Dijet resonance from leptophobic \( Z' \) and light baryonic cold dark matter

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In light of the recent CDF report on the excess in the \( Wjj \) channel, we analyze (non)supersymmetric \( U(1)_{B} \times U(1)_{L} \) model, interpreting the dijet peak as a leptophobic \( U(1)_{B} \) gauge boson. If this excess is confirmed, it has an interesting implication for the baryonic cold dark matter (CDM) in the model: there should be light CDM with a few GeV mass, and direct detection cross section at the level of a few \( \times 10^{-2} \) pb.

INTRODUCTION

Recently the CDF Collaboration reported an excess in the \( Wjj \) channel, with a broad peak in the dijet with mass around 120 – 160 GeV [1]. There is no evidence for enhancement in the \( lvjj \) invariant mass spectrum, so that the excess is less likely to be from a single \( s \)-channel resonance in \( q\bar{q} \) annihilation. Also the dijets in the final state are not dominantly \( b \)-flavored. It would be amusing to speculate what would be the underlying physics for this excess. A simple interpretation of this excess would be to assume a new spin-1 particle with mass around 140 GeV.

In order to avoid the strong constraints from Drell-Yan production, this new spin-1 object better be leptophobic, or its leptonic branching ratio should be very small. There appeared a number of papers which discuss this excess in various contexts: [2–14].

Very recently, the D0 Collaboration also reported their analysis on the \( W + jj \) production with similar experimental cuts to the CDF’s ones [15]. Unlike the CDF results, the D0 Collaboration did not observe any excess on the dijet. However the previous results by the CDF Collaboration are consistent with the analysis with larger data sample of an integrated luminosity of 7.3 fb\(^{-1}\) at the CDF [16]. Up to now two analyses are in conflict with each other and we could not exclude the possibility that both results are statistical fluctuation. Eventually this issue should be settled down by more data analysis at the Tevatron and the LHC.

In this Letter, we consider leptophobic \( Z' \equiv Z_{B} \), associated with gauged \( U(1)_{B} \), based on our recent model [17]. A nonsupersymmetric anomaly-free \( U(1)_{B} \times U(1)_{L} \) model was constructed in Ref. [18], and the model was extended to supersymmetric one by two of the present authors [17]. (For earlier studies on gauged \( U(1)_{B} \) model, we refer to Refs. [19, 20] and references therein.) The supersymmetric (SUSY) version [17] has both baryonic and leptonic cold dark matter (CDM), in addition to the lightest neutralino CDM, thereby the dark matter sector having very rich structure. In these models, the baryonic gauge boson \( Z_{B} \) has a universal coupling to the SM quarks, and three times larger to the new mirror quarks which are introduced to cancel anomalies. This model has a natural color-singlet baryonic CDM with \( U(1)_{B} \) charge twice larger than the SM quarks. Therefore \( Z_{B} \) can decay into a pair of baryonic CDM’s, if the CDM is lighter than half the \( Z_{B} \) mass \( M_{Z_{B}}/2 \). The new mirror quarks could have constraints from search for the 4th generation fermions. The masses of exotic quarks should be more than \( \sim 300 \) GeV [21], which requires very large Yukawa couplings leading to Landau poles at a low scale.

We interpret the excess reported by the CDF Collaboration in the \( lvjj \) channel as \( p\bar{p} \rightarrow WZ_{B} \rightarrow (lv)(jj) \). Then the CDF data provide informations on \( M_{Z_{B}} \) and the \( U(1)_{B} \) gauge coupling \( g_{B}(\equiv \sqrt{4\pi\alpha_{B}}) \). These informations can be used to study the thermal relic density and the direct detection cross section of baryonic CDM in gauged \( U(1)_{B} \times U(1)_{L} \) model, as well as other collider signatures such as \( \gamma Z_{B}, ZZ_{B}, Z_{B}Z_{B} \). We find that the fermionic CDM in supersymmetric \( U(1)_{B} \times U(1)_{L} \) model can be as light as \( \sim 5 \) GeV, with \( \sigma_{SI} \sim (a \ few) \times 10^{-2} \) pb, which is somewhat larger than the CoGeNT [22] and DAMA [23] signal region.

