New Physics signals from measurable polarization asymmetries at LHC

M. Beccaria\textsuperscript{1}, G. Macorini\textsuperscript{2}, G. Panizzo\textsuperscript{3} and C. Verzegnassi\textsuperscript{3}

\textsuperscript{1} Dipartimento di Matematica e Fisica “Ennio de Giorgi”, Università del Salento and INFN, Sezione di Lecce, Via Arnesano 1, 73100 Lecce, Italy.
\textsuperscript{2} Niels Bohr International Academy and Discovery Center, Blegdamsvej 17 DK-2100 Copenhagen, Denmark
\textsuperscript{3} Dipartimento di Fisica , Università di Trieste and INFN Sezione di Trieste, Strada Costiera, 11 I - 34151 Trieste, Italy.

Abstract

We propose a new type of Z polarization asymmetry in bottom-Z production at LHC that should be realistically measurable and would provide the determination of the so-called \( A_b \) parameter, whose available measured value still appears to be in disagreement with the Standard Model prediction. This polarization can be measured independently of a possible existence of Supersymmetry. If Supersymmetry is found, a second polarization, i.e. the top longitudinal polarization in top-charged Higgs production, would neatly identify the \( \tan \beta \) parameter. In this case, the value of \( A_b \) should be in agreement with the Standard Model. If Supersymmetry does not exist, a residual disagreement of \( A_b \) from the Standard Model prediction would be a clean signal of New Physics of “non Supersymmetric” origin.

1. Introduction

The polarized bottom-Z forward-backward asymmetry has been defined several years ago \cite{1}, and considered to be the best way of measuring, in a theoretical SM approach, a combination of the polarized bottom-Z couplings. The definition of this quantity was chosen as

\[
A_{FB}^{b,Pol} = \frac{(\sigma_{e^-b_F} - \sigma_{e^-b_B}) - (\sigma_{e^-b_B} - \sigma_{e^-b_B})}{\sigma_{e^-b_F} + \sigma_{e^-b_B} + \sigma_{e^-b_B} + \sigma_{e^-b_B}},
\]

where \( b_{F,B} \) indicates forward and backward outgoing bottom quarks respectively (a polarization degree of the incoming beam = 1 is for simplicity assumed). At the Z peak one may easily verify that

\[
A_{FB}^{b,Pol} = \frac{3 g_{Lb}^2 - g_{Rb}^2}{4 g_{Lb}^2 + g_{Rb}^2},
\]
where $g_{L,Rb}$ are the couplings of a left and right handed bottom to the $Z$. Calling

$$A_b = \frac{g_{Lb}^2 - g_{Rb}^2}{g_{Lb}^2 + g_{Rb}^2},$$

one finds that

$$A_{b,\text{pol}}^{F,B} = \frac{3}{4} A_b.$$

(4)

The quantity $A_b$ appears also in an unpolarized transition from an electron-positron to a $b - \bar{b}$ pair. One finds in that case that the unpolarized forward-backward $b$ asymmetry at the $Z$ peak can be written as

$$A_{b}^{F,B} = \frac{3}{4} A_e A_b,$$

(5)

where $A_e$ is the longitudinal electron polarization asymmetry

$$A_e = \frac{g_{Le}^2 - g_{Re}^2}{g_{Le}^2 + g_{Re}^2},$$

(6)

and equations (5) (6) can be extended to a different final quark antiquark couple $f \bar{f}$, giving

$$A_{f}^{F,B} = \frac{3}{4} A_e A_f,$$

(7)

where $A_f$ is the analogue of $A_b$ eq (3) with $f$ replacing $b$. The direct measurement of $A_b$, that requires the use of initially longitudinally polarized electrons, was performed at SLAC [3,4], and the result was found to be in good agreement with the Standard Model prediction, that is [5]

