The relevance of polarized bZ production at LHC

M. Beccaria [a], N. Orlando [a,*], G. Panizzo [b], F.M. Renard [c], C. Verzegnassi [b]

[a] *Dipartimento di Matematica e Fisica "Ennio De Giorgi", Università del Salento and INFN, Sezione di Lecce, Italy*
[b] *Dipartimento di Fisica, Università di Trieste and INFN Sezione di Trieste, Italy*
[c] *Laboratoire Univers et Particules de Montpellier, UMR 5299, Université Montpellier II, Place Eugène Bataillon, CC072, F-34095 Montpellier Cedex 5, France*

ARTICLE INFO

ABSTRACT

We consider the Z polarization asymmetry $A_Z = (\sigma(Z_R) - \sigma(Z_L))/(\sigma(Z_R) + \sigma(Z_L))$ in the process of associated bZ production at the LHC. We show that in the Standard Model (SM) this quantity is essentially given by its Born approximation, remaining almost unaffected by QCD scales and parton distribution functions variations as well as by electroweak corrections. The theoretical quantity that appears in A_Z is the same that provides the LEP1 $Z \to b\bar{b}$ forward–backward asymmetry, the only measured observable still in some contradiction with the SM prediction. In this sense, A_Z would provide the possibility of an independent verification of the possible SM discrepancy, which could reach, if consistency with LEP1 measurements is imposed, values of the relative ten percent size.

© 2012 Published by Elsevier B.V. Open access under CC BY license.

1. Introduction

The Standard Model is confirmed up to per-mille precision by collider data [1]; moreover, very recently, Higgs boson signals [2,3] seems to rise in a narrow mass window around 125 GeV, consistently with predictions based on global fits to electroweak data [1].

The question arises of whether all the theoretical SM predictions have been confirmed by the related experimental measurements. The answer to this fundamental question is nowadays that at least one experimental result still appears in some sizable contradiction (roughly, at 3σ level) with the SM, i.e. the measurement of the forward–backward asymmetry of $b\bar{b}$ production at the Z peak [4], A^b_{FB}.

In fact, a number of models have been proposed that might cure the discrepancy (see [5–7] and references therein). In particular, a slightly embarrassing fact for supersymmetric models is the difficulty that the simplest MSSM version would face to eliminate the discrepancy, as exhaustively discussed in Ref. [8].

The aim of this Letter is that of showing that a specific observable can be defined at LHC that would provide essentially a re-measurement of the same LEP1 A^b_{FB} quantity, in spite of the total difference of the produced final state. This quantity is defined in the production of a bZ pair as the ratio of the difference of production cross sections with different (left, right) Z polarizations (Z_L, Z_R) divided by the corresponding sum.

We shall first show in Section 2 that this quantity is straightforwardly proportional to A^b_{FB} at the simplest partonic Born level,

providing a possible ten percent deviation from its SM prediction if the relevant parameters are chosen to reproduce the experimental LEP1 result for the asymmetry. In Section 3 we shall derive the special property of our considered quantity, i.e. the fact that it remains unaffected, at realistic levels, by variations of the strong scales and of the adopted parton distribution functions (pdfs) as well as by electroweak corrections. This would represent, in our opinion, a strong motivation to perform an accurate measurement of the asymmetry at LHC in a not far future, as qualitatively discussed in the final conclusions.

2. The Z polarization asymmetry at tree-level

We shall consider the process of associated production of a Z boson and a single b-quark, represented in Fig. 1, defined at parton level by subprocesses $bg \to bZ$ involving two Born diagrams with bottom quark exchange in the s-channel and in the u-channel.

This process has been calculated at next-to-leading order in QCD in a previous paper [9] where the theoretical uncertainties assessment on cross section calculation have been addressed as well.

For our purposes we need, though, a derivation of the expressions of the polarized cross sections. This requires a number of formulae that we shall briefly show in what follows, starting from the calculation of the various quantities performed at the Born level.