GAUGED \( U(1)_{B} \times U(1)_{L} \) MODEL

It is well known that \( U(1)_{B} \) is anomalous within the standard model (SM), and one has to introduce new matter fields in order to cancel all the gauge anomalies when we introduce \( U(1)_{B} \) gauge boson which is leptophobic. Recently a simple model was proposed where one family of mirror fermions with baryon number \( Q_{B} = 1 \) were introduced for this purpose. Then another new complex scalar \( X_{B} \) with \( Q_{B} = 2/3 \) was introduced in order to make the heavy mirror fermions decay through the following Yukawa interactions,

\[
L_{Y} = -\lambda_{Q_{i}}X_{B}\overline{Q'_{i}}Q_{i} - \lambda_{D_{i}}X_{B}\overline{D'_{i}}D_{i} - \lambda_{U_{i}}X_{B}\overline{U_{i}}U_{i} + h.c.,
\]

(1)

where \( Q' \), \( D' \), and \( U' \) are the extra mirror quarks required for the anomaly-free conditions and \( \lambda_{i}'s \) are the corresponding Yukawa couplings. This new scalar \( X_{B} \) carrying baryon charge becomes stable due to accidental symmetry, and becomes a good candidate for baryonic CDM of the universe [18]. In the supersymmetric \( U(1)_{B} \times U(1)_{L} \) model, new chiral superfields \( X_{L} \) and \( X'_{L} \) were introduced, lighter of which (either bosonic or
fermionic) can make leptonic CDM [17]. Also the superpartner of $X_B$, Dirac fermion $\tilde{X}_B$, can be another candidate for baryonic CDM. In addition, SUSY $U(1)_B \times U(1)_L$ model has ordinary lightest neutralino as a possible candidate for CDM. Therefore SUSY $U(1)_B \times U(1)_L$ model has a rich structure in dark matter sector. In this Letter, we concentrate on $U(1)_B$ part only, so we will drop $U(1)_L$ model from now on.

If we consider the broad peak in dijet invariant mass reported by the CDF Collaboration as a leptophobic $Z_B$ decaying to $q\bar{q}$ and the bound on $g_B$ from the $pp \rightarrow jj$ process in the UA2 experiments [24, 25], we have important piece of informations on our model: namely $g_B \sim 0.8$ and $M_{Z_B} \sim 140$ GeV [3]. Then we can study more phenomenology of gauged $U(1)_B$ model, both supersymmetric and nonsupersymmetric ones. In particular, the cold dark matter sector can be constrained from the informations on $g_B$ and $M_{Z_B}$ from the CDF data, thermal relic density, and the upper bounds on the direct detection rates.

The complete $U(1)_B \times U(1)_L$ model has the mirror fermions and their superpartners, and they can also affect the dark matter physics through Yukawa couplings. In this Letter, we assume the Yukawa couplings involving mirror particles are very small in order to reduce the number of unknown parameters and simplify the analysis. Then $U(1)_B$ gauge interaction is the only new relevant one, and the mirror fermions do not affect significantly the CDM physics we describe here. Including Yukawa couplings to the mirror particles will be another important subject for further study.

CDF DATA ON $W + jj$

We assume that the CDF data on $W + jj$ are due to the $WZ_B$ boson production with $M_{Z_B} \sim 140$ GeV and $g_B \sim 0.8$. Then, the $Z_B$ could be identified in other diboson channels like the $ZZ_B$, $\gamma Z_B$ and $Z_B Z_B$ production processes if the SM backgrounds can be controlled [7]. Up to the now, there is no significant excess in the $Z + jj$ events so far [1], and it remains to be seen what happens in this channel in the forthcoming analysis from the Tevatron and the LHC.

