncertainty for this particle. We find that the uncertainty on the track curvature of this data sample is well described by our simulation of the detector. The estimated residual background from events containing a lepton with an incorrectly reconstructed charge is less than 0.1 events in the current sample.

Jets in W+jet and Z+jet events can be misidentified as leptons ("fakes") and paired with the lepton from the gauge boson decay to form a same-charge candidate event. We estimate this background by selecting a sample of events with one or more high-momentum leptons that pass our selection criteria, omitting events with same-sign lepton candidates. We determine the number of events in our final selection from this fake background by multiplying the number of isolated tracks in this sample by the misidentification probability ("fake rate"). This probability is measured in a sample triggered by at least one jet with $E_{\mathrm{T}} > 50$ GeV and is defined as the number of identified leptons, divided by the total number of isolated tracks. We parameterize the fake rate as a function of p_{T} and η.

As a further means of controlling untagged photon conversions, we divide the electron candidates into two categories: with and without energy depositions in the silicon microstrip detector ("silicon hits"). Since most photon conversions occur either in the material of this detector or in the inner wall of the drift chamber, electrons with silicon hits are less likely to come from a conversion process. We consider the more pure category of electrons with silicon hits (e_{si}) separately from those without (e). By considering these two classes independently rather than requiring all electrons to have silicon hits, we do not lose acceptance due to inefficiencies in the silicon microstrip detector but gain in statistical power.

We perform numerous tests to assure that we are able to model our backgrounds. These tests can be split into two categories: those that test the overall normalization of a background, and those that test our ability to model detector performance. To probe the overall normalization of the diboson $Z\gamma$ background estimate, we select events with two leptons and a photon with transverse momentum thresholds of $20, 10$, and 10 GeV/c, respectively. The predicted number of events for this selection is 258 ± 16 events, dominated by $Z\gamma$ production. We observe 258 events, in good agreement. Similarly, we probe the normalization of the $W\gamma$ background by selecting events with one lepton with $p_{\mathrm{T}} > 20$ GeV/c, a photon with $E_{\mathrm{T}} > 10$ GeV, and $\not\!\!E_{\mathrm{T}} > 15$ GeV. Using this selection, we expect 1493 ± 90 events, dominated by $W\gamma$ production. We observe 1540 events, in good agreement with our expectation. For both of the above measurements, we require the photon to be well-separated from either the electron or muon, thereby effectively limiting the contribution from photons radiated in the material of the detector. We check our modeling of the material in the detector by selecting events with one electron, one photon, and $\not\!\!E_{\mathrm{T}} < 20$ GeV. These are mostly Drell-Yan events in which one electron has lost most of its energy to a radiated photon. For this selection, we predict 243 ± 15 events and observe 269, thereby validating our understanding of the detector material. Other backgrounds are tested using dedicated selection criteria. We obtain good agreement between the observed and predicted events both in integral counts and kinematic distributions in all regions considered.

The uncertainty on the number of predicted background events is dominated by the uncertainty on the luminosity measurement (5%), the fake estimate (5%) and the conversion modeling (10%). Other uncertainties include those associated with the SM cross sections, lepton reconstruction, and the statistical uncertainty on the Monte Carlo acceptance calculation.

New physics scenarios that lead to like-sign dilepton events, such as the ones mentioned in the introduction to this Letter, often have a WZ-like topology. As such, SM WZ production provides a reference point for the sensitivity of this analysis. The product of geometric acceptance, kinematic acceptance, and like-sign dilepton identification efficiencies ($\mathcal{A}_{\mathrm{geo}} \times \mathcal{A}_{\mathrm{kin}} \times \epsilon$)