The interaction vertices involved in the diagrams of Fig. 1 are defined as follows:

$$gqq: \quad ig_s \not{\epsilon}\left(\frac{\lambda^l}{2}\right), \qquad Zbb: \quad -ie\not{\epsilon}\left(g^L_{Zb}P_L + g^R_{Zb}P_R\right). \tag{1}$$
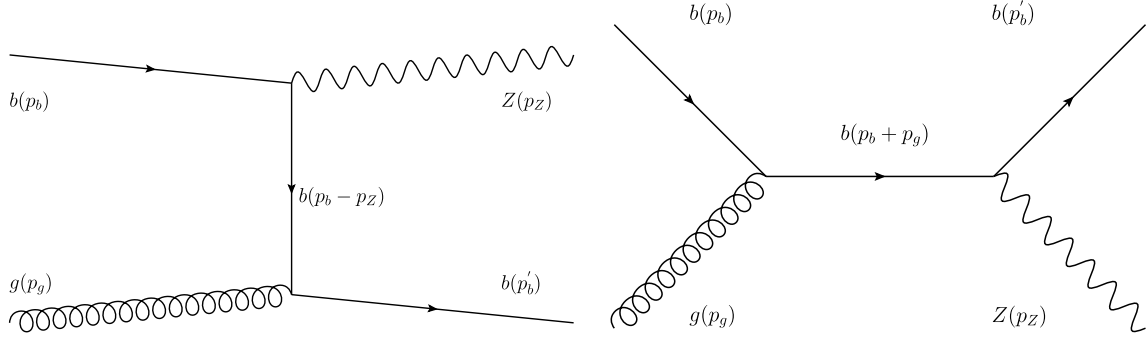
Fig. 1. Born diagrams for associated production of a Z boson and a single b-quark.

Therefore, the Born invariant amplitude is given by

$$A^{Born}(gb \to Zb) = eg_s\left(\frac{\lambda^l}{2}\right)\bar{u}(b')\left(\slashed{\epsilon}\left(g_{Zb}^L P_L + g_{Zb}^R P_R\right)\frac{(\slashed{q}+m_b)\slashed{e}}{s-m_b^2}\right.$$
$$\left. + \frac{\slashed{e}(\slashed{q}'+m_b)\slashed{\epsilon}}{u-m_b^2}\left(g_{Zb}^L P_L + g_{Zb}^R P_R\right)\right)u(b), \quad (2)$$

where e, λ^l are the gluon polarization vector and color matrix, ϵ is the Z polarization vector and $q = p_b + p_g = p_Z + p'_b$, $s = q^2$, $q' = p'_b - p_g = p_b - p_Z$, $u = q'^2$ with the kinematical decompositions

$$p_b = (E_b; 0, 0, p), \qquad p'_b = (E'_b; p'\sin\theta, 0, p'\cos\theta), \quad (3)$$

$$p_g = (p; 0, 0, -p), \qquad p_Z = (E_Z; -p'\sin\theta, 0, -p'\cos\theta), \quad (4)$$

$$e(g) = \left(0; \frac{\mu}{\sqrt{2}}, -\frac{i}{\sqrt{2}}, 0\right), \quad (5)$$

$$\epsilon(Z_T) = \left(0; \frac{\mu'\cos\theta}{\sqrt{2}}, \frac{i}{\sqrt{2}}, \frac{-\mu'\sin\theta}{\sqrt{2}}\right), \quad (5)$$

$$\epsilon(Z_0) = \left(-\frac{p'}{M_Z}; \frac{E_Z}{M_Z}\sin\theta, 0, \frac{E_Z}{M_Z}\cos\theta\right). \quad (6)$$

The decomposition of Dirac spinors and polarization vectors leads to 24 helicity amplitudes denoted as $F_{\lambda\mu\tau\mu'}$ with $\lambda = \pm\frac{1}{2}$, $\mu = \pm 1$, $\tau \pm \frac{1}{2}$, $\mu' = \pm 1, 0$ referring to b, g, b', Z respectively.