$$A_{b}^{\text{SM, th}} = 0.93464 \pm 0.00004 \pm 0.00007.$$

Later, LEP1 performed a number of unpolarized measurements at the $Z$ peak from which the value of $A_b$ was derived. This was obtained from eq. (7) and found to be in severe disagreement, at the $3\sigma$ level, with the SM prediction [6]. This result was in a certain sense unexpected, because the relative decay rate of the $Z$ into bottom pairs $R(b) = \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$ provided a value

$$R_b \simeq g_{Lb}^2 + g_{Rb}^2,$$

(8)

in perfect agreement with the SM prediction [6]. Accepting the LEP1 result for $A_b$, a search started of possible new physics models that might have cured the disagreement. In particular, it was concluded that a conventional MSSM was unable to save the situation [7]. This conclusion remained problematic, since no extra measurements of $A_b$ were eventually performed, and the emerging picture seems definitely unclear. In addition to the previous statements, a new feature has now appeared. In a very recent important paper [8], a SM calculation of $\sin^2 \theta_W^{f,f,b}$ and $R_b$ has been redone including higher order previously neglected effects. The result is that the SM theoretical prediction for $A_b$ and $R_b$ are now different [5], in the sense that the disagreement of $A_b$ has been slightly ($\sim 2.5\sigma$) reduced, while a new disagreement ($\sim 2.4\sigma$) for $R_b$ has appeared. Certainly, a new measurement of $A_b$ and $R_b$ would therefore represent an undoubtedly relevant improvement of our understanding. In this paper, we discuss the possibility of a measurement of $A_b$. 
In a recent paper \[10\], we have defined a certain polarization asymmetry \(A_{bZ}^{\text{pol,b}}\) to be measured in bottom-Z production at LHC, and shown that this would represent a possibility of measuring the \(A_b\) quantity. From a theoretical point of view, this asymmetry exhibits the remarkable properties of being QCD scale and PDF set choice independent, which would represent a quite remarkable feature. From the realistic experimental point of view, this asymmetry should be derived from the experimental determination of the so called polarization fractions (see for example \[9\] and references therein) of the Z boson in bZ associated production, known to be affected by intrinsically large systematic uncertainties. The aim of this paper is that of proposing an alternative quantity, proportional to \(A_b\), measurable in the same process of bottom-Z production at LHC, that would be experimentally clean being eventually limited in precision only by statistical uncertainties. This will be done in the following Section 2 of the paper. In Section 3, the possible relevance of the measurement of another polarization asymmetry, the top longitudinal polarization in top-charged Higgs production, will be discussed in the case of a SUSY discovery. The importance of a measurement of the Z polarization in bottom-Z production with or without Supersymmetry will be finally discussed in Section 4.

2. Helicity amplitudes and \(A_{FB}^{bZ}\)

The process of associated production of a single b-quark and a Z boson with its subsequent decay into a lepton-antilepton pair, represented in Figure 1 is defined at parton level by subprocesses \(bg \rightarrow bl\bar{l}\) involving two Born diagrams with bottom quark exchange in the s-channel and in the u-channel. The interaction vertexes involved in the diagrams of Figure 1 are defined as follows

\begin{align*}
\text{gqq : } & ig_s k \left( \frac{\lambda^k_c}{2} \right) \\
\text{Zff : } & -i\epsilon^{\gamma \mu}[g^{L}_{Z} P_{L} + g^{R}_{Z} P_{R}] \equiv -i\epsilon^{\gamma \mu}[g^{L}_{Z} P_{L}]. (9)
\end{align*}