	$n_{\rm obs}$	$n_{\rm pred}$	$n_{\ell\ell\gamma}$	$n_{\rm WV}$	$n_{\rm ZZ}$	$n_{\rm fake}$
$\rm e_{si}e_{si}$	11	6.3±1.0	3.2	1.4	0.4	1.3
ee	3	1.3±0.3	0.9	0.1	0.0	0.2
$\rm e_{si}e$	9	9.1±1.8	6.4	1.6	0.1	1.0
$\rm e_{si}\mu$	11	6.8±0.8	0.8	2.8	1.1	2.1
$\rm e\mu$	5	6.4±1.2	3.4	1.9	0.2	0.9
$\mu\mu$	5	3.2±0.3	0.1	1.4	0.8	0.8
Total	44	33.2±4.7	14.9	9.3	2.5	6.4

TABLE I: Event counts in the same-charge lepton sample, predicted ($n_{\rm pred}$) and observed ($n_{\rm obs}$), per category. The uncertainties for different channels are correlated. $n_{\ell\ell\gamma}$, $n_{\rm WV}$, $n_{\rm ZZ}$, and $n_{\rm fake}$ refer to the number of background events predicted in the $\ell\ell\gamma$, WV(V = Z or γ), ZZ, and "fake" categories, respectively, and $n_{\rm pred}$ is the sum of these contributions. $\rm e_{si}$ and e refer to electron candidates with and without energy deposits in the silicon microstrip detector.

for leptonic decays for on-shell SM WZ production, given as a proxy for the sensitivity of this analysis, is 8.0%.

In Table I, we present the expected and observed number of events with two same-charge leptons in all different combinations of leptons considered. Combining all channels, we predict 33.2±4.7 events and observe 44. The probability that 33.2 events with an uncertainty of 4.7 events fluctuate to 44 or more is 9%. Figures 1 and 2 show the comparison between the predicted and observed events for several kinematic distributions of interest.

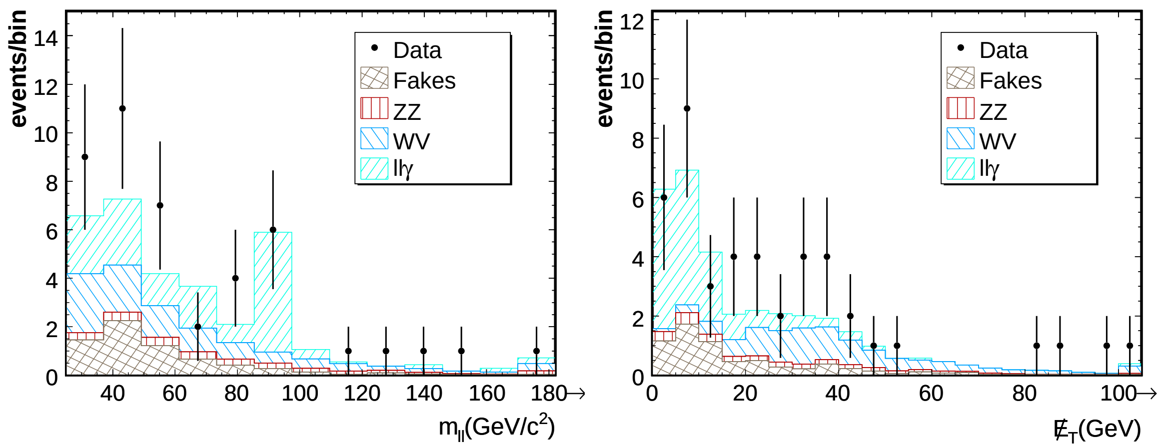

FIG. 1: Invariant mass distribution of the two selected leptons and missing transverse momentum in data and simulation. The rightmost bins are overflow bins. The peak at ≈ 90 GeV in the invariant mass distribution is mostly due to Drell-Yan di-electron production with a hard radiation off one electron, followed by an asymmetric conversion.