However, in order to explore quickly by hand the properties of this subprocess we can neglect m_b/M_Z and $m_b/\sqrt{s}$ terms and consider only the following eight non-vanishing amplitudes: six transverse ones

$$F_{++++} = \frac{2eg_s g_{Zb}^R\sqrt{\beta'}}{\cos\frac{\theta}{2}}, \qquad F_{----} = \frac{2eg_s g_{Zb}^L\sqrt{\beta'}}{\cos\frac{\theta}{2}}, \quad (7)$$

$$F_{+-+-} = 2eg_s g_{Zb}^R\frac{\cos\frac{\theta}{2}}{\sqrt{\beta'}}, \qquad F_{-+-+} = 2eg_s g_{Zb}^L\frac{\cos\frac{\theta}{2}}{\sqrt{\beta'}}, \quad (8)$$

$$F_{+-++} = 2eg_s g_{Zb}^R\cos\frac{\theta}{2}\cdot\frac{M_Z^2}{s}\cdot\frac{\tan^2\frac{\theta}{2}}{\sqrt{\beta'}},$$

$$F_{-+--} = 2eg_s g_{Zb}^L\cos\frac{\theta}{2}\cdot\frac{M_Z^2}{s}\cdot\frac{\tan^2\frac{\theta}{2}}{\sqrt{\beta'}}, \quad (9)$$

and two longitudinal ones

$$F_{+-+0} = -2\sqrt{2}eg_s g_{Zb}^R\frac{\sin\frac{\theta}{2}}{\sqrt{\beta'}}\cdot\frac{M_Z}{\sqrt{s}}, \quad (10)$$

$$F_{-+-0} = 2\sqrt{2}eg_s g_{Zb}^L\frac{\sin\frac{\theta}{2}}{\sqrt{\beta'}}\cdot\frac{M_Z}{\sqrt{s}}, \quad (11)$$

having defined

$$\beta' = \frac{2p'}{\sqrt{s}} \simeq 1 - \frac{M_Z^2}{s}. \quad (12)$$

For our analysis it is instructive to consider the Z density matrix

$$\rho^{ij} = \sum_{\lambda\mu\tau} F_{\lambda\mu\tau i}F^*_{\lambda\mu\tau j}. \quad (13)$$

A priori there are nine independent Z density matrix elements. However with the above Born terms and neglecting again the subleading terms in m_b they reduce to only five ones

$$\rho^{++} = 4e^2 g_s^2\left(\frac{g_{Zb}^{R2}}{\cos^2\frac{\theta}{2}}\left(\beta' + \frac{\sin^4\frac{\theta}{2}}{\beta'}\left(\frac{M_Z^2}{s}\right)^2\right)\right.$$
$$\left. + g_{Zb}^{L2}\frac{\cos^2\frac{\theta}{2}}{\beta'}\right), \quad (14)$$

$$\rho^{--} = 4e^2 g_s^2\left(\frac{g_{Zb}^{L2}}{\cos^2\frac{\theta}{2}}\left(\beta' + \frac{\sin^4\frac{\theta}{2}}{\beta'}\left(\frac{M_Z^2}{s}\right)^2\right)\right.$$
$$\left. + g_{Zb}^{R2}\frac{\cos^2\frac{\theta}{2}}{\beta'}\right), \quad (15)$$

$$\rho^{00} = 8e^2 g_s^2\left(g_{Zb}^{R2} + g_{Zb}^{L2}\right)\sin^2\frac{\theta}{2}\left(\frac{M_Z^2}{s\beta'}\right), \quad (16)$$

$$\rho^{+0} = \rho^{0+} = -4e^2 g_s^2 g_{Zb}^{R2}\frac{\sin^3\frac{\theta}{2}}{\cos\frac{\theta}{2}}\left(\frac{M_Z^3\sqrt{2}}{\beta' s\sqrt{s}}\right),$$

$$\rho^{-0} = \rho^{0-} = 4e^2 g_s^2 g_{Zb}^{L2}\frac{\sin^3\frac{\theta}{2}}{\cos\frac{\theta}{2}}\left(\frac{M_Z^3\sqrt{2}}{\beta' s\sqrt{s}}\right). \quad (17)$$