Therefore, the Born invariant amplitude is given by

\begin{align*}
A^{\text{Born}}(bg \rightarrow bZ \rightarrow b\bar{l}l) &= 4\pi\alpha_s \left( \frac{\lambda^k_c}{2} \right) \tilde{u}(b') \left[ \gamma^\mu \{g^L_{Z} P_{L}\} \frac{s - m_b^2}{s - m_b^2} \left( \frac{\not{q} + m_b}{u - m_b^2} \right) \right] u(b) \ D_Z(p^2_{Z}) \ \tilde{u}(l) \ \gamma^\mu \{g^L_{Z} P_{L}\} \ v(\bar{l}), (10)
\end{align*}
where $\epsilon, \lambda^k_\epsilon$ are the gluon polarization vector and colour matrix, $p_t + p_l \equiv p_Z$, $D_Z(p_Z^2)$ is the usual Z effective propagator, $q = p_\bar{b} + p_g = p_Z + p_b'$, $s = q^2$, $q' = p_b' - p_g = p_b - p_Z$, $u = q'^2$ and with the kinematic decompositions in the center of mass frame (all fermion massless)

$$p_b = (p; 0, 0, p), \quad p_b' = (p_1; 0, p_1 \sin \theta_1, p_1 \cos \theta_1)$$

$$p_g = (p; 0, 0, -p) \ ,$$

$$p_t = (p_2; p_2 \sin \theta_2 \sin \phi_2, p_2 \sin \theta_2 \cos \phi_2, p_2 \cos \theta_2) \ ,$$

$$p_l = (p_3; p_3 \sin \phi_3, p_3 \sin \theta_3 \cos \phi_3, p_3 \cos \theta_3) \ ,$$

$$\epsilon(g) = \left(0; \frac{\lambda_g}{\sqrt{2}}, -\frac{i}{\sqrt{2}}, 0\right) \ ,$$

where the set of variables $p_t, \theta_i, \phi_i$ is underconstrained for clarity of notation; a more appropriate set of variables that fulfill $p_b + p_g = p_b' + p_t + p_l$ is found rotating the three momenta of the leptons in a new ‘helicity’ frame, in which the polar axis is the direction of $b'$ and the azimuthal angle is measured from the normal to the production plane (i.e. the one spanned by the colliding and decaying bottom quarks momenta$^2$). The rotation matrix between the two coordinate systems is

$$R_{\theta_1} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_1 & -\sin \theta_1 \\ 0 & \sin \theta_1 & \cos \theta_1 \end{pmatrix} \ ,$$

from which one can define the polar angles $\theta_1, \theta_l$ and the azimuthal angle $\phi'$

$$p_t^{bf} = (p_2; p_2 \sin \theta_l \sin \phi', p_2 \sin \theta_l \cos \phi', p_2 \cos \theta_l) \ ,$$

$$p_l^{bf} = (p_3; -p_3 \sin \theta_l \sin \phi', -p_3 \sin \theta_l \cos \phi', p_3 \cos \theta_l) \ .$$

In this frame the coplanarity of the final particles is manifest through the dependence on the same variable $\phi'$ for both leptons. Energy conservation leads, in this frame and for massless particles, to simple formulas for the energies of the final particles ($\{\theta_l, \theta_1\}^b \equiv \{\theta_l, \theta_1\}/2$):

$$p_1 = p \left(1 - \cot(\theta_l^h) \cot(\theta_l^h)\right) \ ,$$

$$p_2 = p \cos(\theta_l^h) \csc(\theta_l^h) \csc(\theta_l^h + \theta_l^h) \ ,$$

$$p_3 = p \csc(\theta_l^h) \cos(\theta_l^h) \csc(\theta_l^h + \theta_l^h) \ ,$$

which make manifest the (maximal) domain of integration

$$\theta_l \in [0, \pi], \theta_l \in [\pi - \theta_l, \pi] \ .$$

---

1. An additional azimuthal angle for $b'$ would manifest itself only through overall phase factors in the amplitudes.

2. The ambiguity coming from the orientation of the normal to the production plane will be canceled after integration over the azimuthal angle in the definition of observable quantities.
The introduction of this reference frame is motivated by the cleaner form the matrix elements assume there. In the massless case, the helicity amplitudes can be expressed as