In Table II, we present the expected and observed number of events after imposing two

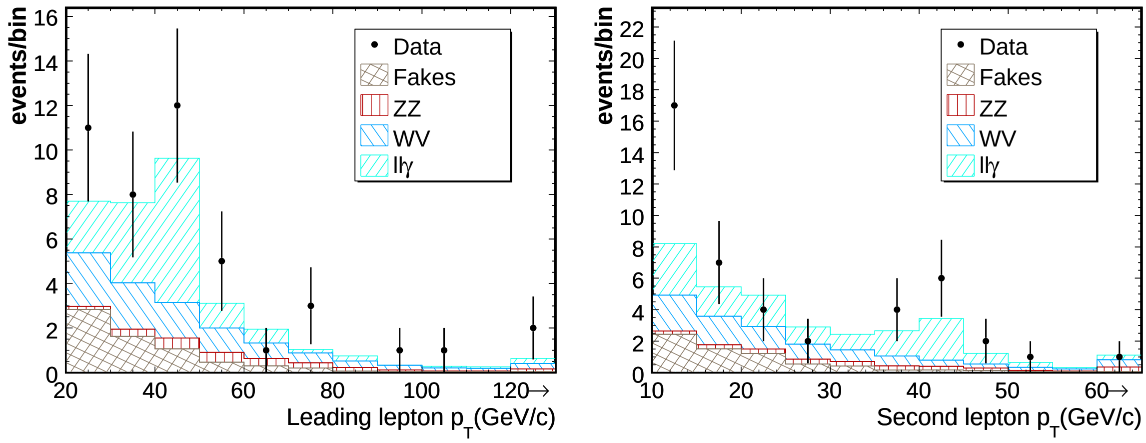

FIG. 2: Leading and sub-leading lepton transverse momentum in data and simulation. The right-most bins are overflow bins.

	$n_{\rm obs}$	$n_{\rm pred}$	$n_{\ell\ell\gamma}$	$n_{\rm WV}$	$n_{\rm ZZ}$	$n_{\rm fake}$
$\rm e_{si}e_{si}$	1	1.3±0.3	0.4	0.6	0.0	0.4
ee	1	0.1±0.1	0.0	0.1	0.0	0.0
$\rm e_{si}e$	2	1.5±0.3	0.1	1.2	0.0	0.2
$\rm e_{si}\mu$	4	1.7±0.2	0.0	1.0	0.1	0.7
$\rm e\mu$	4	2.3±0.5	0.6	1.4	0.0	0.2
$\mu\mu$	1	0.9±0.1	0.0	0.5	0.1	0.4
Total	13	7.8±1.1	1.1	4.7	0.2	1.8

TABLE II: Event counts in the same-charge lepton sample, with additional selection criteria for a SUSY-like physics scenario. The table headings are explained in the caption to Table I.

additional requirements aimed at increasing the signal sensitivity for a SUSY-like physics scenario where the stable, neutral and lightest supersymmetric particle escapes detection. We require a large transverse momentum imbalance ($\not\!\!E_{\rm T} > 15$ GeV) and reject events in which the invariant mass of one of our selected leptons and another lepton of the same flavor and opposite charge are consistent with a Z boson ($66 < m_{\ell^+\ell^-} < 116$ GeV$/c^2$). We predict 7.8 ± 1.1 events and observe 13. The probability that 7.8 events with an uncertainty of 1.1 events fluctuate to 13 or more is 7%. The value of $\mathcal{A}_{\rm geo} \times \mathcal{A}_{\rm kin} \times \epsilon$ for WZ events, as described above but adding a $\not\!\!E_{\rm T} > 15$ GeV requirement, is 7%.

In conclusion, we have performed a search for events with two leptons of the same electric charge using the CDF Run II data. We observe a slight excess in the number of predicted events in almost all lepton categories. However, the kinematic distributions do not show any anomalous deviation from expectations in any particular region of parameter space. Large future data sets expected at the Tevatron will reveal whether this observed slight excess persists.

