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CompHEP: developments and applications

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Abstract. New developments of the CompHEP package and its applications to the top quark and the Higgs boson physics at the LHC collider are reviewed. These developments were motivated mainly by the needs of experimental searches of DO (Tevatron) and CMS (LHC) collaborations where identification of the top quark and the Higgs boson in the framework of the Standard Model (SM) or possible extensions of the SM played an important role. New useful features of the CompHEP Graphics User Interface (GUI) are described.

1. Introduction

The general plan of development of the CompHEP project was proposed more than twenty five years ago [1]. Despite the fact that the initial objectives of the project were related to the calculation of the most relevant for the 1990-ies signal and background processes at the e^+e^- collider LEP2 and the $p\bar{p}$ collider Tevatron, very general approach to the simulation of particle production channels was developed. It was supposed to generate unweighted events for the detector simulation of any signal in the SM or beyond using a database for basic Lagrangians which would allow to generate complete gauge-invariant sets of diagrams for the signal and the irreducible background in the fully automatic regime with the following evaluation of squared amplitudes. The original scheme can be found in [2]. The primary version of CompHEP used the Pascal language for PC AT and generated automatically REDUCE [3] format code for the squared amplitude corresponding to a gauge-invariant set of diagrams [2, 4]. It was expected that time that analytic results for the differential and the total cross sections could be straightforwardly obtained and used to interpret an experimental data. Obviously, such a development strategy did not allow to reduce to an acceptable form bulky analytical expressions for the matrix element squared which correspond to several tens or hundreds of diagrams, forming a complete set. So developers had to give up modelling based on compact analytical results (such as signal processes library in the approximation of infinitely small width) and go to generation of FORTRAN codes on the basis of exact symbolic matrix element squared, which were used in the following numerical integration. Automatic generation of FORTRAN codes suitable for the following Monte Carlo (MC) integration by means of BASES generator [5, 6], which was provided by the GRACE [7] group, was an important step forward. Jointly, although using different methods, MC calculations were performed for a large set of LEP2 processes [8], which allowed to test reliably all the algorithms involved in calculation. A number of phenomenological applications were related not only to e^+e^- mode, but also to possible γe and $\gamma\gamma$ modes of JLC



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and TESLA linear colliders [9]. In the following the channels of four-fermion production at LEP2 were evaluated [10]–[14], which were the first calculations of high precision at the complete tree-level. Numerous cross-checks of CompHEP and GRACE algorithms and comparisons of results for a large set of physical channels were very important for the following applications to collider physics.

In the last twenty years extensive symbolic and numerical calculations and generation of unweighted events for LEP2, HERA, TESLA, Tevatron, ILC and LHC analyses [15]–[30],[31] have been performed by means of CompHEP versions 3 and 4 [32, 33, 34, 35]. Single top quark production at the Tevatron $p\bar{p}$ collider [36] was followed by the single top observation at the LHC [37, 38]. CompHEP-based calculations of the complete tree-level sets of diagrams and the following event generation at the next-to-leading order (NLO) level were used for analyses of the single top quark signal [39]. Simulations of the single top quark production are important both for precise measurements and for searches of new physics [40, 41]. Convincing statistical significance determined a discovery of the Higgs-like boson signal at the LHC in 2012 [42, 43], which was investigated intensively in many production channels for identification purposes, either it was a signal of the Standard Model (SM) Higgs boson or a signal beyond the SM (BSM signal). Simulation of the Higgs boson signal at the LHC can be sensibly performed only for complete sets of tree-level diagrams, when large backgrounds, typical for hadronic colliders, can be put under control. A number of CompHEP technical developments which have been used in the LHC analyses are described in some details below.

2. Model-independent SM extensions for the top quark and the Higgs boson production

In order to measure precisely the couplings of the Higgs boson to vector bosons and fermions of the SM or a model BSM, a combined analysis of all the observed production channels has been performed. Combined analysis gives a possibility to extract 'pseudo observables' [44, 45] which depend on ratios of the experimentally observed production cross sections and decay widths to those calculated in the SM. In such analyses it is assumed that properties of the SM Higgs boson are modified by a new physics at the TeV scale Λ , so the SM is an effective theory at the W^\pm, Z scale. In the framework of the technical modification under consideration either a generic set of the higher-dimension effective operators is introduced in addition to the SM Lagrangian (note that the same set of effective operators can be a remnant of different field theory models at a multiTeV energy scale), or consequences of a definite renormalizable model are evaluated at the electroweak scale. In both types of extensions the question to what extent the observed boson is consistent with the SM Higgs boson seems most interesting to be addressed.

