Search for second generation scalar leptoquarks

The CDF Collaboration
URL http://www-cdf.fnal.gov
(Dated: August 27, 2004)

We report on the search for pair production of scalar leptoquarks using ~ 200 pb^{-1} of proton-antiproton collision data recorded by the CDF experiment during Run II of the TeVatron.
Leptoquarks are assumed to be pair produced and to decay into a charged lepton and a quark of the same generation with branching fraction β. Cases where (i) both leptoquarks decay into a muon and a quark, and (ii) one leptoquark decays into a muon and a quark while the other goes to a neutrino and a quark are considered. We observed no evidence for leptoquark production and set an upper cross section limit of 0.06 pb ($\beta = 1$) at 95% C.L. for the $\mu q \mu q$ channel and 0.28 pb ($\beta = 0.5$) at the 95% C.L. for the $\mu q \nu q$ channel.
These limits translate into 95% C.L. upper limits on the scalar leptoqaurk mass, of, respectively, 241 GeV/c^2 ($\beta = 1$) and 175 GeV/c^2 ($\beta = 0.5$).

Preliminary Results for Summer 2004 Conferences

I. INTRODUCTION

A common feature of theoretical models trying to imagine possible scenarios for new physics is the symmetry between quarks and leptons suggested by the Standard Model, and the search for a more foundamental relation between them. Theories like Grand Unification and R-parity violating Supersymmetry introduce the idea of quark to lepton transitions, therefore suggesting that particles carrying both lepton and baryon number exist. Among the rich fauna of exotic particles, leptoquarks are of special interest as they could be the mediator of this new kind of lepton-quark interaction.

Leptoquarks are hypothetical color-triplet particles carrying both baryon and lepton quantum numbers and are predicted by many extension of the Standard Model as new bosons coupling to a lepton-quark pair. Their masses are not predicted. They can be scalar particles (spin 0) or vector (spin 1) and at high energy hadron colliders they would be produced directly in pairs, mainly through gluon fusion or quark antiquarks annihilation. The couplings of the leptoquarks to the gauge sector are predicted due to the gauge symmetries, up to eventual anomalous coupling in the case of vector leptoquarks, whereas the fermionic couplings are free parameters of the models. In most models leptoquarks are expected to couple only to fermions of the same generations because of experimental constraints as non observation of flavor changing neutral currents or helicity suppressed decays. At the TeVatron leptoquarks would be pair produced and would decay into a lepton and quark of the same generation. Traditionally the branching ratio describing the decay of the leptoquark into a charge lepton and and quark is called β. The cross section for the pair production of scalar leptoquarks in $p\bar{p}$ has been calculated to next-to-leading order (NLO) in perturbative QCD [1].

We report on a search for scalar leptoquarks in the di-muon and jets topology and muon, missing transverse energy and jets topology, sensitive respectively to $\beta = 1$ and $\beta = 0.5$, using $\sim$ 200 pb^{-1} of $p\bar{p}$ collisions data at a center of mass energy of 1.96 TeV recorded by the Collider Detector at Fermilab (CDF) during the 2002-2003 TeVatron Run II. Previous limits on leptoquarks production from TeVatron Run I, HERA and LEP are summarized in [2].

CDF is a general purpose detector and is described in detail in [3]. A short description of its main components is briefly outlined here. Closest to the beam pipe is the charged particle tracking system used to reconstruct particle momenta and the collision vertex. It consists of a multi-layer silicon detectors and a large open-cell drift chamber covering the pseudorapidity region $|\eta| \leq 1$. The tracking system is enclosed in a superconducting solenoid. It is surrounded by a calorimeter, organized into electromagentic and hadronic sections segemented into projective tower geometry covering the $|\eta| \leq 3.6$ region. The central and plug electromagnetic calorimeters utilize a lead scintillator sampling technique, whereas the central, wall and plug hadron calorimeter use iron-scintillator technology. Outside the central calorimeter there is a muon detection system, which covers the range $|\eta| \leq 2$.

II. THE $\mu q \mu q$ CHANNEL

A. Data Sample & Event Selection

This analysis is based on an integrated luminosity of 198 pb^{-1} collected with the CDFII detector between March 2002 and September 2003. The data is collected with an inclusive lepton trigger that requires a muon with p_T >18 GeV.

