RESONANT PRODUCTION OF THE FOURTH FAMILY SLEPTON AT THE LHC

O. Çakir†, S. Kuday‡

Department of Physics, Ankara University, Faculty of Sciences, Ankara, Turkey

I.T. Çakir§

Department of Physics, CERN, Geneva, Switzerland

S. Sultansoy¶

Physics Division, TOBB University of Economics and Technology, Ankara, Turkey
and
Institute of Physics, Academy of Sciences, Baku, Azerbaijan

(Received September 16, 2011)

The resonant production of the fourth family slepton $\tilde{l}_4$ via R-parity violating interactions of supersymmetry at the Large Hadron Collider has been investigated. We study the decay mode of $\tilde{l}_4$ into the fourth family neutrino ν_4 and W boson. The signal will be a like-sign dimuon and dijet if the fourth family neutrino has Majorana nature. We discuss the constraints on the R-parity violating couplings λ and λ' of the fourth family charged slepton at the LHC with the center of mass energies of 7, 10 and 14 TeV.

DOI:10.5506/APhysPolB.43.63
PACS numbers: 12.60.Jv, 14.60.St

The mass and mixing patterns of the Standard Model (SM) fermions form the greatest mystery of particle physics. Even the number of families is not predicted by the SM. The existence of the fourth SM family may shed light on some open questions within the SM (see [1, 2] and references therein). Recent studies [3, 4, 5, 6, 7, 8, 9, 10, 11, 12] on the allowed parameter

† ocakir@science.ankara.edu.tr
‡ kuday@science.ankara.edu.tr
§ tcakir@mail.cern.ch
¶ ssultansoy@etu.edu.tr

space for the fourth family fermions from precision electroweak data show that this space is large enough: there is an infinite number of SM4 points (analogs of well-known SUGRA points) which are in pretty good agreement with the precision electroweak data. The experimental limits on the masses of the fourth family quarks from Collider Detector at Fermilab (CDF) are: $m_{u_4} > 335$ GeV at 95% C.L. [13], $m_{d_4} > 338$ GeV at 95% C.L. [14]. There are also limits on the masses of the fourth family leptons [15]: $m_{l_4} > 100$ GeV, $m_{\nu_4} > 90$ (80) GeV for Dirac (Majorana) neutrinos. On the other hand, the partial wave unitarity leads to an upper bound 700 GeV for fourth SM family fermion masses [16].

Obviously, if the fourth SM family exists in nature then the Minimal Supersymmetric Standard Model (MSSM) should be enlarged to include fourth family superpartners. The inclusion of the fourth SM family into MSSM is straightforward [17] (we denote minimal supersymmetric standard model with three and four families as MSSM3 and MSSM4, respectively). Concerning precision electroweak data the parameter space of the MSSM4 is more tightly constrained [18] if the neutrino has Dirac nature. However, this statement may be relaxed if the neutrino has Majorana nature (as in the SM4 case [12]).

The search for supersymmetry (SUSY) is a significant part of the physics program of TeV scale colliders. As mentioned in [19], it is difficult to differentiate MSSM3 and MSSM4 at hadron colliders, because the light superpartners of the third and fourth family quarks have almost the same decay chains if the R-parity is conserved. For this reason, the pair production of fourth family charged sleptons at future e^+e^- colliders has been proposed in [19] to differentiate the MSSM with three and four families.

The R-parity is defined as $R = (-1)^{3(B-L)-2S}$, where B, L and S are the baryon number, lepton number and spin, respectively. It is a useful assignment for the phenomenology, because all the SM particles and Higgs boson have even R-parity, while all the sfermions, gauginos and Higgsinos of the supersymmetry have odd R-parity. The rich phenomenology of the MSSM becomes even richer if R-parity is violated (see [20] and references therein). Concerning MSSM4, R-parity violation (RPV) could provide opportunity to differentiate MSSM3 and MSSM4 at hadron colliders.

The R-parity violating part of the MSSM superpotential is given by

$$W_{\mathrm{RPV}} = \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \lambda''_{ijk} U_i^c D_j^c D_k^c \,, \tag{1}$$

where $L(E)$ is an SU(2) doublet (singlet) lepton superfield and $Q(U,D)$ is (are) an SU(2) doublet (singlet) quark superfield(s), and indices i,j,k denote flavor. The coefficients λ_{ijk} and λ''_{ijk} corresponds to the lepton number violating and baryon number violating couplings, respectively. The second term in Eq. (1) allows the resonance production of sleptons at hadron colliders. In the framework of the MSSM3 this process was first considered in [21] and the specific case for stau production was considered in [22] (see also review [23]).