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium für Bildung und Forschung, Germany; the Korean Science and Engineering Foundation and the Korean Research Foundation; the Particle Physics and Astronomy Research Council and the Royal Society, UK; the Russian Foundation for Basic Research; the Comision Interministerial de Ciencia y Tecnologia, Spain; and in part by the European Community's Human Potential Programme under contract HPRN-CT-2002-00292, Probe for New Physics.

[1] T. Han and B. Zhang, Phys. Rev. Lett. **97**, 171804 (2006) [arXiv:hep-ph/0604064].

[2] H. E. Haber and G. L. Kane., Phys. Rep. **117**, 75 (1985).

[3] CDF Collaboration, D. Acosta *et al.*, Phys. Rev. Lett. **93**, 061802 (2004) [arXiv:hep-ex/0405063]; CDF Collaboration, T. Affolder *et al.*, Phys. Rev. Lett **87**, 251803 (2001) [arXiv:hep-ex/0106061]; CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett **83**, 2133 (1999) [arXiv:hep-ex/9908063].

[4] DØ Collaboration, V. M. Abazov *et al.*, Phys. Rev. Lett **97**, 151804 (2006) [arXiv:hep-ex/0607032].

[5] CDF Collaboration, D. Acosta *et al.*, Phys. Rev. D **71**, 032001 (2005) [arXiv:hep-ex/0412071].

[6] C. S. Hill, Nucl. Instrum. Methods A **530**, 1 (2004); A. Sill, Nucl. Instrum. Methods A **447**, 1 (2000); A. Affolder, Nucl. Instrum. Methods A **453**, 84 (2000).

[7] T. Affolder *et al.*, Nucl. Instrum. Methods A **526**, 249 (2004).

[8] We use a cylindrical coordinate system about the beam axis in which θ is the polar angle, ϕ is the azimuthal angle, and $\eta \equiv -\ln\tan(\theta/2)$. $E_{\rm T} \equiv E\sin\theta$ and $p_{\rm T} \equiv p\sin\theta$ where E is energy measured by the calorimeter and p is momentum measured by the spectrometer. We

define the missing transverse momentum $\vec{\not{E}}_{\rm T} \equiv -\sum_i E_{\rm T}^i \mathbf{n}_i$, where $\mathbf{n}_i$ is the unit vector in the azimuthal plane that points from the beamline to the ith calorimeter tower.

[9] CDF Collaboration, A. Abulencia *et al.*, arXiv:hep-ex/0508029. Submitted for publication to Phys. Rev. D.

[10] L. Balka *et al.*, Nucl. Instrum. Methods A **267**, 272 (1988); M. Albrow *et al.*, Nucl. Instrum. Methods A **480**, 524 (2002).

[11] S. Bertolucci *et al.*, Nucl. Instrum. Methods A **267**, 301 (1988).

[12] G. Ascoli *et al.*, Nucl. Instrum. Methods A **268**, 33 (1988); T. Dorigo *et al.*, Nucl. Instrum. Methods A **461**, 560 (2001).

[13] D. Acosta *et al.*, Nucl. Instrum. Methods A **494**, 57 (2002).

[14] R. Brun *et al.*, CERN Report No. CERN-DD-78-2-REV (unpublished).

[15] U. Baur and E. L. Berger, Phys. Rev. D **41**, 1476 (1990); U. Baur and E. L. Berger, Phys. Rev. D **47**, 4889 (1993).

[16] F. Maltoni and T. Stelzer, J. High Energy Phys. **0302**, 027 (2003) [arXiv:hep-ph/0208156]; T. Stelzer and W. F. Long, Comput. Phys. Commun. **81**, 357 (1994) [arXiv:hep-ph/9401258].

[17] T. Sjöstrand *et al.*, J. High Energy Phys. **0605**, 026 (2006) [arXiv:hep-ph/0603175].

[18] J. Pumplin *et al.*, J. High Energy Phys. **0207**, 012 (2002) [arXiv:hep-ph/0201195].