With these powerful but extremely simple mathematical expressions at hand, we can explore some physical observables of the process under consideration that keep informations of the Zb vertex structure. Let's stick for the moment at the partonic level. The first obvious quantity that one can inspect is the subprocess unpolarized angular distribution: with the color sum $\sum_{col}\mathrm{Tr}(\frac{\lambda^l}{2}\frac{\lambda^l}{2}) = 4$, the unpolarized subprocess angular distribution (averaged on gluon and b spins and colors) is given by

$$\frac{d\sigma}{d\cos\theta} = \frac{\beta'}{768\pi s\beta}\sum_{\lambda\mu\tau\mu'}|F_{\lambda\mu\tau\mu'}|^2. \quad (18)$$

One sees that it is proportional to $(\rho^{++} + \rho^{--} + \rho^{00})$ and, summing the above density matrix expressions, solely depends on $(g_{Zb}^R)^2 + (g_{Zb}^L)^2$:

$$\sum_{\lambda\mu\tau\mu'}|F_{\lambda\mu\tau\mu'}|^2 = \left((g_{Zb}^R)^2 + (g_{Zb}^L)^2\right)C_{diff}, \quad (19)$$

with

$$C_{diff} = 4e^2 g_s^2 \beta' \cos^2 \frac{\theta}{2} \left(\frac{1}{\cos^4 \frac{\theta}{2}} + \frac{1}{\beta'^2} + \left(\frac{M_Z^2}{s} \frac{\tan^2 \frac{\theta}{2}}{\beta'} \right)^2 \right.$$
$$\left. + \frac{2M_Z^2}{s\beta'^2} \tan^2 \frac{\theta}{2} \right). \tag{20}$$

In order to separate the g_{Zb}^R and g_{Zb}^L contributions, and to check so their possible anomalous behaviors, one needs to be sensitive to different density matrix combinations than the sum just found in the unpolarized distribution. This can be achieved only keeping track of the final Z polarization. The general procedure of its measurement has been described in [10,11] for Tevatron processes. The Z polarization can be analyzed by looking at Z decay distributions, for example in lepton pairs. It is shown that each density matrix element is associated to a specific θ_l, ϕ_l dependence. The polarized quantities, therein called σ^P and σ^I, respectively proportional to $(\rho^{++} - \rho^{--})$ and to $(\rho^{+0} - \rho^{-0})$ are the only ones in which the combination $(g_{Zb}^R)^2 - (g_{Zb}^L)^2$ appears, as one can check by using the above expressions (14)–(17) of the density matrix elements. They respectively produce lepton angular dependencies of the types $\cos \theta_l$ and $\sin 2\theta_l \cos \phi_l$ as compared to the unpolarized part proportional to $(1 + \cos^2 \theta_l)$. The specific generalization of that analysis to the LHC case is under consideration at the moment.

From this brief discussion, we are naturally led to define the Z boson polarization asymmetry A_Z in bZ production as

$$A_Z \equiv \frac{\sigma(Z_R) - \sigma(Z_L)}{\sigma(Z_R) + \sigma(Z_L)} = \frac{(g_{Zb}^R)^2 - (g_{Zb}^L)^2}{(g_{Zb}^R)^2 + (g_{Zb}^L)^2} C_{pol}, \tag{21}$$

where C_{pol} is given as a convolution involving the bottom quark (b and $\bar{b}$) and gluon (g) pdfs:

$$C_{pol} = \frac{(bg + \bar{b}g) \otimes \left(\frac{1}{\cos^4 \frac{\theta}{2}} - \frac{1}{\beta'^2} + \left(\frac{M_Z^2}{s} \cdot \frac{\tan^2 \frac{\theta}{2}}{\beta'} \right)^2 \right)}{(bg + \bar{b}g) \otimes \left(\frac{1}{\cos^4 \frac{\theta}{2}} + \frac{1}{\beta'^2} + \left(\frac{M_Z^2}{s} \cdot \frac{\tan^2 \frac{\theta}{2}}{\beta'} \right)^2 \right)}. \tag{22}$$