In this work, we consider the resonant production of fourth family slepton via the process $pp \to \tilde{l}_4{}^+ X \to \nu_4 \mu^+ X$ and followed by the decay $\nu_4 \to W^- \mu^+$ for the Majorana nature of neutrino at the Large Hadron Collider (LHC) with $\sqrt{s} = 7$, 10 and 14 TeV. If the W-boson decays hadronically, the signal will be seen in detector as $\mu^+\mu^+ jj$. Below, we assume $m_{\nu_4} < m_{l_4} + m_W$ which is preferred by the precision electroweak data. It should be noted that this process is specific to MSSM4, while the similar signature in MSSM3 can proceed via resonant production of $\tilde{\mu}^+$ followed by R-parity conserving decay $\tilde{\mu}^+ \to \mu^+ \tilde{\chi_1}^0$, where $\tilde{\chi_1}^0$ decays into $\mu^+ jj$ via RPV [24, 25].

The RPV supersymmetric trilinear interaction terms for the charged fourth family slepton can be written as

$$\begin{aligned} L_{\mathrm{RPV}} = \; & \lambda_{i4k} \tilde{l}_{4\mathrm{L}} \bar{l}_{k\mathrm{R}} \nu_i + \lambda_{ij4} \tilde{l}^*_{4\mathrm{R}} \bar{\nu}^c_i l_{j\mathrm{L}} - \lambda_{4jk} \tilde{l}_{4\mathrm{L}} \bar{l}_{k\mathrm{R}} \nu_j - \lambda_{ij4} \tilde{l}^*_{4\mathrm{R}} \bar{\nu}^c_j l_{i\mathrm{L}} \\ & - \lambda'_{4jk} \tilde{l}_{4\mathrm{L}} \bar{q}_{k\mathrm{R}} q_{j\mathrm{L}} + \mathrm{h.c.}\,, \end{aligned} \tag{2}$$

where $\tilde{l}_{4\mathrm{L(R)}}$ is the fourth family slepton field, $q_{\mathrm{L(R)}}$ is the left-handed (right-handed) quark field, and indices i, j, k denote flavor.

The mass matrix of the fourth family charged sleptons in the $(\tilde{l}_{4\mathrm{L}}, \tilde{l}_{4\mathrm{R}})$ basis is given by

$$M^2_{\tilde{l}_4} = \begin{pmatrix} m^2_{\tilde{l}_{4\mathrm{L}}} & a_{l_4} m_{l_4} \\ a_{l_4} m_{l_4} & m^2_{\tilde{l}_{4\mathrm{R}}} \end{pmatrix}, \tag{3}$$

where $m^2_{\tilde{l}_{4\mathrm{L}}} = M^2_{\tilde{\mathrm{L}}_4} + m^2_{l_4} - m^2_Z \cos 2\beta (\frac{1}{2} - \sin^2\theta_W)$; $m^2_{\tilde{l}_{4\mathrm{R}}} = M^2_{\tilde{E}_4} + m^2_{l_4} - m^2_Z \cos 2\beta \sin^2\theta_W$; $a_{l_4} = A_{l_4} - \mu \tan\beta$, and A_{l_4} is the Higgs-fourth family charged lepton trilinear parameter (the notation of [26] is used).

The mass eigenstates $\tilde{l}_{4l}$ and $\tilde{l}_{4h}$ are related to $\tilde{l}_{4\mathrm{L}}$ and $\tilde{l}_{4\mathrm{R}}$ by

$$\begin{pmatrix} \tilde{l}_{4l} \\ \tilde{l}_{4h} \end{pmatrix} = \begin{pmatrix} \cos\theta_{\tilde{l}_4} & \sin\theta_{\tilde{l}_4} \\ -\sin\theta_{\tilde{l}_4} & \cos\theta_{\tilde{l}_4} \end{pmatrix} \begin{pmatrix} \tilde{l}_{4\mathrm{L}} \\ \tilde{l}_{4\mathrm{R}} \end{pmatrix} \tag{4}$$