\[ \mathcal{M}_{\lambda_f \lambda_i} ; \lambda_f \lambda_i \equiv \delta_{\lambda_f \lambda_i} \delta_{\lambda_f \lambda_i} \mathcal{M}_{\lambda_f} ; \lambda_f \lambda_i , \]

where \( \lambda_f = \pm \frac{1}{2} \equiv \pm, \lambda_g = \pm 1 \equiv \pm \) and \( \lambda_i \equiv -\lambda_i \). Modulo a common factor

\[ \mathcal{M}_{\lambda_f} ; \lambda_f \lambda_i \equiv \left( D_Z(p_Z^2) \ 16\sqrt{2} \pi \alpha g_i \lambda_i^k \right) F_{\lambda_i} ; \lambda_f \lambda_i , \]

the non vanishing helicity amplitudes factors read:

\[ F_{+++} = -i \left( g_{Z_0}^R g_{Z_1}^R \right) e^{i\phi'} \sqrt{\frac{p_1 p_2 p_3}{p}} \frac{\cos \theta_1^h \sin \theta_1^h}{\cos \theta_1^i} , \quad (20) \]

\[ F_{++-} = i \left( g_{Z_0}^R g_{Z_1}^L \right) e^{i\phi'} \sqrt{\frac{p_1 p_2 p_3}{p}} \frac{\sin \theta_1^h}{\cos (\theta_1^h + \theta_1^i)} \frac{\cos \theta_1^h}{\cos \theta_1^i} \left( \cos \theta_1^h \sin \theta_1^h - e^{i\phi'} \sin \theta_1^h \cos \theta_1^h \right)^2 , \quad (21) \]

\[ F_{-++} = i \left( g_{Z_0}^R g_{Z_1}^R \right) e^{-i\phi'} \sqrt{\frac{p_1 p_2 p_3}{p}} \frac{\sin \theta_1^h}{\cos (\theta_1^h + \theta_1^i)} \frac{\cos \theta_1^h}{\cos \theta_1^i} \left( \cos \theta_1^h \sin \theta_1^h + e^{i\phi'} \sin \theta_1^h \cos \theta_1^h \right)^2 , \quad (22) \]

\[ F_{---} = -i \left( g_{Z_0}^L g_{Z_1}^L \right) e^{-i\phi'} \sqrt{\frac{p_1 p_2 p_3}{p}} \frac{\cos \theta_1^h \sin \theta_1^h}{\cos \theta_1^i} . \quad (23) \]

while the other four can be derived by these by parity conjugation, that in our conventions is represented by complex conjugation together with the switch \( g_{Z_0}^L \leftrightarrow g_{Z_1}^R \). As an example

Note that formulas related by switch of the lepton helicities are related one to each other by the replacements

\[ (\theta_1 \leftrightarrow \theta_1', \phi' \rightarrow \phi' + \pi) \equiv \ l \leftrightarrow \bar{l} , \quad (24) \]

\[ g_{Z_0}^L \leftrightarrow g_{Z_1}^R . \quad (25) \]

From these formulas one can build the total cross section by introducing the usual flux factor and the convolution with the relevant partons density functions for the proton. For our purposes it suffices to define the squared amplitude summed over the initial state helicities as

\[ \rho_{\lambda_f \lambda_i} \equiv \sum_{\lambda_0} |\mathcal{M}_{\lambda_0} ; \lambda_0 \lambda_i| \]

and to identify

\[ \rho_{++} + \rho_{--} \equiv \left( g_{L_0}^2 g_{L_1}^2 + g_{R_0}^2 g_{R_1}^2 \right) f(\theta_1^h, \theta_1^h, \theta_1, \phi') \]