As one sees, Eq. (21) is simply proportional to the asymmetry parameter $\mathcal{A}_b$:

$$\mathcal{A}_b = \frac{(g_{Zb}^L)^2 - (g_{Zb}^R)^2}{(g_{Zb}^L)^2 + (g_{Zb}^R)^2}, \tag{23}$$

the same quantity that is measured in the forward–backward $b\bar{b}$ asymmetry in e^+e^- annihilation at the Z pole [4]:

$$A_{FB}^b = \frac{3}{4} \mathcal{A}_e \mathcal{A}_b, \quad \text{where } \mathcal{A}_e = \frac{(g_{Ze}^L)^2 - (g_{Ze}^R)^2}{(g_{Ze}^L)^2 + (g_{Ze}^R)^2}. \tag{24}$$

In order to exhibit the relation between A_Z and $\mathcal{A}_b$ without any approximations, we have implemented a numerical calculation of the full helicity amplitude retaining the bottom mass effects; in our calculation we require a final state b-quark with $p_T > 25$ GeV and rapidity $|y| < 2$ to reproduce the typical experimental phase space cuts. The gluon and bottom quark in the initial state are folded with CTEQ6 [12] parton distribution functions. The polarization asymmetry A_Z in bZ production at LHC with $\sqrt{s} = 7$ TeV is shown in Fig. 2 as function of $\mathcal{A}_b$ along with the SM prediction [4] (red band) and the measured LEP1 value [4] (green band).

As can be argued by inspection of Fig. 2, the A_Z measurement at the LHC could be sufficiently sensitive to $\mathcal{A}_b$ in order to discriminate between LEP1 measurement and SM prediction provided that a $\sim 8\%$ precision will be achieved on A_Z measurement at LHC. To better realize if such required precision could be reached in the
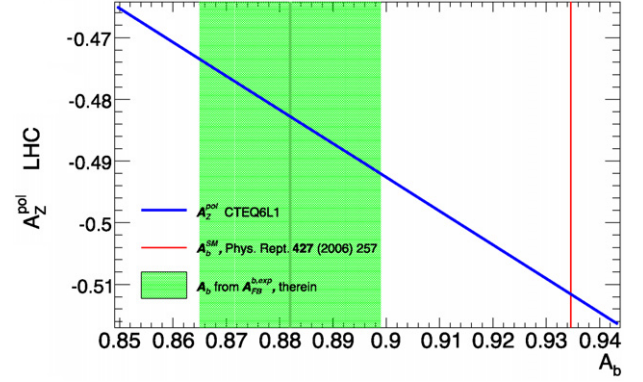

Fig. 2. Polarization asymmetry A_Z in bZ production at LHC with $\sqrt{s} = 7$ TeV. The green band displays the $\pm 1\sigma$ bounds [4] for the measured asymmetry parameter $\mathcal{A}_b$ while the SM prediction [4] is shown in red. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

A_Z calculation we need now to assess the effect of its dominant theoretical uncertainties.

3. Impact of the scale/pdf choices and radiative corrections

The previous discussion has been performed at the simplest Born level. The next relevant question is that of verifying whether the expression of A_Z remains essentially identical when possible sources of theoretical uncertainties or NLO corrections are considered.

We have proceeded in the following way. First, we have taken into account possible effects of either strong scales or pdf variations; as shown in Ref. [9], these variations generate a sensible effect, of the almost ten percent relative size, in the total cross section. Next, we have considered the possible contribution of NLO electroweak radiative corrections; their effect on the total and angular cross section have been determined in a recent paper [13] and found to be possibly relevant.

