Global Constraints on Lepton-Quark Contact Interactions

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Abstract

The Large Hadron Collider can do precision physics at a level that is competitive with electroweak precision constraints when probing physics beyond the Standard Model. We present a simple yet general parameterization of the effect of an arbitrary number of lepton-quark contact interactions on any di-lepton observable at hadron colliders. This parameterization can be easily adopted by the experimental collaborations to put bounds on arbitrary combinations of lepton-quark contact interactions. We compute the corresponding bounds from current di-lepton resonance searches at the LHC and find that they are competitive with and often complementary to indirect constraints from electroweak precision data. We combine all current constraints in a global analysis to obtain the most stringent bounds on lepton-quark contact interactions. We also show that the high-energy phase of the LHC has a unique potential in terms of discovery and discrimination power among different types of lepton-quark contact interactions.

The Large Hadron Collider (LHC) is a discovery machine at the energy frontier. However, it can also do precision physics, probing physics beyond the Standard Model (SM) in a complementary and even competitive way to electroweak precision data (EWPD). Model-independent bounds on departures from the SM can be systematically computed by means of effective Lagrangians. Assuming the SM particle content and symmetries and neglecting lepton number violation, the leading corrections arise from dimension-six operators

\[
\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{i} \frac{\alpha_i}{\Lambda^2} \mathcal{O}_i + \ldots,
\]

where \(\mathcal{L}_{\text{SM}}\) is the SM Lagrangian and \(\Lambda\) is the cut-off scale at which the effective Lagrangian ceases to be valid. The list of required operators was systematically classified for the first time by Ref. [1]. Several redundancies were discussed by many authors [2] and the first list of truly independent operators was given in Ref. [3] (see Ref. [4] for a recent alternative). In this work we consider the constraints that current searches for di-lepton resonances imply on lepton-quark four-fermion interactions (see Refs. [5, 6] for related analyses). The most general lepton-quark four-fermion interaction can be parameterized in terms of the following dimension-six operators:

\[
\begin{align*}
\mathcal{O}_{lq}^{(1)} &= (\bar{l}\gamma^\mu l)(\bar{q}\gamma^\mu q), & \mathcal{O}_{lq}^{(3)} &= (\bar{l}\sigma_I \gamma^\mu l)(\bar{q}\tau_I \gamma^\mu q), \\
\mathcal{O}_{ce} &= (\bar{e}\gamma^\mu e)(\bar{u}\gamma^\mu u), & \mathcal{O}_{cd} &= (\bar{e}\gamma^\mu e)(\bar{d}\gamma^\mu d), \\
\mathcal{O}_{lu} &= (\bar{l}\gamma^\mu l)(\bar{u}\gamma^\mu u), & \mathcal{O}_{ld} &= (\bar{l}\gamma^\mu l)(\bar{d}\gamma^\mu d), \\
\mathcal{O}_{qe} &= (\bar{q}\gamma^\mu q)(\bar{e}\gamma^\mu e), & \mathcal{O}_{qde} &= (\bar{q}e)(\bar{d}e) \\
\mathcal{O}_{lqe} &= (\bar{l}e)(\bar{q}^T u), & \mathcal{O}_{qle} &= (\bar{q}e)(\bar{l}^T u),
\end{align*}
\]

The LHC is an international particle physics research facility located near Geneva, Switzerland, that has been undergoing upgrades since its inception. It is a discovery machine at the energy frontier, but it can also do precision physics, probing physics beyond the Standard Model (SM) in a complementary and even competitive way to electroweak precision data (EWPD). Model-independent bounds on departures from the SM can be systematically computed by means of effective Lagrangians. Assuming the SM particle content and symmetries and neglecting lepton number violation, the leading corrections arise from dimension-six operators

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\end{align*}
\]
where $l$ and $q$ are the SM lepton and quark doublets; $e, u$ and $d$ denote the SM lepton and quark singlets; $\sigma$ are the Pauli matrices; and $\epsilon = i\sigma_2$. Flavor indices are not explicitly shown.