(one can check that actually in the sum in the RHS the couplings factorize out). The complete unpolarized squared amplitude can now be simply written as

\[ |\mathcal{M}|^2 = \left( g_{L_0}^2 g_{L_1}^2 + g_{R_0}^2 g_{R_1}^2 \right) f(\theta_1^h, \theta_1^h, \theta_1, \phi') + \left( g_{L_0}^2 g_{R_1}^2 + g_{R_0}^2 g_{L_1}^2 \right) \bar{f}(\theta_1^h, \theta_1^h, \theta_1, \phi') \quad (26) \]

\[ \equiv c_+ \frac{f + \bar{f}}{2} + c_- \frac{f - \bar{f}}{2} , \quad (27) \]
where $\bar{f} \equiv f|_{l \leftrightarrow \bar{l}}$. In the last line (27), the two terms have definite symmetry properties under $l \leftrightarrow \bar{l}$, with coefficients

$$c_+ = \left( g_{Lb}^2 + g_{Rb}^2 \right) \left( g_{Li}^2 + g_{Ri}^2 \right),$$
$$c_- = \left( g_{Lb}^2 - g_{Rb}^2 \right) \left( g_{Li}^2 - g_{Ri}^2 \right),$$
$$\frac{c_-}{c_+} = A_b A_l.$$

This allows us to extract $(c_-) c_+$ simply measuring (anti) symmetrized combination of cross sections in kinematic domains related one to each other under exchange of the two leptons angles. The simplest choice in the CM frame is

$$\mathcal{D}_\pm \equiv \theta_l \gtrless \theta_{\bar{l}}. \quad (28)$$

To be more explicit, note that the condition $\theta_l \gtrless \theta_{\bar{l}}$ translates in the $Z$ rest frame to the experimentally simpler condition of Forward/Backward lepton momentum respect to the bottom momentum versor. This finally leads to the definition of $A_{FB}^{b,LHC}$

$$A_{FB}^{b,LHC} \equiv \frac{\sigma(\mathcal{D}_F) - \sigma(\mathcal{D}_B)}{\sigma(\mathcal{D}_F) + \sigma(\mathcal{D}_B)}, \quad (29)$$

where the reference axis is the $b$ momentum in the $Z$ rest frame. From (27) this quantity will be proportional, modulo a kinematic factor $k$, to the LEP $A_{FB}^b$

$$A_{FB}^b = k A_{FB}, \quad (30)$$

where $FB$, as already emphasized, has different meaning in the two expressions.

A theoretical prediction of $A_{FB}^{b,LHC}$ (and, in particular, of the numerical value of the kinematical constant $k$) has to take into account several experimental issues, thus needing a realistic simulation of the detector features, and in particular of its geometrical properties and of intrinsic cuts applied to the event reconstruction. In such a contest, kinematic cuts on transverse momentum and pseudorapidity of the decaying particles introduce some subtleties in the derivation of a direct connection of $A_{FB}^{b,LHC}$ to the LEP asymmetry $A_{FB}^b$. To prove the validity of (30) also in the presence of a realistic event selection, one can vary fictitiously $g_{Zb}^{L,R}$ in a wide range of values, determining the corresponding values of $A_{FB}^{b,LHC}$ with usual kinematic cuts. Figure 2 shows the results of a simulation with 10 different choices of $g_{Zb}^{L,R}$, including the SM one (for the events simulation we have used CalcHEP [11] and checked good agreement with different event generators). The particular choice of selection criteria closely follows the one used by ATLAS for the $Z$-$b$-jets cross section analysis [12]. With these assumptions, the kinematical constant $k$ is found to be $-0.37$ at LO. Its QCD scale dependence has been inspected varying simultaneously the renormalization and factorization scales and computing the corresponding $A_{FB}^{b,LHC}$ values, Figure 3. Similarly the PDF set choice dependence is depicted in Figure 4. The total theoretical uncertainty in both cases is at the 1 percent level. For a detector level simulation one has to choose an appropriate procedure to measure the $b$-jet charge, that can be achieved adapting the LEP procedure to the LHC case [13,14].