with the eigenvalues

$$m^2_{\tilde{l}_{4(l,h)}} = \frac{1}{2}\left(m^2_{\tilde{l}_{4\mathrm{L}}} + m^2_{\tilde{l}_{4\mathrm{R}}}\right) \mp \frac{1}{2}\sqrt{\left(m^2_{\tilde{l}_{4\mathrm{L}}} - m^2_{\tilde{l}_{4\mathrm{R}}}\right)^2 + 4a^2_{l_4} m^2_{l_4}} \tag{5}$$

and the mixing angle $\theta_{\tilde{l}_4}$ is given by

$$\cos\theta_{\tilde{l}_4} = \frac{-a_{l_4} m_{l_4}}{\sqrt{\left(m^2_{\tilde{l}_{4\mathrm{L}}} - m^2_{\tilde{l}_{4l}}\right)^2 + a^2_{l_4} m^2_{l_4}}}\,. \tag{6}$$

As seen from Eq. (5), $\tilde{l}_{4l}$ is expected to be the lightest charged slepton because of large value of m_{l_4}.

The hadronic cross-section for the process $pp \to \tilde{l}^+_{4l}X \to \mu^+\nu_4 X$ is defined by

$$\sigma = \sum_{i,j} \int\int dx_1 dx_2\, \hat{\sigma}_{\text{part}}(x_1 x_2 s) \times \left[f_i\left(x_1, Q^2\right) f_j\left(x_2, Q^2\right) + f_i\left(x_2, Q^2\right) f_j\left(x_1, Q^2\right)\right] , \tag{7}$$

where x_1 and x_2 are the fractions of parton momentum to proton momentum for two proton beams, s is the square of the center of mass energy, and Q is the factorization scale. For the subprocess shown in Fig. 1 (a), the partonic cross-section $\hat{\sigma}_{\text{part}}(\hat{s})$ is calculated as

$$\hat{\sigma}_{\text{part}}\left(\hat{s}\right) = \sum_{jk} \frac{C_{\text{F}}\left(\lambda'^{\text{eff}}_{4jk}\lambda^{\text{eff}}_{442}\right)^2 \left(\hat{s} - m^2_{\nu_4}\right)^2}{16\pi\hat{s}\left[\left(\hat{s} - m^2_{\tilde{l}_{4l}}\right)^2 + m^2_{\tilde{l}_{4l}} \Gamma^2_{\tilde{l}_{4l}}\right]} , \tag{8}$$

where $m_{\tilde{l}_4}$ and m_{ν_4} are the masses of fourth family charged slepton and fourth family neutrino, respectively; C_{F} is the color factor, and the effective couplings are defined as $\lambda^{\text{eff}}(\lambda'^{\text{eff}}) = \cos\theta_{\tilde{l}_4}\lambda(\lambda')$. Here $\Gamma_{\tilde{l}_{4l}}$ is total decay width of $\tilde{l}_{4l}$. We assume that RPV decay modes are dominant, which is certainly valid if $m_{\tilde{l}_{4l}} < m_{l_4} + m_{\tilde{\chi}^0_1}$ and $m_{\tilde{l}_{4l}} < m_{\nu_4} + m_{\tilde{\chi}^+_1}$.

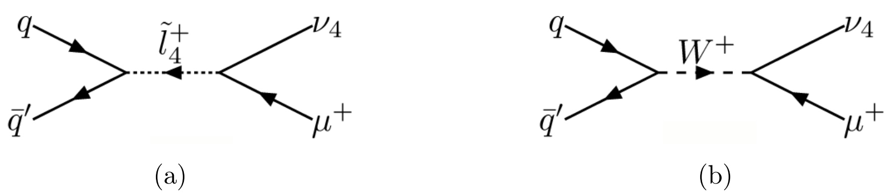

Fig. 1. Feynman diagrams of subprocess $q\bar{q}' \to \nu_4\mu^+$: (a) signal, (b) background.

For numerical calculations we implement the vertices from interaction Lagrangian (Eq. (2)) into CompHEP [27] with the CTEQ6M [28] parton distribution functions. Masses of the fourth family (Majorana) neutrino and charged slepton are taken as $m_{\nu_4} = 100$ GeV and $m_{\tilde{l}_4} = 300$ GeV, respectively. It should be noted that the main background for our signal, namely $\mu^+\mu^+jj$, will come from the fourth SM family itself (see Fig. 1 (b)). This background is proportional to $|U_{\nu_4\mu}|^2$. Recent analysis of PMNS matrix elements in the presence of a fourth generation showed that $|U_{\nu_4\mu}| < 0.115$ [29].