From this inclusive lepton dataset we select events offline with two reconstructed isolated muons with p_T greater than 25 GeV. The first muon is required to be central ($|\eta| \leq 1$) and contain muon detector (CMUP, CMX) hits which are well aligned with the track. The second muon can be CMUP, CMX or be in the plug or central region ($|\eta| \leq 2$) with no requirements from the muon detectors (TRK). Events are further selected if there are at least two jets with E_T >30 GeV in the range $|\eta| \leq 2$. The dataset selected above is dominated by QCD production of Z bosons in association with jets and top quark (where both the W's from top decay go into a muon and neutrino). To reduce this background, while at the same time maintain a reasonable efficiency for detecting the LQ signal the following cuts are applied:

- Removal of events with $76 < M_{\mu\mu} < 110$ GeV/c^2;
- $E_T(j_1) + E_T(j_2) > 85$ GeV AND $E_T(e_1) + E_T(e_2) > 85$ GeV;
- $\sqrt{((E_T(j_1) + E_T(j_2))^2 + (E_T(e_1) + E_T(e_2))^2)} > 200$ GeV

B. Total Signal Acceptance

The efficiency for detecting leptoquarks decaying into muons and quarks is the product of several factors:

$$\epsilon_{total} = A(M) \times \epsilon_{ID} \times \epsilon_{trigger} \times \epsilon_{vertex} \times \epsilon_{isolation}$$

where A(M) is the product of the kinematical and geometrical acceptance, obtained from MC simulated LQ data (the PYTHIA Monte Carlo program [4] was used), ϵ_{id} is the identification efficiency for 2 muons, obtained from Z-data $\epsilon_{trigger}$ is the trigger efficiency, ϵ_{vertex} is the efficiency for the event vertex cut, also obtained from data, and $\epsilon_{isolation}$ is the efficiency in selecting muons which are isolated from jets. A separate efficiency is calculated for each combination of muon-detectors for the muons.

The final signal efficiencies are reported in Figure 1.

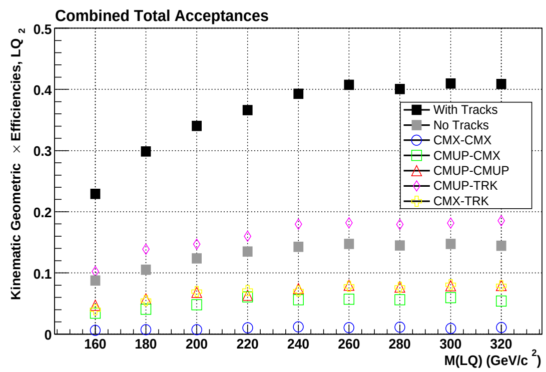

FIG. 1: Signal efficiency as function of the leptoquark mass, $\mu q \mu q$ analysis

C. Backgrounds

The main SM processes representing irreducible background to the Leptoquark production process are due to $\gamma/Z \to \mu\mu$ events accompanied by jets due to radiation. The main component of this background is eliminated by cuts on $M_{\mu\mu}$ around the mass of the Z boson and the ΣE_T cuts. However there are still events from the DY-continuum, and Z events that fail the cuts due to mis-measurement. We studied the distribution of this background by generating the process $Z+ \geq 2$ jets with Alpgen[6] and using the MC parton generator mcfm[5] to obtain the NLO cross section. Another source of background is represented by $t\bar{t}$ production where both W's decay into $\mu\nu$. Other backgrounds from $b\bar{b}$, $Z \to \tau\bar{\tau}$, WW are expected to be negligible due to the muon isolation and large muon and jet transverse energy requirements. The expected number of DY + $\geq$ 2 jets events in 198pb-1 is 1.82 ± 0.12. The expected number of $t\bar{t}$ events is 0.34 ± 0.05 events. Background events due to processes in which particles fake a muon is estimated to be 1.0 ± 1.0. To normalize simulated events to data we used the theoretical cross section for $t\bar{t}$, $\sigma(t\bar{t}) \times Br(W \to e\nu)$, and the theoretical cross section for $\gamma\ Z \to \mu\mu\ + \geq$2 jets obtained with mcfm. The total number of expected background events is 3.15 +/- 1.17.