3. The top longitudinal polarization in top-charged Higgs production.
Figure 2: Event level (i.e. without parton showering) dependence of the asymmetry defined in the text on $A_{FB}^B$, in a ficticiously wide range of $A_{FB}^B$ values, aiming to prove the exact direct proportionality also in the presence of typical kinematic cuts [12] on decay products pseudorapidities and transverse momenta. The uncertainty on $k$ is only numerical (see below).

Figure 3: Comparison between the LO $\mu_F = \mu_R = kM_Z$ scale variation dependencies of the total cross section and our asymmetry.
Figure 4: Comparison of different pdf set LO asymmetry predictions taking CTEQ6L1 as reference.

The previous discussion about $A_b$ is not dependent on the assumption of a supersymmetric model of New Physics. In particular, there is no impact of SUSY on $A_b$ if one assumes a heavy enough charged Higgs and sbottoms/stops squarks which seems to be the case. If Supersymmetry is found, a different asymmetry measurement becomes relevant at LHC, the top longitudinal polarization asymmetry in top-charged Higgs production. This quantity has been exhaustively discussed in a previous paper [15], where it was shown that its value would essentially mostly depend on that of the MSSM tan $\beta$ parameter, and would be almost rigorously QCD scale and PDF choice independent. In particular, it was shown in Ref. [15] that varying tan $\beta$ from approximately one to approximately ten, the value of the asymmetry changes sign, making an experimental determination effective even in the presence of a realistic experimental and theoretical error. For larger tan $\beta$ values, on the contrary, the asymmetry remains essentially constant and provides a minor but still relevant information, and we defer to Ref. [15] for more details. The relevance of the considered asymmetry appears to us to have been enormously increased by the latest results on the Higgs boson mass derived at LHC [16,17]. If one wants to retain a MSSM scheme, the residual range of the Supersymmetric parameters has been greatly reduced. In particular the allowed values of tan $\beta$ lie exactly in our “optimal” range, roughly from one to ten, with a mass of the charged Higgs in the $300 - 600$ GeV range. Indeed, according to a recent analysis [18], while the best fit MSSM point derived from the latest LHC Higgs data gives $M_{H^\pm} \approx 600$ GeV and tan $\beta \approx 1$, data are still in a good agreement with low tan $\beta$ values and $M_{H^\pm}$ values down to $300$ GeV (the reason being that the $\chi^2$ is relatively flat). The variation of the top polarization asymmetry with tan $\beta$ in scenarios of this kind is shown in Fig. 5. In our calculation, we have used the previous results of Ref. [19] and have remained essentially limited to an effective Born approximation. The Figure shows the top polarization asymmetry for three different choices of the Higgs mass: the center of mass energy is $\sqrt{s} = 7$ TeV and, following [19,20], the factorization scale $\mu_F$ is set to $1/6(M_{H^\pm} + m_t)$ to minimize the QCD corrections. The value of the bottom mass in the Yukawa coupling $tbH^\pm$ is
The main conclusion of our analysis is that a determination of \( \tan \beta \) in the residual range would not request an “extremely” precise experimental measurement. This is a consequence of the fact that a jump from a positive value of approximately twenty percent to the same value of opposite sign would not escape a “reasonable” determination.

4. \( A_{b} \) indications if Supersymmetry is not found at LHC.

Coming back to the bottom Z process, assuming that Supersymmetry is found, the proposed determination of \( A_{b} \) from Z polarization becomes now extremely relevant, given the fact that Supersymmetry would be unable to explain a discrepancy with the available Standard Model result. But this asymmetry could also play a fundamental role in the case of a negative Supersymmetric search at LHC. In particular we shall consider two opposite cases:

A) The \( A_{b} \) value is in disagreement with the Standard Model prediction. This result would completely eliminate Supersymmetry, even at a more powerful proton-proton CERN collider, but would necessarily indicate the presence of New Physics of non Supersymmetric nature, like that discussed in some recent papers (see e.g. [21] and references therein).

B) The \( A_{b} \) value is in agreement with the Standard Model prediction. This would leave an “open door” for very heavy Supersymmetry, to be searched at a future more powerful CERN collider, or also exclude effects at LHC due to a large class of considered New Physics models [21].