In the following we will assume that the operator coefficients are flavor-diagonal and family-universal in the quark sector. This guarantees the absence of contributions to quark flavor changing neutral currents (FCNC) from the first seven operators ($O_{1q}^{(1)} - O_{qg}$). Note that, while EWPD is sensitive to the couplings to all families, the largest constraints from LHC searches come from the coupling to valence quarks. Therefore, we will only consider the contributions to LHC observables from the couplings to the first-generation quarks. Regarding the lepton sector, we consider three different options: a flavor-diagonal family-universal coupling; interactions aligned with the SM fermion basis in a way that there are couplings only to electrons; and couplings only to muons.

For the last three operators ($O_{qle}, O_{lge}, O_{qge}$) the above assumptions still result on minimal flavor violating interactions in the quark sector. (Coefficients proportional to the quark mixing matrices would be required to remove FCNC.) Even in the absence of FCNC, these three operators still give sizable contributions to charged-current interactions mediating rare decays. Such contributions are strongly constrained, e.g., the experimental value of $R_e = \Gamma(\pi^+ \rightarrow \nu \nu^+)/\Gamma(\pi^+ \rightarrow \nu \ell^+)$ sets bounds $|\alpha_l/\Lambda^2| \lesssim \mathcal{O}(10^{-3})$ TeV$^{-2}$ for corrections only to the muon channel, and two orders of magnitude smaller for the electron channel [6]. As we will see, such limits are significantly stronger than the LHC and EWPD constraints discussed here. Therefore, we will not include these three operators in our numerical analyses, although they are included in all our equations for the sake of completeness.

The contribution of the operators in (2) to Drell-Yan production reads, at the partonic level,

$$
48\pi \frac{d\sigma}{dt}(\bar{u}u \rightarrow \ell^+ \ell^-) = \left[ A_{\ell R}^{SM} \frac{\alpha_{q\ell}}{\Lambda^2} \right]^2 + \left[ A_{u R}^{SM} \frac{\alpha_{q\ell}}{\Lambda^2} \right]^2 + \left[ A_{uu R}^{SM} \frac{\alpha_{q\ell}}{\Lambda^2} \right]^2 + \frac{1}{2\Lambda^4} \left[ (\alpha_{q\ell})^2 + \Re(\alpha_{q\ell} \alpha_{q\ell}^*) \right] \frac{\hat{u}^2}{s^2} + \frac{1}{2\Lambda^4} \left[ (\alpha_{q\ell})^2 + \Re(\alpha_{q\ell} \alpha_{q\ell}^*) \right],
$$

$$
48\pi \frac{d\sigma}{dt}(d\bar{d} \rightarrow \ell^+ \ell^-) = \left[ A_{d R}^{SM} \frac{\alpha_{q\ell}}{\Lambda^2} \right]^2 + \left[ A_{dd R}^{SM} \frac{\alpha_{q\ell}}{\Lambda^2} \right]^2 + \left[ A_{dd R}^{SM} \frac{\alpha_{q\ell}}{\Lambda^2} \right]^2 + \frac{1}{2\Lambda^4} \left[ (\alpha_{q\ell})^2 + \Re(\alpha_{q\ell} \alpha_{q\ell}^*) \right] \frac{\hat{u}^2}{s^2} + \frac{1}{2\Lambda^4} \left[ (\alpha_{q\ell})^2 + \Re(\alpha_{q\ell} \alpha_{q\ell}^*) \right],
$$

where we have defined

$$
A_{\ell R}^{SM} = \frac{e^2 Q_\ell Q_\ell}{s} + \frac{g_\ell g_\ell}{s - m_\ell^2 + \text{Im} m_\ell \Gamma_\ell},
$$

with $g_\ell = \frac{e}{c_W} [T_3^\ell - s_W^2 Q_\ell], Q$ the electric charge, $T_3^\ell$ the third component of weak isospin, $g$ the $SU(2)_L$ coupling, $m_\ell$ and $\Gamma_\ell$ the $Z$-boson mass and width, and $s_W (c_W)$ the sine (cosine) of the weak angle. This result completes previous partial calculations [5, 7].