The dependence of A_Z on factorization and renormalization scales, μ_F and μ_R respectively, is evaluated at LO by varying their values simultaneously by a conservative factor three with respect to the central value. A_Z is shown in Fig. 3 as function of $\mathcal{A}_b$ for $\mu_F = \mu_R = k\mu_0$ with $\mu_0 = M_Z$ and $k = 1, 3$ and $1/3$; the inset displays the ratio between the A_Z calculations performed with varied scales, corresponding to $k = 3$ and $k = 1/3$, and the central predictions. As can be observed from Fig. 3 effect of scales variation on A_Z is below 1%. However is worth noting that the total cross section dependence on μ_R could be strongly reduced by using the "Principle of Maximum Conformality" scale-setting (see for instance [14]).

The asymmetry dependence on the pdf is examined performing the numerical calculation with different pdf sets. In Fig. 4, we present A_Z as function of $\mathcal{A}_b$ for three different LO pdf sets: CTEQ [12]; MSTW2008 [15] and NNPDF [16]; the inset in Fig. 4 show the ratio between the asymmetry A_Z calculated with MSTW2008 and NNPDF pdf sets with respect to the central prediction obtained by the CTEQ set.

As one sees, the dependence on the pdf set is below 2% while the total cross section can be affected by large variations of order 7% [17].

The NLO EW effects on A_Z deserve a rather different discussion. In principle, these effects would not introduce any appreciable theoretical uncertainty, since the values of the involved parameters are all known with great accuracy. The goal of their calculation would simply be that of offering a more complete theoretical prediction for A_Z. In fact, it is well known that electroweak
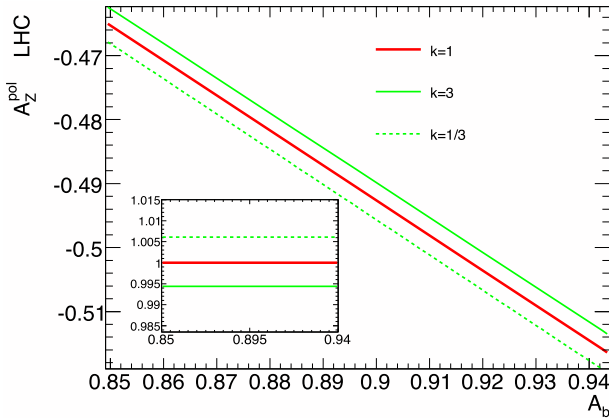
Fig. 3. Polarization asymmetry A_Z as function of $\mathcal{A}_b$ for three different choice of factorization and renormalization scales, respectively μ_F and μ_R, $\mu_F = \mu_R = k\mu_0$ with $\mu_0 = M_Z$ and $k = 1, 3$ and $1/3$.

Fig. 4. Polarization asymmetry A_Z as function of $\mathcal{A}_b$ for three different choice pdf set as described in the text.
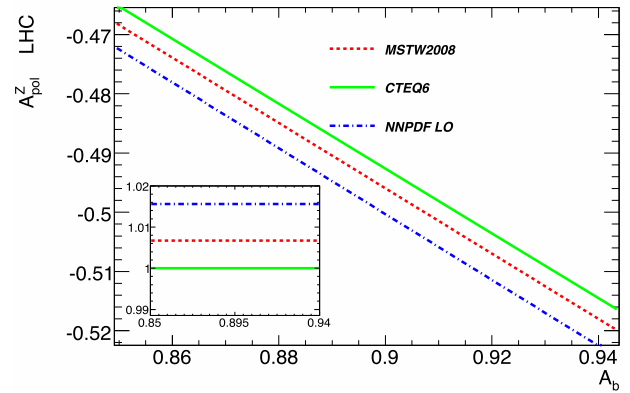
corrections can have sizable effects on processes involving W or Z production at LHC. We have observed it in associated top and W production [18,19] and recent papers on $W + $ jet or $Z + $ jet production had also mentioned it, see [13,20]. These effects can reach the several percent size and even more than ten percent on the subprocess cross sections. This can be immediately understood by looking at the simple Sudakov (squared and linear) logarithmic terms which affect the amplitudes at high energy [21–24]. To estimate the size of this type of effect at lower energies one also can use the so-called "augmented Sudakov" terms, in which constant terms have been added to the logarithmic ones [25]. Using this approach, one can immediately be convinced that the polarization asymmetry A_Z will be essentially not affected by these electroweak corrections. Actually, looking at the transverse Born amplitudes, one first remarks that because $g_{Zb}^L \sim 5g_{Zb}^R$, the dominant amplitudes are F_{-+-+} and F_{----}. The other ones will contribute to the total cross section by terms suppressed by a factor $1/25$. Then, applying the Sudakov rules of Refs. [18,19,21,22,25], one sees that the leading logs associated to the b_L and Z states are very similar for these two amplitudes. A raw estimate gives effects of several percents in the 1 TeV range which should directly affect the cross section.