The conclusion that we personally think can be derived from our paper is that, in full generality, a measurement of the Z polarization and top longitudinal asymmetries, which could be
performed at LHC under reasonably expected experimental conditions, is, to use a mild definition, “worth”. We are ready and willing to collaborate with possibly interested experimental teams to make this project fulfilled.

Acknowledgements: We are very grateful to Abdelhak Djouadi for useful discussions and comments on the manuscript.
References

[1] A. Blondel, B. W. Lynn, F. M. Renard and C. Verzegnassi, Nucl. Phys. B 304 (1988) 438.
[2] B. W. Lynn and C. Verzegnassi, Phys. Rev. D 35 (1987) 3326.
[3] K. Abe et al. [SLD Collaboration], SLAC-PUB-6513 (94/05, rec. Aug.) 9 p
[4] K. Abe et al. [SLD Collaboration], Phys. Rev. Lett. 84 (2000) 5945 [hep-ex/0004026].
[5] M. Baak, M. Goebel, J. Haller, A. Hoecker, D. Kennedy, R. Kogler, K. Moenig and M. Schott et al., Eur. Phys. J. C 72 (2012) 2205 [arXiv:1209.2716 [hep-ph]].
[6] S. Schael et al. [ALEPH and DELPHI and L3 and OPAL and SLD and LEP Electroweak Working Group and SLD Electroweak Group and SLD Heavy Flavour Group Collaborations], Phys. Rept. 427 (2006) 257 [hep-ex/0509008].
[7] J. Cao and J. M. Yang, JHEP 0812 (2008) 006 [arXiv:0810.0751 [hep-ph]].
[8] A. Freitas and Y. -C. Huang, JHEP 1208 (2012) 050 [arXiv:1205.0299 [hep-ph]].
[9] J. Stirling and E. Vryonidou, arXiv:1302.1365 [hep-ph].
[10] M. Beccaria, N. Orlando, G. Panizzo, F. M. Renard and C. Verzegnassi, Phys. Lett. B 713 (2012) 457 [arXiv:1204.5315 [hep-ph]].
[11] A. Belyaev, N. D. Christensen and A. Pukhov, Comput. Phys. Commun. 184 (2013) 1729 [arXiv:1207.6082 [hep-ph]].
[12] G. Aad et al. [ATLAS Collaboration], Phys. Lett. B 706 (2012) 295 [arXiv:1109.1403 [hep-ex]].
[13] R. Akers et al. [OPAL Collaboration], Z. Phys. C 67 (1995) 365.
[14] D. Krohn, M. D. Schwartz, T. Lin and W. J. Waalewijn, Phys. Rev. Lett. 110 (2013) 212001 [arXiv:1209.2421 [hep-ph]].
[15] J. Baglio, M. Beccaria, A. Djouadi, G. Macorini, E. Mirabella, N. Orlando, F. M. Renard and C. Verzegnassi, Phys. Lett. B 705 (2011) 212 [arXiv:1109.2420 [hep-ph]].
[16] [ATLAS Collaboration], ATLAS-CONF-2013-014.
[17] [CMS Collaboration], CMS-PAS-HIG-13-005.
[18] A. Djouadi, L. Maiani, G. Moreau, A. Polosa, J. Quevillon and V. Riquer, arXiv:1307.5205 [hep-ph].
[19] M. Beccaria, G. Macorini, L. Panizzi, F. M. Renard and C. Verzegnassi, Phys. Rev. D 80 (2009) 053011 [arXiv:0908.1332 [hep-ph]].
[20] T. Plehn, Phys. Rev. D 67 (2003) 014018; S. Zhou, Phys. Rev. D 67 (2003) 075006.
[21] A. Djouadi, G. Moreau and F. Richard, Nucl. Phys. B 773 (2007) 43 [hep-ph/0610173].