D. Systematic uncertainty

The following systematic uncertainty is considered:

- Luminosity: 6%
- Acceptance:
  - pdf 4.3%
  - statistical error of MC 2.2%
  - Jet energy scale < 1%

- Electron ID efficiency
  - statistical error of $Z \to \mu\mu$ sample: 0.3%
- Event vertex cut : 0.5%

Adding the above systematic uncertainty in quadrature will give a total systematic uncertainty of about 7%. The total relative uncertainty on the acceptances varies from 8% to about 7%. Final signal efficiencies and uncertainties are reported in table below.

M(LQ) GeV/c^2	Acceptance (%)	Abs Stat	Abs Sys	Relative total Uncertainty
200	33.3	0.4	2.5	7.7
220	35.9	0.5	2.7	7.6
240	38.5	0.5	2.9	7.6
260	40.4	0.5	3.0	7.6
280	39.3	0.5	2.9	7.6
300	40.1	0.5	3.0	7.6
320	40.1	0.5	3.0	7.6

TABLE I: Final Signal Efficiency and Errors.

E. Results

After all selection cuts, 2 events are left.
The production cross section s of the process $LQ\overline{LQ} \to \mu q \mu q$ can be written as follows:

$$\sigma \times Br(LQ\overline{LQ} \to \mu q \mu q) = \sigma \times \beta^2 = \frac{N}{(\epsilon \times L)},$$

where N is the number of observed events on data after our selection, ϵ is the total selection efficiency as a function of M(LQ) and it L is the integrated luminosity. As we find 2 candidate events in our selection, we set a 95% C.L. upper limit on the cross section as a function of M(LQ) defined as:

$$\sigma_{lim} = \frac{N_{lim}}{(\epsilon \times L \times \beta^2)}$$

In Figure 2 the limit cross-section as function of M(LQ) is compared with the theoretical expectations for $\beta = 1$. At the intersection point between experimental and theoretical curves we find the lower limit on M(LQ) at 241 GeV/c^2.

III. THE $\mu q \nu q$ CHANNEL

A. Data Sample & Event Selection

This analysis is based on an integrated luminosity of 198 pb^{-1} collected with the CDFII detector between March 2002 and September 2003. The data are collected with an inclusive lepton trigger that requires a muon with p_T >18 GeV.

From this inclusive lepton dataset we select events offline with one reconstructed isolated muon p_T greater than 25 GeV. The muon is required to be central ($|\eta| \leq 1$). We veto events with a second central or stubless muon (to be orthogonal to the previous analysis). We then select events where there is large missing transverse energy, $\not{E}_T > 60$ GeV and at least two jets with E_T >30 GeV in the range $|\eta| \leq 2$. The dataset selected above is dominated by QCD production of W bosons in association with jets and top quark (decaying into dilepton and lepton + jets mode). To reduce this background, while at the same time maintaining a reasonable efficiency for detecting the LQ signal the following cuts are applied:

- $\Delta\Phi(\not{E}_T - jet) > 5^o$ ($\Delta\Phi(\not{E}_T - \mu) < 175^o$) to veto events where the transverse missing energy is mismeasured due to a mismeasured jet (muon);

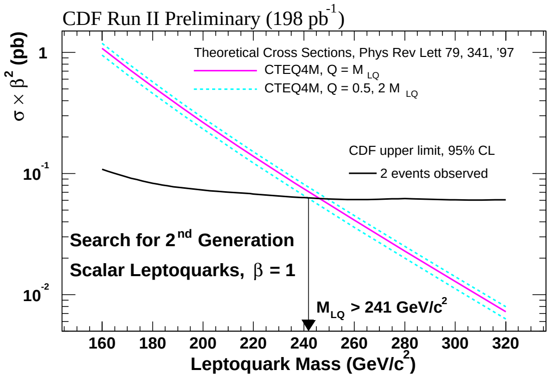

FIG. 2: Limit cross section for second generation leptoquarks decaying 100% to μq as a function of M(LQ) compared with the theoretical expectations calculated at NLO accuracy. At the intersection points between experimental and theoretical curves we find a lower limit on M(LQ) at 241 GeV/c^2 for $\beta = 1$.