However for A_Z, dominated by $(|F_{-+-+}|^2 - |F_{----}|^2)/(|F_{-+-+}|^2 + |F_{----}|^2)$ ratio, the common electroweak corrections to each of these amplitudes in the numerator and in the denominator will cancel out. So a small non-zero effect will only come from the smaller amplitudes (which contribute by a factor 25 less) and from the small differences due to the subleading (mass suppressed) terms.

Using the augmented Sudakov expressions written in Ref. [25] we have checked that the effects on A_Z reach at most the one percent level. In this spirit, we shall consider in this preliminary paper the SM NLO electroweak corrections as probably irrelevant. A more complete determination of their numerical effect will be given in a forthcoming paper.

4. Conclusion

We have shown that the Z polarization asymmetry A_Z in bZ production at the LHC is strictly connected to the well-known forward–backward $b\bar{b}$ asymmetry at Z pole, A_{FB}^b, measured at LEP1. Our results indicate that A_Z is almost free from theoretical uncertainties related to QCD scale variations as well as to pdf set variations; this property strongly suggests in our opinion a mea-

surement of A_Z at LHC as a unique candidate to possibly clarify the long standing puzzle related to the A_{FB}^b measurement at LEP1.

More in general it can be observed that polarization asymmetry observables would be quite relevant theoretical observables at LHC, as shown by a recent paper [26], where a polarization asymmetry was studied in the context of polarized top production in association with a charged Higgs boson [27], as a possible way of determining the $\tan \beta$ parameter in the MSSM. A rather general conclusion of our paper is therefore in our opinion that measurements of polarization at LHC would represent a tough but possibly quite rewarding experimental effort. A more complete discussion of Z polarization measurements at LHC will be treated in a forthcoming paper.