Eqs. (3) allow us to parameterize any di-lepton observable at the LHC in the presence of arbitrary lepton-quark contact interactions. Any such observable can be written in terms of the cross section in a particular region of phase space as measured by experiments, $\sigma$, which can in turn be written in the form of a master equation with a small number of parameters. In the limit of large di-lepton invariant masses, the master equation takes the following simple form

$$
\sigma = \sigma^{SM} + \frac{1}{\Lambda^2} \sum_{q=u,d} \left[ F_q^1 A_1^q + F_q^2 A_2^q \right] + \frac{1}{\Lambda^4} \sum_{q=u,d} \left[ G_q^1 B_1^q + G_q^2 B_2^q + G_q^3 B_3^q \right],
$$

(4)
where we have neglected corrections proportional to $m_f^2/s \ll 1$. The coefficients $A_{1,2}^{u,d}$ and $B_{1,2,3}^{u,d}$ encode the dependence on the four-fermion operators

\[\begin{align*}
A_1^u &= [e^2 Q_u Q_e + g_{ul} g_{el}] (\alpha_{lq}^{(1)} - \alpha_{lq}^{(3)}) + [e^2 Q_d Q_e + g_{ur} g_{er}] \alpha_{eu}, \\
A_2^u &= [e^2 Q_u Q_e + g_{ul} g_{el}] \alpha_{qe} + [e^2 Q_d Q_e + g_{ur} g_{er}] \alpha_{lu}, \\
A_1^d &= [e^2 Q_d Q_e + g_{dl} g_{el}] (\alpha_{lq}^{(1)} + \alpha_{lq}^{(3)}) + [e^2 Q_u Q_e + g_{dr} g_{er}] \alpha_{ed}, \\
A_2^d &= [e^2 Q_d Q_e + g_{dl} g_{el}] \alpha_{qe} + [e^2 Q_u Q_e + g_{dr} g_{er}] \alpha_{ld}, \\
B_1^u &= 4(\alpha_{lq}^{(1)} - \alpha_{lq}^{(3)})^2 + 4\alpha_{eu}^2 - 2\text{Re}(\alpha_{lq} \alpha_{qe}^*), \\
B_2^u &= 4\alpha_{qe}^2 + 4\alpha_{lu}^2 + 2|\alpha_{qlc}|^2 + 2\text{Re}(\alpha_{lq} \alpha_{qlc}^*), \\
B_3^u &= 2|\alpha_{qlc}|^2 + 2\text{Re}(\alpha_{lq} \alpha_{qlc}^*), \\
B_1^d &= 4(\alpha_{lq}^{(1)} + \alpha_{lq}^{(3)})^2 + 4\alpha_{ed}^2, \\
B_2^d &= 4\alpha_{qe}^2 + 4\alpha_{ld}^2, \\
B_3^d &= 2|\alpha_{qlc}|^2.
\end{align*}\]

\(\sigma_{SM}, F_{1,2}^{u,d}\) and \(G_{1,2,3}^{u,d}\) on the other hand depend on the particular phase space region we are considering for the observable we want to compute, and encode the effects of the parton distribution functions and the cuts involved in the experimental analyses. A further simplification can be obtained in the case of forward-backward symmetric observables, for which we can impose the following extra conditions:

\[\begin{align*}
F_1^u &= F_2^u, & F_1^d &= F_2^d, \\
G_1^u &= G_2^u, & G_1^d &= G_2^d
\end{align*}\] (symmetric observables),

since the corresponding contributions are related by a \(t \leftrightarrow \bar{u}\) exchange. Finally, for symmetric observables for which the experimental acceptance is approximately constant along the detector coverage, we can also impose

\[G_3^u = 3G_1^u, \quad G_3^d = 3G_1^d,\]

relating the contributions proportional to \(s\) with those proportional to \(t\) and \(\bar{u}\).