- $E_T(j_1) + E_T(j_2) > 80GeV$
- $M_T(e\nu) > 120GeV/c^2$ to reduce the W + 2 jets background.

Finally we select events falling in mass windows defined around the nominal LQ masses. This cut allows us to better discriminate background from signal as the background events will lay in a random way in respect to the preferential position of signal around the LQ mass.

To select leptoquark candidates of a given mass we build the invariant mass of the muon-jet system and the transverse mass of the neutrino-jet system. Given the decay of the two leptoquarks, there are two possible mass combinations for the electron and the neutrino with the 2 leading jets. We require the two invariant masses for each system to pass either one of two different mass ranges. These mass ranges are determined for each leptoquark mass by fitting the peak of the μ-jet distribution with a Gaussian. We then operate a $2\sigma_e$ cut around the nominal leptoquark mass to select leptoquark candidates of a given mass. The $\nu - jet$ transverse mass distribution is only required to pass a low mass cut. The spread σ_μ ranges from 10-25% of the leptoquark mass for the leading jet and 15-30% of the leptoquark mass for the second leading jet (increasing with the LQ mass).

B. Total Signal Acceptance

The efficiency for detecting leptoquarks decaying into electron/neutrino and quarks is the product of several factors:

$$\epsilon_{total} = A(M) \times \epsilon_{id} \times \epsilon_{trigger} \times \epsilon_{vertex} \times_{isolation}$$

where A(M) is the product of the kinematical and geometrical acceptance, obtained from MC simulated LQ data (the PYTHIA Monte Carlo program [4] was used), ϵ_{id} is the identification efficiency for 1 central electron, obtained from Z-data, $\epsilon_{trigger}$ is the trigger efficiency ϵ_{vertex} is the efficiency for the event vertex cut, also obtained from data, and $\epsilon_{isolation}$ is the efficiency for the muon to be isolated from jets. Kinematical and geometrical efficiencies are multiplied by the scale factor between data and simulation. The final signal efficiency is reported in Figure 3.

C. Backgrounds

The main SM processes contrbuting to the irreducible background to the LQ signal, is due to $W \to \mu\nu$ events accompanied by jets due to radiation. The main component of this background is eliminated by cuts on M_T of the muon and neutrino. We studied the distribution of this background by generating the process $W+ \geq 2$ jets with Alpgen[6] and using the MC parton generator mcfm[5] to obtain the NLO cross section. Another source of background is represented by $t\bar{t}$ production where both the W decay into $\mu\nu$ and one lepton is mismeasured or one of the W decays leptonically and the other hadronically (lepton + jets). A small source of background is represented by $Z+ \geq 2$ jets, where one of the muons is misidentified . These are generated with Alpgen. The background from $W \to \nu\tau$ + 2 jets is negligible after the final window mass cut. To normalize simulated events to data we use the central value of

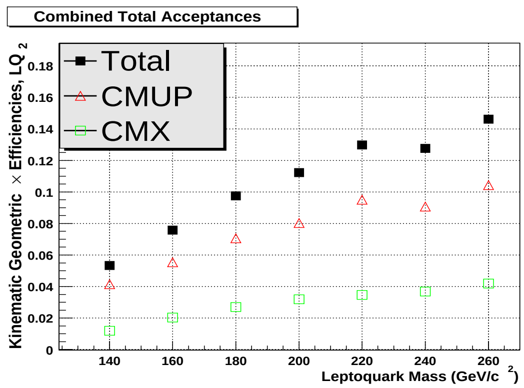

FIG. 3: Signal efficiency as function of the leptoquark mass, $\mu q \nu q$

the theoretical cross section for $t\bar{t}$, $\sigma(t\bar{t}) = 6.7$ pb , and the theoretical cross section for $W+ \geq 2$ jets and $Z+ \geq 2$ jets from mcfm (294 pb for $W+ \geq 2$ jets$\times Br(W \rightarrow \ell\nu)$ and 98pb for $Z+ \geq 2$ jets $\times Br(Z \rightarrow \ell\ell)$).

The QCD multijet background is estimated by extrapolating the number of QCD events in the low missing transverse energy region to the signal region. The upper limit on the QCD multijet background events is 0.29 ± 0.29.