The signal cross-sections at LHC with $\sqrt{s} = 7$, 10 and 14 TeV are given in Tables I, II, III, respectively. In numerical calculations, we assume $\lambda^{\rm eff}_{442} = 0.05$, in columns 2–7 corresponding $\lambda'^{\rm eff}_{4jk}$ is equal to 0.05 and remaining ones are zero, in the last columns all $\lambda'^{\rm eff}_{4jk}$ are equal to 0.05. Using $|U_{\nu_4\mu}| = 0.05$ and $m_{\nu_4} = 100$ GeV, we also calculate the background cross-sections as 0.016, 0.024 and 0.035 pb for LHC with $\sqrt{s} = 7$, 10 and 14 TeV, respectively. We use the branching ratio $\mathrm{BR}(\nu_4 \to \mu^\pm W^\mp) = 0.34$ which is predicted within the parametrization [30] compatible with the experimental data on the masses and mixings in the leptonic sector this parametrization predicts $\mathrm{BR}(\nu_4 \to \tau^\pm W^\mp) = 0.16$ and $\mathrm{BR}(\nu_4 \to e^\pm W^\mp) = 4 \times 10^{-4}$ for other decay modes of the fourth family neutrino). In the last two rows of Tables I–III, we present the statistical significance for the signal observations and required integrated luminosity for reaching 3σ.

TABLE I

Cross-sections and significance depending on effective RPV couplings at $\sqrt{s} = 7$ TeV with $L_{\rm int} = 1\ \mathrm{fb}^{-1}$.

	$\lambda'^{\rm eff}_{411}$	$\lambda'^{\rm eff}_{412}$	$\lambda'^{\rm eff}_{421}$	$\lambda'^{\rm eff}_{413}$	$\lambda'^{\rm eff}_{422}$	$\lambda'^{\rm eff}_{423}$	$\lambda'^{\rm eff}_{4jk}$
σ_S [pb]	0.15	0.11	0.02	0.06	9.3×10^{-3}	3.9×10^{-3}	0.35
$S/\sqrt{B}$	22	16	3	8.8	1.4	0.6	52
$L_{\rm int}$ [pb^{-1}] for 3σ	18.8	35	1×10^3	120	5×10^3	2.8×10^4	3.4

TABLE II

The same as for Table I but for $\sqrt{s} = 10$ TeV and $L_{\rm int} = 100\ \mathrm{fb}^{-1}$.

	$\lambda'^{\rm eff}_{411}$	$\lambda'^{\rm eff}_{412}$	$\lambda'^{\rm eff}_{421}$	$\lambda'^{\rm eff}_{413}$	$\lambda'^{\rm eff}_{422}$	$\lambda'^{\rm eff}_{423}$	$\lambda'^{\rm eff}_{4jk}$
σ_S [pb]	0.24	0.19	0.033	0.11	0.021	9.6×10^{-3}	0.6
$S/\sqrt{B}$	287	225	38.7	130	25.2	11.4	716
$L_{\rm int}$ [pb^{-1}] for 3σ	11	17.8	6×10^2	53.4	1.4×10^3	6.9×10^3	1.753

TABLE III

The same as for Table I but for $\sqrt{s} = 14$ TeV.

	$\lambda'^{\rm eff}_{411}$	$\lambda'^{\rm eff}_{412}$	$\lambda'^{\rm eff}_{421}$	$\lambda'^{\rm eff}_{413}$	$\lambda'^{\rm eff}_{422}$	$\lambda'^{\rm eff}_{423}$	$\lambda'^{\rm eff}_{4jk}$
σ_S [pb]	0.36	0.29	0.061	0.177	0.042	0.02	0.96
$S/\sqrt{B}$	350	290	60	175	41.4	19.7	946
$L_{\rm int}$ [pb^{-1}] for 3σ	7.23	10.7	247	30	525	2.3×10^3	1

In Figs. 2, 3 and 4 we plot integrated luminosity needed for 3σ significance reach depending on $\lambda'^{\rm eff}_{4jk} \equiv \lambda'^{\rm eff}$ for three different values of $|U_{\nu_4\mu}|$ assuming $m_{\nu_4} = 100$ GeV, $m_{\tilde{l}_4} = 300$ GeV and $\lambda^{\rm eff}_{442} = 0.05$. In Table IV we present observable values of $\lambda'^{\rm eff}$ for 3σ observation at the LHC runs with $\sqrt{s} = 7$, 10 and 14 TeV.