This master equation, Eqs. (4) and (5), constitutes the main result of the present paper. It can be easily adopted by the LHC experimental collaborations and, once they have computed the specific values of the observable-dependent coefficients and their uncertainties, bounds on arbitrary combinations of lepton-quark contact interactions can be easily obtained.

To show how this can be done, we have computed the observable-dependent coefficients by implementing the effective operators in FeynRules 1.6 \cite{8}. We have then used MadGraph 5 \cite{9} to generate di-lepton events at the partonic level, Pythia 6 \cite{10} for hadronization and showering and Delphes 3.0.9 \cite{11} for fast detector simulation. We have implemented the latest ATLAS \cite{12} and CMS \cite{13} di-lepton searches using all the collected luminosity at the LHC with \(\sqrt{s} = 8\) TeV. Di-electron and dimuon final states are studied separately in these analyses. We have considered results for the following bins in the di-lepton invariant mass (in TeV) to avoid contamination from non-Drell Yan backgrounds

\[
\begin{align*}
\text{CMS} : & \quad b_1 = [0.9, 1.3], \quad b_2 = [1.3, 1.8], \quad b_3 = [1.8, -], \\
\text{ATLAS} : & \quad b_4 = [1.2, 3],
\end{align*}
\]

resulting in a total of 8 bins, counting electrons and muons. The observable considered is the number of events on each bin. This is a symmetric observable for which the experimental acceptances are reasonably constant along the detector coverage. Thus we can use the simplifying conditions Eqs. (6),
Table 1: Observable-dependent coefficients for di-lepton LHC searches (see Eq. (8) for details). The observable considered is the number of events on each bin. The coefficients $F_{i}^u$ and $G_{i}^d$ are in units of TeV$^{-2}$ and TeV$^{-4}$, respectively. Eqs. (6) and (7) should be used to fix the remaining parameters. The observed number of events is also reported in each case.

|       | $b_1(e)$ | $b_2(e)$ | $b_3(e)$ | $b_4(e)$ | $b_1(\mu)$ | $b_2(\mu)$ | $b_3(\mu)$ | $b_4(\mu)$ |
|-------|----------|----------|----------|----------|-------------|-------------|-------------|-------------|
| $N_{\text{SM}}$ | 32.6     | 4.68     | 0.60     | 8.72     | 37.0        | 5.38        | 0.74        | 9.44        |
| $F_{1}^u$ | 2514     | 731      | 202      | 1324     | 2746        | 811         | 251         | 1410        |
| $F_{1}^d$ | 1484     | 359      | 80.2     | 677      | 1590        | 481         | 93.6        | 775         |
| $G_{1}^u$ | 346      | 203      | 116      | 404      | 376         | 219         | 134         | 415         |
| $G_{1}^d$ | 200      | 106      | 46.1     | 199      | 219         | 118         | 53.0        | 207         |
| $N_{\text{Obs}}$ | 41       | 4        | 0        | 10       | 49          | 11          | 1           | 8           |
Lepton-quark contact interactions also contribute to precision observables, and therefore are indirectly constrained by EWPD. These limits are dominated by low-energy measurements (e.g., atomic parity violation experiments) and by the $e^+e^-$ → hadrons data taken at energies above the $Z$ pole at LEP2. The electroweak bounds for all the dimension-six interactions that can be generated at tree level and can interfere with the SM were computed in Refs. [15, 16]. The EWPD fits in this work include all the updates discussed in the analysis of the electroweak constraints in Ref. [17], the latest values of $\alpha_S$ and the top mass, and the final results of $e^+e^- → f\bar{f}$ at LEP2 [18]. In all cases, we assume real values for the dimension-six operator coefficients. We extend the results in Ref. [10] for the first seven operators in [2], for the case of diagonal and universal quarks interactions, and the different lepton flavor hypotheses discussed in the introduction. The corresponding bounds are shown in the last three columns of Table 2.