In Fig. 1 (a) and (b), we show the cross sections for the $WZ_B$, $ZZ_B$, $\gamma Z_B$ and $Z_B Z_B$ productions at the Tevatron with the center-of-momentum energy $\sqrt{s} = 1.96$ TeV and at the LHC with $\sqrt{s} = 7$ TeV, respectively, as functions of the $Z_B$ mass $M_{Z_B}$ with $g_B = 0.8$ imposing the UA2 bound [24, 25]. For the $\gamma Z_B$ production, we impose the photon transverse-momentum cut $p_T^\gamma > 30$ GeV and the photon pseudorapidity cut $|\eta^\gamma| < 1.1$, which are consistent with the experiments at the Tevatron [26]. The cross sections for other $g_B$ values can be easily scaled by $(g_B/0.8)^2$ for the $WZ_B$, $ZZ_B$ and $\gamma Z_B$ channels and by $(g_B/0.8)^2$ for the $Z_B Z_B$ channel, respectively. For $M_{Z_B} = 140$ GeV and $g_B = 0.8$, we find that $\sigma(WZ_B) \sim 2.2$ pb at the Tevatron, which is about half the cross section for the $W + jj$ excess at CDF with an assumption on the hypothesized narrow Gaussian contribution. In order to fit the cross section to the CDF excess, we can require a larger coupling with smaller $Z_B$ mass. Or the current CDF data could be an upper fluctuation. This issue could be resolved in the near future with more data accumulated and analyzed. In the other diboson productions, we find that $\sigma(ZZ_B) = 0.90$ pb, $\sigma(Z_B Z_B) = 0.33$ pb and $\sigma(\gamma Z_B) = 1.8$ pb at the Tevatron for $M_{Z_B} = 140$ GeV and $g_B = 0.8$, respectively. At the LHC, we expect that $\sigma(WZ_B) = 9.4$ pb, $\sigma(ZZ_B) = 3.3$ pb, $\sigma(Z_B Z_B) = 1.3$ pb and $\sigma(\gamma Z_B) = 3.3$ pb, respectively. In order to make definite conclusion about the possibility to find the $Z_B$ boson in the diboson channels at the Tevatron or at the LHC, we need more thorough study on the signal-to-background ratio with the detector simulation, which is out of scope of this work.

BARYONIC COLD DARK MATTER

The CDF data on $W + jj$ events can be accommodated with leptophobic $Z_B$ gauge boson, if $g_B \sim 0.8$ and $M_{Z_B} \sim 140$ GeV. If we take this value in the gauged $U(1)_B \times U(1)_L$ model, one can constrain the dark matter sector more or less from the WMAP measurement of thermal relic density of CDM and upper bounds from direct detection experiments.

For nonsupersymmetric $U(1)_B$ model, a baryonic complex scalar $X_B$ can make a good CDM candidate. Neglecting its Yukawa couplings to the mirror fermions $Q', u$ and $d'$, we can calculate thermal relic density from $X_B \chi_B \rightarrow Z_B \rightarrow SM$ particles. It turns out that thermal relic density of bosonic $X_B$ is too large, unless $m_{X_B} \simeq M_{Z_B}/2 \sim 70$ GeV (the $s$-channel resonance annihilation into the SM quarks). In order to achieve small enough relic density consistent with the WMAP data without using the $s$-channel resonance annihilation, other channels involving mirror fermions and their superpartners need to be considered. Also, if the CDF dijet excess becomes less prominent in the future and $g_B$ becomes smaller, we have to invoke Yukawa couplings to mirror fermions in order to get the correct thermal relic density.

For supersymmetric case, Dirac fermion $\tilde{X}_B$ and its antiparticle carrying $Q_B = \pm 2/3$ can be good CDM candidates [17], because the annihilation cross section has $S$-wave contribution. In Fig. 2, we show the contour plots for thermal relic density $(\Omega h^2)$ in the $(m_{\tilde{X}_B}, g_B)$ plane. There remains a small corner of parameter space with $m_{\tilde{X}_B} \sim 4 - 6$ GeV and $g_B < 0.8$ (the red line) which could be safe against the UA2 bound. In this region of parameter space, the direct detection cross section is around $\sigma_{SI} \sim 0.01 - 0.05$ pb, which is slightly above the...
FIG. 1: Production cross sections for $W Z_B$, $Z_B Z_B$, $Z B Z_B$ and $\gamma Z_B$ (a) at the Tevatron ($\sqrt{s} = 1.96$ TeV) and (b) at the LHC ($\sqrt{s} = 7$ TeV) as functions of $Z_B$ mass for $g_B = 0.8$. For the $\gamma Z_B$ mode, we apply the photon transverse-momentum and pseudorapidity cuts, $p_T^{\gamma} > 30$ GeV and $|\eta^{\gamma}| < 1.1$.