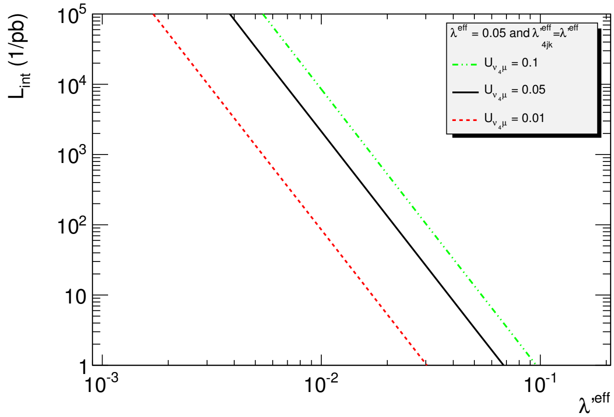

Fig. 2. Integrated luminosity *versus* $\lambda'^{\rm eff}$ for 3σ significance at $\sqrt{s} = 7$ TeV.

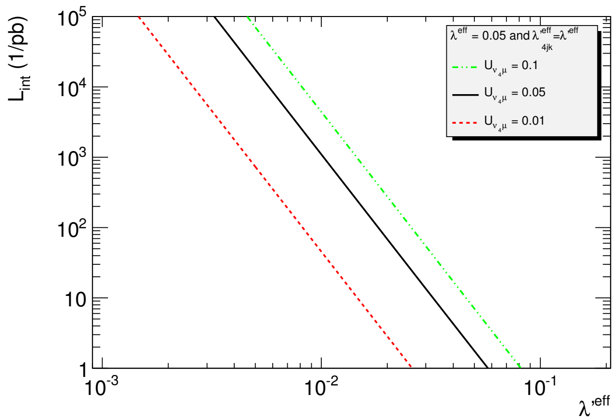

Fig. 3. Integrated luminosity *versus* $\lambda'^{\rm eff}$ for 3σ significance at $\sqrt{s} = 10$ TeV.

The analysis shows that fourth family sleptons can be measured with 3σ significance having 10^{-3} for $\lambda'^{\rm eff}$ and 10^{-2} for $|U_{\nu_4\mu}|$ at the LHC (14 TeV) with 100 fb^{-1}. Let us remind that while obtaining these results we take into account only irreducible backgrounds from SM4. However, in principle there could be backgrounds from SM3 and SUSY itself. In order to estimate the SM3 background, one can use the results of Ref. [24], where it was

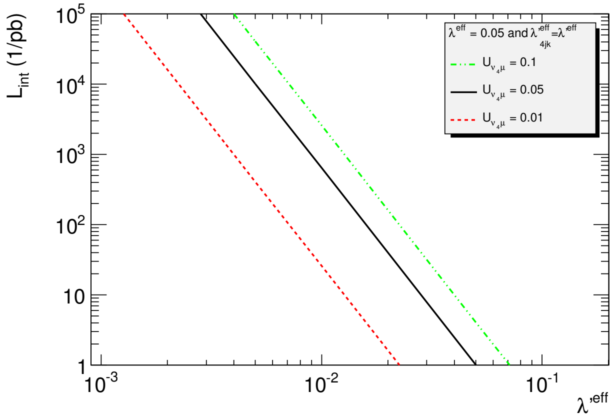

Fig. 4. Integrated luminosity *versus* λ'^{eff} for 3σ significance at $\sqrt{s} = 14$ TeV.

TABLE IV

Achievable value of λ'^{eff} for 3σ observation.

$\lvert U_{\nu_4\mu}\rvert$	$\sqrt{s} = 7$ TeV $L_{\text{int}} = 1$ fb^{-1}	$\sqrt{s} = 10$ TeV $L_{\text{int}} = 100$ fb^{-1}	$\sqrt{s} = 14$ TeV $L_{\text{int}} = 100$ fb^{-1}
0.1	0.017	0.0048	0.0040
0.05	0.010	0.0032	0.0028
0.01	0.0045	0.0015	0.0012

shown that SM3 background gives 4.9 ± 1.6 events for $\sqrt{s} = 14$ TeV and integrated luminosity of 10 fb^{-1}. For comparison, in this case our irreducible background predicts 350 events for $|U_{\nu_4\mu}| = 0.05$. If one impose an invariant mass cut for $\mu^+\mu^+jj$, this will significantly reduce SM3 background whereas irreducible background decreases slightly. Concerning SUSY background, as mentioned in [24], it could be strongly reduced by vetoing all events when there are more than two jets each with $p_{\text{T}} > 50$ GeV. A detailed study of these issues is in progress and will be reported elsewhere.