Several conclusions can be extracted from the results in Table 2. Even though indirect constraints from EWPD are still in many cases more stringent than those from LHC searches, the latter are already quite competitive in general and in some cases much superior. The operators involving muons are very poorly constrained by EWPD. In these cases the LHC constraints are more than an order of magnitude more stringent. The previous most stringent bounds on these operators come from Tevatron data [19]. They are discussed in Ref. [6] and are weaker than the ones from LHC data. Also there is quite often (see, e.g., $O_{\text{eu},\text{lu},\text{ld},\text{qe}}$) a nice complementarity between both results, with each experimental data set (EWPD or LHC) improving the worst limit derived from the other. It should be noted, however, that, due to the different energies probed by each set, the range of validity of the effective description is different in each case. In particular, since we are probing energies up to ~ 3 TeV in LHC searches, the bounds we have obtained are only valid if the coefficients of the effective operators satisfy

$$\alpha \gtrsim 9 \frac{\alpha}{\Lambda^2} \mid_{\text{max}} \quad \text{or} \quad \alpha \lesssim 9 \frac{\alpha}{\Lambda^2} \mid_{\text{min}},$$

where $\alpha/\Lambda^2 \mid_{\text{max(min)}}$ stands for the upper bound in the case of a positive (negative) $\alpha$.

Once we have obtained the bounds on lepton-quark contact interactions from LHC searches and

$$\left| O_{\text{iu},\text{ld},\text{qe}} \right| = -2 \left| O_{\text{eu},\text{ld},\text{qe}} \right| \left( \xi^\mu \xi^\mu \right),$$

1In Ref. [10] all fermion interactions are assumed to be diagonal and family-universal. Also, a different basis for four-fermion interactions is employed. In particular, the operators $O_{\text{eu},\text{ld},\text{qe}}$ in Ref. [16] are related to those in this paper by the Fierz reordering $(\bar{\psi}_L^\gamma \gamma^\mu \psi_R^\nu)(\xi_R^\mu \xi_R^\nu) = -2 \left( \bar{\psi}_R^\nu \xi_R^\mu \right)(\xi_L^\mu \psi_L^\nu)$.
Given how stringent the global constraints are and the fact that LHC searches with $\sqrt{s} = 8$ TeV are already competitive with EWPD bounds, it is worth considering the ability of the LHC to measure these operators in di-lepton searches during its high-energy phase. Furthermore, in case a departure from the SM prediction is observed, it would be crucial to try to understand the origin of such a departure. It is clear that any di-lepton search at the LHC can be only sensitive to the combination of operators described by the coefficients in Eq. (5). Nevertheless, a very simple study of angular distributions can discriminate between contributions that are mostly forward, mostly backward or symmetric. In order to test this, we have generated di-muon events at $\sqrt{s} = 14$ TeV and computed the observed number of events and a forward-backward asymmetry, defined as

$$A_{FB} = \frac{\sigma(\Delta \eta > 0) - \sigma(\Delta \eta < 0)}{\sigma(\Delta \eta > 0) + \sigma(\Delta \eta < 0)},$$

where $\Delta \eta \equiv (\eta_{-} - \eta_{+})/(\eta_{-} + \eta_{+})$ is positive (negative) for a forward (backward) negatively charged lepton in the center of mass frame, with respect to the direction of the incoming quark (when this direction is estimated by the beam axis in the direction of the di-lepton momentum in the lab frame).