Acknowledgements

References

[1] ALEPH Collaboration, CDF Collaboration, D0 Collaboration, DELPHI Collaboration, L3 Collaboration, OPAL Collaboration, SLD Collaboration, LEP Electroweak Working Group, Tevatron Electroweak Working Group, SLD Electroweak Heavy Flavour Groups, arXiv:1012.2367v2 [hep-ex], 2011.
[2] G. Aad, et al., ATLAS Collaboration, Phys. Lett. B 710 (2012) 49, arXiv:1202.1408 [hep-ex].
[3] S. Chatrchyan, et al., CMS Collaboration, arXiv:1202.1488 [hep-ex].
[4] ALEPH Collaboration, DELPHI Collaboration, L3 Collaboration, OPAL Collaboration, SLD Collaboration, LEP Electroweak Working Group Collaboration, SLD Electroweak Group Collaboration, SLD Heavy Flavour Group Collaboration, Phys. Rept. 427 (2006) 257, arXiv:hep-ex/0509008.
[5] M.S. Chanowitz, Phys. Rev. Lett. 87 (2001) 231802, arXiv:hep-ph/0104024.
[6] X.-G. He, G. Valencia, Phys. Rev. D 68 (2003) 033011, arXiv:hep-ph/0304215.
[7] L. Da Rold, JHEP 1102 (2011) 034, arXiv:1009.2392 [hep-ph].
[8] J. Cao, J.M. Yang, JHEP 0812 (2008) 006, arXiv:0810.0751 [hep-ph].
[9] J.M. Campbell, R.K. Ellis, F. Maltoni, S. Willenbrock, Phys. Rev. D 69 (2004) 074021, arXiv:hep-ph/0312024.
[10] E. Mirkes, Nucl. Phys. B 387 (1992) 3.
[11] E. Mirkes, J. Ohnemus, Phys. Rev. D 51 (1995) 4891, arXiv:hep-ph/9412289.
[12] J. Pumplin, D.R. Stump, J. Huston, H.L. Lai, P.M. Nadolsky, W.K. Tung, JHEP 0207 (2002) 012, arXiv:hep-ph/0201195.
[13] A. Denner, S. Dittmaier, T. Kasprzik, A. Muck, JHEP 1106 (2011) 069, arXiv:1103.0914 [hep-ph].
[14] S.J. Brodsky, X.-G. Wu, arXiv:1204.1405 [hep-ph].
[15] A.D. Martin, W.J. Stirling, R.S. Thorne, G. Watt, Eur. Phys. J. C 63 (2009) 189, arXiv:0901.0002 [hep-ph].
[16] R.D. Ball, V. Bertone, F. Cerutti, L. Del Debbio, S. Forte, A. Guffanti, J.I. Latorre, J. Rojo, et al., Nucl. Phys. B 849 (2011) 296, arXiv:1101.1300 [hep-ph].

[17] G. Aad, et al., ATLAS Collaboration, Phys. Lett. B 706 (2012) 295, arXiv:1109.1403 [hep-ex].

[18] M. Beccaria, C.M. Carloni Calame, G. Macorini, E. Mirabella, F. Piccinini, F.M. Renard, C. Verzegnassi, Phys. Rev. D 77 (2008) 113018, arXiv:0802.1994 [hep-ph].

[19] M. Beccaria, C.M. Carloni Calame, G. Macorini, G. Montagna, F. Piccinini, F.M. Renard, C. Verzegnassi, Eur. Phys. J. C 53 (2008) 257, arXiv:0705.3101 [hep-ph].

[20] A. Denner, S. Dittmaier, T. Kasprzik, A. Muck, JHEP 0908 (2009) 075, arXiv:0906.1656 [hep-ph].

[21] M. Beccaria, F.M. Renard, C. Verzegnassi, LC-TH-2002-005, arXiv:hep-ph/0203254.

[22] M. Beccaria, M. Melles, F.M. Renard, S. Trimarchi, C. Verzegnassi, Int. J. Mod. Phys. A 18 (2003) 5069, arXiv:hep-ph/0304110.

[23] U. Baur, Phys. Rev. D 75 (2007) 013005, arXiv:hep-ph/0611241.

[24] G. Balossini, G. Montagna, C.M. Carloni Calame, M. Moretti, O. Nicrosini, F. Piccinini, M. Treccani, A. Vicini, JHEP 1001 (2010) 013, arXiv:0907.0276 [hep-ph].

[25] G.J. Gounaris, F.M. Renard, Acta Phys. Polon. B 42 (2011) 2107, arXiv:1106.2707 [hep-ph].

[26] J. Baglio, M. Beccaria, A. Djouadi, G. Macorini, E. Mirabella, N. Orlando, F.M. Renard, C. Verzegnassi, Phys. Lett. B 705 (2011) 212, arXiv:1109.2420 [hep-ph].

[27] K. Huitu, S. Kumar Rai, K. Rao, S.D. Rindani, P. Sharma, JHEP 1104 (2011) 026, arXiv:1012.0527 [hep-ph].