D. Systematic uncertainty

The following systematic uncertainty is considered:

- Luminosity: 6%
- Acceptances
  - pdf 2.1%
  - statistical error of MC 2.2%
  - Jet energy scale ¡ 1%
- Event vertex cut : 0.5%
- ISR/FSR 1.8%

Final signal efficiencies and uncertainties are reported in table below.

M(LQ) GeV/c^2	Acceptance (%)	Abs Stat	Abs Sys	Relative total Uncertainty
140	5.3	0.1	0.4	8.44
160	7.6	0.1	0.6	7.92
180	9.7	0.1	0.7	7.61
200	11.2	0.2	0.8	7.23
220	13.0	0.2	0.9	7.01
240	12.8	0.2	0.9	6.93

TABLE II: Final Signal Efficiency and Errors for the $\mu q \nu q$ channel.

E. Results

The number of events surviving in each mass region, compared with the background expectations are reorted in table III.

As before, the production cross section s of the process $LQ\overline{LQ} \rightarrow \mu q \nu q$ can be written as follows:

	140	160	180	200	220
$W+$ jets	0.92 ± 0.06	1.39 ± 0.09	1.39 ± 0.10	1.62 ± 0.11	1.60 ± 0.11
$t\bar{t}$	1.69 ± 0.21	1.84 ± 0.23	1.35 ± 0.17	1.00 ± 0.37	0.80 ± 0.29
$Z+$ jets	0.18 ± 0.01	0.22 ± 0.02	0.19 ± 0.01	0.18 ± 0.01	0.14 ± 0.01
QCD multijet	0.29 ± 0.29	0.29 ± 0.29	0.29 ± 0.29	0.29 ± 0.29	0.29 ± 0.29
Total	3.09 ± 0.57	3.74 ± 0.62	3.22 ± 0.56	3.08 ± 0.53	2.83 ± 0.51

TABLE III: Final number of events surviving all cuts, compared with background expectations

$$\sigma \times Br(LQ\overline{LQ} \to \mu q \nu q) = \sigma \times 2\beta(1-\beta) = \frac{N}{(\epsilon \times L)},$$

where N is the number of observed events on data after our selection, ϵ is the total selection efficiency as a function of M(LQ) and it L is the integrated luminosity. Given the number of surviving events, we set a 95% C.L. upper limit on the cross section as a function of M(LQ) defined as:

$$\sigma_{lim} = \frac{N_{lim}}{(\epsilon \times L \times 2\beta(1-\beta))}$$

In Figure 4 the limit cross-section as function of M(LQ) is compared with the theoretical expectations for $\beta = 0.5$. At the intersection point between experimental and theoretical curves we find the lower limit on M(LQ) at 175 GeV/c^2.

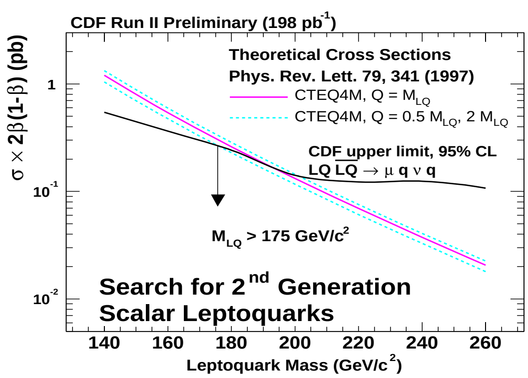

FIG. 4: Limit cross section for second generation leptoquarks decaying 50% to μq as a function of M(LQ) compared with the theoretical expectations calculated at NLO accuracy. At the intersection points between experimental and theoretical curves we find a lower limit on M(LQ) at 175 GeV/c^2 for $\beta = 0.5$.

In Figure 5 the final invariant μ-leading-jet mass distribution (top) and μ-second-leading-jet mass (bottom) background distributions are shown. In Figure 6 the same is shown for the transverse mass distribution ν-leading-jet (top) and ν-second-leading-jet (bottom). The hatched areas are the mass regions excluded by the cut.

IV. CONCLUSIONS

We have reported on the search for pair production of scalar leptoquarks using $\sim$ 200 pb^{-1} of proton-antiproton collision data recorded by the CDF experiment during Run II of the TeVatron.