FIG. 2: Relic density of baryonic CDM, $\tilde{X}_B$. The gray region corresponds to $\Omega_{\tilde{X}_B} h^2 \geq 0.12$ and each dashed line is for $\Omega_{\tilde{X}_B} h^2 = 0.10, 0.08, 0.06, 0.04, 0.02$ from bottom to top. The yellow region is excluded by XENON10 (90 % C.L.) and the blue is CDMS (90 % C.L.) [27]. The red line is the UA2 bound on $g_B \leq 0.8$.

FURTHER COLLIDER SIGNATURES

For non-SUSY $U(1)_B$ model, the bosonic baryonic CDM $X_B$ has mass close to $M_{Z_B}/2$ if we fix $M_{Z_B} \sim 140$ GeV and $g_B \sim 0.8$ in order to explain the CDF $W+jj$ excess. For these parameter values, the invisible decay width of $Z_B \rightarrow \tilde{X}_B \tilde{X}_B$ will be negligible. If $g_B$ turns out smaller or if one would like to use other channels rather than the $s$-channel annihilation of the dark matter pair through $Z_B$, it would be possible to have light bosonic $X_B$ without conflict with the direct detection bounds. In this case, the invisible decay $Z_B \rightarrow X_B X_B^\dagger$ could be possible. This would help to study the diboson productions with at least one $Z_B$. However, this possibility depends on parameters other than $M_{Z_B}$ and $g_B$, and we do not consider this case further in this Letter.

For SUSY version, the fermionic baryonic CDM could be light so that the invisible decay mode can have $B(Z_B \rightarrow \tilde{X}_B \tilde{X}_B) \approx 21\%$. Then high $p_T$ monojet (or single photon) with large missing $E_T$ from $q \bar{q} \rightarrow g Z_B$ (or $\gamma Z_B$) or $q \bar{q}' \rightarrow q(\bar{q})Z_B$ followed by $Z_B \rightarrow \tilde{X}_B \tilde{X}_B$ would make clean signatures of our model. Note that the missing $E_T$ signature from $Z_B \rightarrow \tilde{X}_B \tilde{X}_B$ makes a unique feature of gauged $U(1)_B$ model with light baryonic cold dark matter. The $q \bar{q}' \rightarrow W Z_B \rightarrow (l\nu)(\tilde{X}_B \tilde{X}_B)$ channel could lead to a single high $p_T$ charged lepton plus missing $E_T$, which however would suffer severe background at hadron colliders. In Fig. 3, we depict the distribution of the number of the jet in the monojet production.

CRESST bound, $\sigma_{SI} \lesssim O(10^{-3})\text{pb}$ [27]. There are several CDM candidates in our model, so that $\tilde{X}_B$ could be subdominant. If $m_{\tilde{X}_B}$ is heavier or the Yukawa contribution is large enough to reduce the relic density of $\tilde{X}_B$, the upper bound of $\sigma_{SI}$ could be enhanced by the factor $(0.11/\Omega_{\tilde{X}_B} h^2)$. However, we may face the stronger bound from collider experiments in the scenario with light CDM, as we discuss in the below.
at the Tevatron and LHC as a function of the transverse energy of the jet for \(g_B = 0.8\) and the dark matter mass \(m_X = 5\) GeV with the integrated luminosity of \(1\) fb\(^{-1}\).

If the \(M_{Z_B}\) mass is around 140 GeV, then the two jets + missing energy signals through \(e^+e^- \rightarrow q\bar{q} \rightarrow q\bar{q} + Z_B\) with the subsequent decay \(Z_B \rightarrow X_B\bar{X}_B\) at LEP II may give useful constraints on \(M_{Z_B}\) and \(g_B\). We find that \(\sigma(q\bar{q}Z_B) \times Br(Z_B)_{\text{invisible}} \simeq 2 \times 10^{-5}\) pb for \(M_{Z_B} = 140\) GeV and \(g_B = 0.8\), which is out of reach at LEP II. It could be studied at future linear colliders.

The mass of baryonic scalar \(S_B\), whose nonzero VEV breaks \(U(1)_B\) spontaneously, can be as large as a few hundred GeV in non-SUSY case, and it will mix with the SM Higgs boson \(h_{\text{SM}}\). \(S_B \rightarrow Z_BZ_B \rightarrow 4q\bar{s}\) or \(S_B \rightarrow h_{\text{SM}} \rightarrow bb, t\bar{t}, WW, ZZ\) depending on \(S_B\) mass. Production of \(S_B\) is by \(S_B\)–strahlung (similarly to the Higgs-strahlung), and the production rate will be smaller than the SM Higgs if \(S_B\) mass is heavier than \(h_{\text{SM}}\).