We show in Fig.1 the di-muon $A_{FB}$ as a function of the observed number of events, both computed with di-muon candidates with $M_{\mu^{+}\mu^{-}} \geq 1.8$ TeV, for two representative operators, at the LHC with $\sqrt{s} = 14$ TeV and an integrated luminosity of 300 fb$^{-1}$. As a reference we also plot the expected values for the SM. In the figure we have varied the coefficients of the different operators within their current limits. Both discovery in terms of number of events and discrimination among different operators are clearly possible at this center of mass energy.

In summary, we have provided a general parameterization of the effect of an arbitrary number of lepton-quark contact interactions on di-lepton production at hadron colliders. This is expressed in the form of a master equation, Eqs. (4) and (5), in terms of a small number of observable-dependent parameters (4 plus the SM prediction for forward-backward symmetric observables). Once these parameters have been computed for the particular observable considered, the bounds on an arbitrary combination of lepton-quark contact interactions can be obtained. We have also found that it is important to consider more than one bin in di-lepton invariant masses as different operators are more

| $\mathcal{O}_i$ | Universal | Only $e$ | Only $\mu$ |
|-----------------|-----------|---------|---------|
| $\mathcal{O}_{lq}^{(1)}$ | $[-0.011, 0.053]$ | $[-0.012, 0.053]$ | $[-0.042, 0.084]$ |
| $\mathcal{O}_{lq}^{(3)}$ | $[-0.006, 0.011]$ | $[-0.006, 0.011]$ | $[-0.117, 0.027]$ |
| $\mathcal{O}_{eu}$ | $[-0.036, 0.026]$ | $[-0.046, 0.024]$ | $[-0.044, 0.117]$ |
| $\mathcal{O}_{ed}$ | $[-0.073, 0.035]$ | $[-0.074, 0.037]$ | $[-0.128, 0.086]$ |
| $\mathcal{O}_{lu}$ | $[-0.029, 0.071]$ | $[-0.035, 0.075]$ | $[-0.053, 0.095]$ |
| $\mathcal{O}_{ld}$ | $[-0.023, 0.073]$ | $[-0.021, 0.083]$ | $[-0.117, 0.094]$ |
| $\mathcal{O}_{qe}$ | $[-0.038, 0.013]$ | $[-0.043, 0.012]$ | $[-0.051, 0.070]$ |

Table 3: Combination of the different 95% C.L. limits on lepton-quark contact interactions.
Figure 1: Forward-backward asymmetry as a function of the observed number of events for two representative operators. We have considered $\sqrt{s} = 14$ TeV with 300 fb$^{-1}$ of integrated luminosity and $M_{\ell^+\ell^-} \geq 1.8$ TeV. The coefficients of the operators are varied within the current allowed values. The bands represent the 1 $\sigma$ uncertainty on the asymmetry. The SM result is represented, with 1 $\sigma$ uncertainties with a gray rectangle.

efficiently constrained at different values of the di-lepton invariant mass. We have shown how to obtain such constraints by combining LHC searches with indirect constraints from EWPD, assuming one operator at a time. LHC searches are already sometimes competitive and quite often complementary to EWPD. The very stringent global constraints that we have obtained still leave room for a discovery at the high-energy phase of the LHC. We have also discussed how one can use angular observables to distinguish among different classes of lepton-quark contact interactions.

Acknowledgments

We thank F. del Águila for useful comments. The work of J.B. has been supported in part by the U.S. National Science Foundation under Grant PHY-1215979. The work of M.C. and J.S. has been partially supported by MINECO projects FPA2006-05294 and FPA2010-17915, by Junta de Andalucía grants FQM 101 and FQM 6552. M.C. is also supported by the MINECO under the FPU program.

References

[1] W. Buchmuller and D. Wyler, Nucl. Phys. B 268 (1986) 621.