In conclusion, we have studied the resonance production of fourth family sleptons through R-parity violating couplings at the LHC energies, and it could be the first manifestation of the MSSM4 at the LHC.

This work is partially supported by the Turkish Atomic Energy Authority (TAEK) and State Planning Organization (DPT) under grant DPT 2006K-120470.

REFERENCES

[1] B. Holdom *et al.*, *PMC Phys.* **A3**, 4 (2009).
[2] M. Sahin, S. Sultansoy, S. Turkoz, *Phys. Rev.* **D83**, 054022 (2011).
[3] M. Maltoni *et al.*, *Phys. Lett.* **B476**, 107 (2000).
[4] H.J. He, N. Polonsky, S. Su, *Phys. Rev.* **D64**, 053004 (2001).
[5] G. Kribs *et al.*, *Phys. Rev.* **D76**, 075016 (2007).
[6] M. Bobrowski *et al.*, *Phys. Rev.* **D79**, 113006 (2009).
[7] M.S. Chanowitz, *Phys. Rev.* **D79**, 113008 (2009).
[8] A.K. Alok, A. Dighe, D. London, *Phys. Rev.* **D83**, 073008 (2011) [arXiv:1011.2634[hep-ph]].
[9] M.S. Chanowitz, *Phys. Rev.* **D82**, 035018 (2010).
[10] J. Erler, P. Langacker, *Phys. Rev. Lett.* **105**, 031801 (2010).
[11] O. Eberhardt, A. Lenz, J. Rohrwild, *Phys. Rev.* **D82**, 095006 (2010).
[12] O. Cobanoglu *et al.*, *Comput. Phys. Commun.* **182**, 1732 (2011) [http://cpc.cs.qub.ac.uk/summaries/AEIW_v1_0.html].
[13] J. Conway *et al.* [CDF Collaboration], CDF Note 10110.
[14] T. Aaltonen *et al.* [CDF Collaboration], *Phys. Rev. Lett.* **104**, 091801 (2010) [arXiv:0912.1057[hep-ex]].
[15] K. Nakamura *et al.* [Particle Data Group], *J. Phys. G* **37**, 075021 (2010).
[16] M.S. Chanowitz, M.A. Furman, I. Hinchliffe, *Phys. Lett.* **B78**, 285 (1978); *Nucl. Phys.* **B153**, 402 (1979).
[17] M.S. Carena *et al.*, *Nucl. Phys.* **B472**, 55 (1996).
[18] Z. Murdock *et al.*, *Phys. Lett.* **B668**, 303 (2008).
[19] V. Ari *et al.*, *Europhys. Lett.* **94**, 21001 (2011).
[20] R. Barbier *et al.*, *Phys. Rep.* **420**, 1 (2005).
[21] S. Dimopoulos *et al.*, *Phys. Rev.* **D41**, 2099 (1990).
[22] J. Kalinowski *et al.*, *Phys. Lett.* **B414**, 297 (1997).
[23] B. Allanach *et al.*, arXiv:hep-ph/9906224v2.
[24] H. Dreiner, P. Richardson, M. Seymour, *Phys. Rev.* **D63**, 055008 (2001).
[25] M.A. Bernhardt *et al.*, *Phys. Rev.* **D78**, 015016 (2008).
[26] A. Bartl *et al.*, *Z. Phys.* **C76**, 549 (1997).
[27] E. Boos *et al.*, *Nucl. Instrum. Methods* **A534**, 250 (2004) [arXiv:hep-ph/0403113].
[28] J. Pumplin *et al.*, *J. High Energy Phys.* **07**, 012 (2002).
[29] H. Lacker, A. Menzel, *J. High Energy Phys.* **07**, 1 (2010) [arXiv:1003.4532 [hep-ph]].
[30] A.K. Ciftci, R. Ciftci, S. Sultansoy, *Phys. Rev.* **D72**, 053006 (2005).