In SUSY case, there is a tree-level upper bound on the \(S_B\) mass, \(m_{S_B} \leq M_{Z_B}\), similarly to the bound on the neutral Higgs mass \(m_h \leq M_Z\) at tree level. This upper bound however can be raised somewhat by loop effects involving squarks (especially scalar mirror quarks). Therefore \(S_B\) cannot be too heavy and \(S_B \rightarrow Z_BZ_B\) is likely to be kinematically forbidden. Its main decay will be into the SM fermions or weak gauge bosons through \(S_B - h_{\text{SM}}\) mixing induced by the one loop involving squarks. Again the final states are \(Z_B S_B \rightarrow (q\bar{q})(b\bar{b}, t\bar{t}, WW, ZZ)\). The strategy for searching \(S_B\) would be similar to Higgs boson search, but it is probably more difficult if \(Z_B \rightarrow q\bar{q}\).

On the other hand, our model has a light CDM, and \(Z_B\) has a moderate invisible branching ratio \(\sim 21\%\). Therefore this could be used to suppress the QCD background.

**CONCLUSIONS**

If we assume that the peak around \(m_{jj} \sim 140\) GeV reported by CDF in the \(lvjj\) channel is due to leptophobic \(Z_B\), the reported cross section can be reproduced if \(g_B \sim 0.8\). Within anomaly-free (non)supersymmetric \(U(1)_B \times U(1)_L\) model with baryonic and leptonic CDM candidates, we studied the implications on dark matter physics and other possible collider signatures. In particular, SUSY \(U(1)_B\) model predicts a light baryonic Dirac fermion CDM. Its direct detection cross section is predicted to be in the range of \(0.01 - 0.05\) pb, which is somewhat larger than the DAMA or CoGeNT region. The CRESST experiment is subtle because it touches this region. If the CDF dijet excess is confirmed with its present value, it is inevitable to consider heavier CDM or sizable Yukawa contributions. Then the relic density of our light CDM becomes subdominant and the WMAP data could be explained by the other CDMs. It would also be very important to study the collider signatures of our scenario. In fact, the monojet signals at Tevatron and LHC will strongly constrain our scenario.

On the other hand, if this excess in dijet becomes less prominent in the future, \(WZ_B\) or its relative modes will constrain the \(U(1)_B\) sector in terms of \(M_{Z_B}\) and \(g_B\), and the implication for baryonic CDM will be modified. If the \(g_B\) should be weaker than the value we adopted in this Letter, annihilation cross section of baryonic CDM studied in this Letter may not be large enough, and we may have to include other contributions such as mirror fermions or their superpartners, as well as scalar exchanges. In this case, we have a number of additional parameters in the Yukawa couplings involving mirror fermions, and mixings among scalar bosons, and phenomenological analysis of the model would be very involved. It would be a subject in the future when the situation about the CDF dijet excess is clarified by other experiments. And our discussions are complete within our model when the CDF dijet excess survives.

**Note Added**

While we are finalizing this Letter, there appeared a couple of papers [30, 31]. In Ref. [31], the authors consider a similar model to this work, concentrating on light baryonic scalar dark matter \(X_B\). Their results on the direct detection of the scalar dark matter are similar to ours, and \(\sigma_{SI}\) seems to be small enough to evade...
the bound from CRESST because of the small $g_B \sim 0.3$. However in this case the contribution to the $Wjj$ production is too small ($\sim 0.3$ pb). We emphasize that the coupling used in Ref. [31] for explanation of CoGeNT/DAMA data cannot explain the CDF $Wjj$ excess. In the present work we also discussed the model with the fermionic dark matter and presented more careful discussion on the collider signature including the monojet + missing energy signals at the LHC. The authors of Ref. [32] discussed the CDF dijet anomaly within a $U(1)_X$ Stueckelberg extension of the SM. Effectively their model is almost same as our model except the coupling, baryonic charge and dark matter contents.