[2] R. Rattazzi, Z. Phys. C 40 (1988) 605; B. Grzadkowski, Z. Hioki, K. Ohkuma and J. Wudka, Nucl. Phys. B 689 (2004) 108 [hep-ph/0310159]; P. J. Fox, Z. Ligeti, M. Papucci, G. Perez and M. D. Schwartz, Phys. Rev. D 78 (2008) 054008 [arXiv:0704.1482 [hep-ph]]; J. A. Aguilar-Saavedra, Nucl. Phys. B 812 (2009) 181 [arXiv:0811.3842 [hep-ph]]; Nucl. Phys. B 821 (2009) 215 [arXiv:0904.2387 [hep-ph]]; C. Grojean, W. Skiba and J. Terning, Phys. Rev. D 73 (2006) 075008 [hep-ph/0602154].

[3] B. Grzadkowski, M. Iskrzynski, M. Misiak and J. Rosick, JHEP 1010 (2010) 085 [arXiv:1008.4884 [hep-ph]].
[4] R. Contino, M. Ghezzi, C. Grojean, M. Muhlleitner and M. Spira, JHEP 1307 (2013) 035 [arXiv:1303.3876 [hep-ph]].

[5] N. Di Bartolomeo and M. Fabbrichesi, Phys. Lett. B 406 (1997) 237 [hep-ph/9703375]; A. E. Nelson, Phys. Rev. Lett. 78 (1997) 4159 [hep-ph/9703379]; W. Buchmuller and D. Wyler, Phys. Lett. B 407 (1997) 147 [hep-ph/9704317]; V. D. Barger, K. -m. Cheung, K. Hagiwara and D. Zeppenfeld, Phys. Rev. D 57 (1998) 391 [hep-ph/9707412]; A. F. Zarnecki, Eur. Phys. J. C 11 (1999) 539 [hep-ph/9904334]; K. -m. Cheung, Phys. Lett. B 517 (2001) 167 [hep-ph/0106251]; A. Friedland, M. L. Graesser, I. M. Shoemaker and L. Vecchi, Phys. Lett. B 714 (2012) 267 [arXiv:1111.5331 [hep-ph]].

[6] M. Carpentier and S. Davidson, Eur. Phys. J. C 70 (2010) 1071 [arXiv:1008.0280 [hep-ph]].

[7] E. Eichten, K. D. Lane and M. E. Peskin, Phys. Rev. Lett. 50 (1983) 811, and references there in.

[8] N. D. Christensen and C. Duhr, Comput. Phys. Commun. 180 (2009) 1614 [arXiv:0806.4194 [hep-ph]].

[9] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer and T. Stelzer, JHEP 1106 (2011) 128 [arXiv:1106.0522 [hep-ph]].

[10] T. Sjostrand, S. Mrenna and P. Z. Skands, JHEP 0605 (2006) 026 [hep-ph/0603175].

[11] S. Ovyn, X. Rouby and V. Lemaitre, arXiv:0903.2225 [hep-ph].

[12] ATLAS Collaboration, ATLAS-CONF-2013-017.

[13] CMS Collaboration, CMS-PAS-EXO-12-027; CMS-PAS-EXO-12-031.

[14] J. Beringer et al. [Particle Data Group Collaboration], Phys. Rev. D 86 (2012) 010001.

[15] Z. Han and W. Skiba, Phys. Rev. D 71 (2005) 075009 [hep-ph/0412166].

[16] F. del Aguila and J. de Blas, Fortsch. Phys. 59 (2011) 1036 [arXiv:1105.6103 [hep-ph]].

[17] J. de Blas, J. M. Lizana and M. Perez-Victoria, JHEP 1301 (2013) 166 [arXiv:1211.2229 [hep-ph]].

[18] S. Schael et al. [ALEPH and DELPHI and L3 and OPAL and LEP Electroweak Working Group Collaborations], arXiv:1302.3415 [hep-ex].

[19] http://www-d0.fnal.gov/Run2Physics/WWW/results/np.htm D0 note 4922-CONF, D0 note 4552-CONF.