Leptoquarks are assumed to be pair produced and to decay into a charged lepton and a quark of the same generation with branching fraction β. Cases where (i) both leptoquarks decay into a muon and a quark and (ii) one leptoquark decays into a muon and a quark while the other goes to a neutrino and a quark are considered. We observe no evidence for leptoquark production and set an upper cross section limit of 0.06 pb ($\beta = 1$) at 95% C.L. for the $\mu q \mu q$ channel and 0.28 pb ($\beta = 0.5$) at the 95% C.L. for the $\mu q \nu q$ channel.

These limits translate into 95% C.L. upper limits on the scalar leptoqaurk mass, of, respectively, 241 GeV/c^2 ($\beta =$ 1) and 175 GeV/c^2 ($\beta = 0.5$).

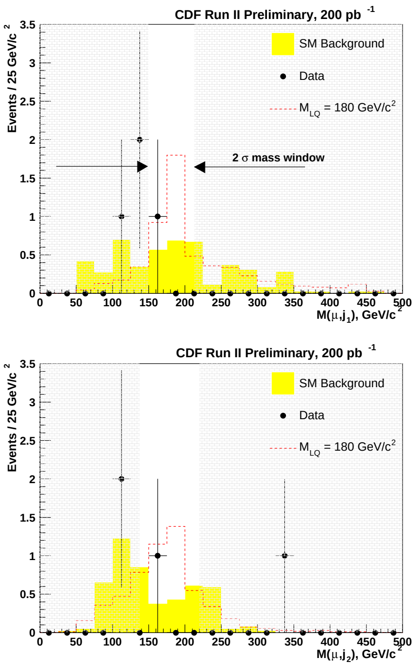

FIG. 5: Invariant mass distributions of the muon-jets for the leading jet (top) and second leading jet (bottom) for $M(LQ) = 180$ GeV/c^2. The dashed line shows the theoretical leptoquark signal, and the bullets represent the data.

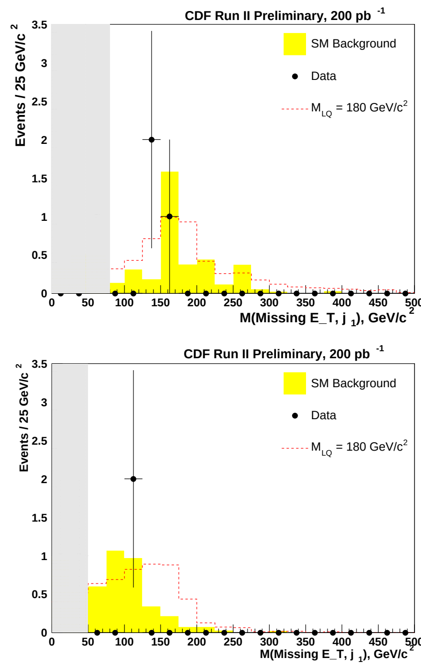

FIG. 6: Transverse mass distributions of the neutrino-jets for the leading jet (top) and second leading jet (bottom) for $M(LQ) = 180$ GeV/c^2. The dashed line shows the theoretical leptoquark signal, and the bullets represent the data.

Acknowledgments

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 fuer 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-20002, Probe for New Physics.

---

[1] Pair Production of scalar LeptoQuarks at the TeVatron, M. Kramer et al., Phys Rev Lett 79, 341 (1997).
[2] G. Moortgat-Pick, S. Rolli, A.F. Zarnecki, Physics at large p(T)**2 and Q**2: summary, , Acta Phys. Polon.B33:3955-3981, (2002).
[3] F. Abe, et al., Nucl. Instrum. Methods Phys. Res. A **271**, 387 (1988); D. Amidei, et al., Nucl. Instum. Methods Phys. Res. A **350**, 73 (1994); F. Abe, et al., Phys. Rev. D **52**, 4784 (1995); P. Azzi, et al., Nucl. Instrum. Methods Phys. Res. A **360**, 137 (1995); The CDFII Detector Technical Design Report, Fermilab-Pub-96/390-E
[4] T. Sjostrand et al., High-Energy-Physics Event Generation with PYTHIA 6.1, Comput. Phys. Commun. **135**, 238 (2001).
[5] http://mcfm.fnal.gov/
[6] http://mlm.home.cern.ch/mlm/alpgen/