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[1] T. Aaltonen et al. [CDF Collaboration], Phys. Rev. Lett. 106, 171801 (2011) [arXiv:1104.0699 [hep-ex]].
[2] M. R. Buckley, D. Hooper, J. Kopp and E. Neil, Phys. Rev. D 83, 115013 (2011) [arXiv:1103.6035 [hep-ph]].
[3] F. Yu, Phys. Rev. D 83, 094028 (2011) [arXiv:1104.0243 [hep-ph]].
[4] E. J. Eichten, K. Lane and A. Martin, Phys. Rev. Lett. 106, 251803 (2011) [arXiv:1104.0976 [hep-ph]].
[5] C. Kilic and S. Thomas, Phys. Rev. D 84, 055012 (2011) [arXiv:1104.1002 [hep-ph]].
[6] X. P. Wang, Y. K. Wang, B. Xiao, J. Xu and S. h. Zhu, Phys. Rev. D 83, 117701 (2011) [arXiv:1104.1161 [hep-ph]].
[7] K. Cheung and J. Song, Phys. Rev. Lett. 106, 211803 (2011) [arXiv:1104.1375 [hep-ph]].
[8] J. A. Aguilar-Saavedra and M. Perez-Victoria, Phys. Lett. B 701, 93 (2011) [arXiv:1104.1385 [hep-ph]].
[9] X. G. He and B. Q. Ma, arXiv:1104.1894 [hep-ph].
[10] X. P. Wang, Y. K. Wang, B. Xiao, J. Xu and S. h. Zhu, Phys. Rev. D 83, 115010 (2011) [arXiv:1104.1917 [hep-ph]].
[11] R. Sato, S. Shirai and K. Yonekura, Phys. Lett. B 700, 122 (2011) [arXiv:1104.2014 [hep-ph]].
[12] A. E. Nelson, T. Okui and T. S. Roy, arXiv:1104.2030 [hep-ph].
[13] B. A. Dobrescu and G. Z. Krnjaic, arXiv:1104.2893 [hep-ph].
[14] Z. Sullivan and A. Menon, Phys. Rev. D 83, 091504 (2011) [arXiv:1104.3790 [hep-ph]].
[15] V. M. Abazov et al. [D0 Collaboration], Phys. Rev. Lett. 107, 011804 (2011) [arXiv:1106.1921 [hep-ex]].
[16] http://www-cdf.fnal.gov/physics/ewk/2011/wjj/7_3.html.
[17] P. Ko and Y. Omura, Phys. Lett. B 701, 363 (2011) [arXiv:1012.4679 [hep-ph]].
[18] P. Fileviez Perez and M. B. Wise, Phys. Rev. D 82, 011901 (2010) [Erratum-ibid. D 82, 079901 (2010) [arXiv:1002.1754 [hep-ph]] ; T. R. Dulaney, P. Fileviez Perez and M. B. Wise, Phys. Rev. D 83, 023520 (2011) [arXiv:1005.0617 [hep-ph]].
[19] M. L. Mangano, G. Altarelli, N. Di Bartolomeo, F. Feruglio and R. Gatto, arXiv:hep-ph/9610469.
[20] M. Drees, O. J. P. Eboli and J. K. Mizukoshi, Phys. Lett. B 447, 116 (1999) [arXiv:hep-ph/9811343].
[21] J. Alitti et al., Z. Phys. C49, 17-28 (1991).
[22] J. Alitti et al., Nucl. Phys. B400, 3-24 (1993).
[23] CDF Collaboration, CDF note 10355 (2010).
[24] J. Alitti et al. [UA2 Collaboration ], Z. Phys. C49, 17-28 (1991).
[25] J. Alitti et al. [UA2 Collaboration ], Z. Phys. C49, 17-28 (1991).
[26] CDF Collaboration, CDF note 10355 (2010).
[27] C. Savage, G. Gelmini, P. Gondolo and K. Freese, JCAP 0904, 010 (2009) [arXiv:0808.3607 [astro-ph]].
[28] F. Maltoni and T. Stelzer, JHEP 0302, 027 (2003) [arXiv:hep-ph/0208156].
[29] R. Bernabei et al., Eur. Phys. J. C 67, 39 (2010) [arXiv:1002.1028 [astro-ph.GA]].
[30] J. Alitti et al. [UA2 Collaboration ], Z. Phys. C49, 17-28 (1991).
[31] J. Alitti et al. [UA2 Collaboration ], Z. Phys. C49, 17-28 (1991).
[32] X. G. He and B. Q. Ma, arXiv:1104.1894 [hep-ph].