Extensions by the dimension-six effective operators have been considered recently in different bases (e.g.[46]–[49]). In the following we use [50, 51, 52] where a rather general framework of the SM extension by the dimension-six effective operators was analysed. At the electroweak energy scale the new physics degrees of freedom can be integrated out and the low-energy effective Lagrangian can be written as

$$L_{eff} = L_{SM} + \frac{1}{\Lambda^2} \sum_{k=V,F} C_{k\Phi} O_{k\Phi}$$

where Λ is a scale of new physics and the anomalous couplings $C_{k\Phi}$ modify the SM Higgs boson couplings to the vector bosons and to the fermions. A general set of the dimension-six operators from [50] in the Buchmueller-Wyler basis [53] modified by the subtraction of v.e.v.: $\Phi^\dagger\Phi \rightarrow \Phi^\dagger\Phi - v^2/2$ (see [54]) to avoid undesirable mixing in the gauge field kinetic terms, can be reduced to a restricted set of only five fermion-Higgs and vector boson-Higgs operators $O_{t\Phi}$, $O_{b\Phi}$, $O_{\tau\Phi}$ and $O_{\Phi}^{(1)}$, $O_{\Phi G}$, disposing the tensor structure of interaction vertices identical to the

SM and dependent only on the two anomalous couplings. The coupling c_V rescales the vector boson-Higgs vertices, and the coupling c_F rescales the fermion-anti-fermion-Higgs vertices. The anomalous couplings C_n, C_{mn} in front of the dimension-six operators O_n, O_{mn} are conformably redefined [50], for example

$$c_F = 1 + C_{t\Phi} \cdot \frac{v^2}{\Lambda^2}, \quad c_V = 1 + \frac{v^2}{2\Lambda^2} \cdot C_{\Phi}^{(1)}, \quad c_G = c_F + \frac{6\pi}{\alpha_s} \cdot C_{\Phi G} \cdot \frac{v^2}{\Lambda^2}, \quad \dots$$

(here $v = 246$ GeV). The last equation above means that in the case under consideration the one-loop $H \rightarrow \gamma\gamma$ and $H \rightarrow gg$ vertices are 'resolved' in the sense that the anomalous parameters c_V and c_F are included in the one-loop effective c_G and c_γ couplings which parametrise $H \rightarrow gg$ and $H \rightarrow \gamma\gamma$ vertices. This circumstance is different from 'kappa-framework'.

Anomalous interactions of the third generation fermions (t, b) appear from the general local $SU(3) \times SU(2) \times U(1)$ invariant effective Lagrangian terms [56]. Seven dimension-six effective operators provide anomalous contributions to the Wtb vertex. Various contributions of these operators which include the gauge bosons and the Higgs sector isodoublet are usually denoted by $O_{qW}, O_{\Phi q}^3, O_{Db}, O_{bW\Phi}, O_{Dt}, O_{tW\Phi}$ and O_{t3} . Experimental restrictions on the rare processes exclude some contributions. Application of the equations of motion move some operators to other category leaving only two meaningful operators of the seven, $O_{bW\Phi}$ and $O_{tW\Phi}$:

$$\begin{aligned} O_{tW\Phi} &= C_{tW\Phi}[(\bar{q}_L \sigma^{\mu\nu} \tau^i t_R) \Phi + \Phi^+(\bar{t}_R \sigma^{\mu\nu} \tau^i q_L)] W_{\mu\nu}^i \\ O_{bW\Phi} &= C_{bW\Phi}[(\bar{q}_L \sigma^{\mu\nu} \tau^i b_R) \Phi + \Phi^+(\bar{b}_R \sigma^{\mu\nu} \tau^i q_L)] W_{\mu\nu}^i \end{aligned}$$

where q_L is the left-handed third-family doublet, Φ is the Higgs boson doublet, $\tau^i = \sigma^i/2$, $W_\mu = \tau^i W_\mu^i$. Redefining anomalous couplings C after rotation to the physical fields $f_{2L} = \frac{C_{tW\Phi} v \sqrt{2} m_W}{\Lambda^2 g}$ and $f_{2R} = \frac{C_{bW\Phi} v \sqrt{2} m_W}{\Lambda^2 g}$ ($v \sqrt{g^2 + g'^2} = 2m_Z$, $s_W^2 = 1 - m_W^2/m_Z^2$) we get the standard representation of the anomalous top quark interaction Lagrangian

$$L_{Wtb} = \frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (f_{1L} P_L + f_{1R} P_R) t W_\mu^- + \frac{g}{\sqrt{2}} \bar{b} \frac{\sigma^{\mu\nu}}{m_W} (f_{2L} P_L + f_{2R} P_R) t W_{\mu\nu}^- + h.c. \quad (1)$$

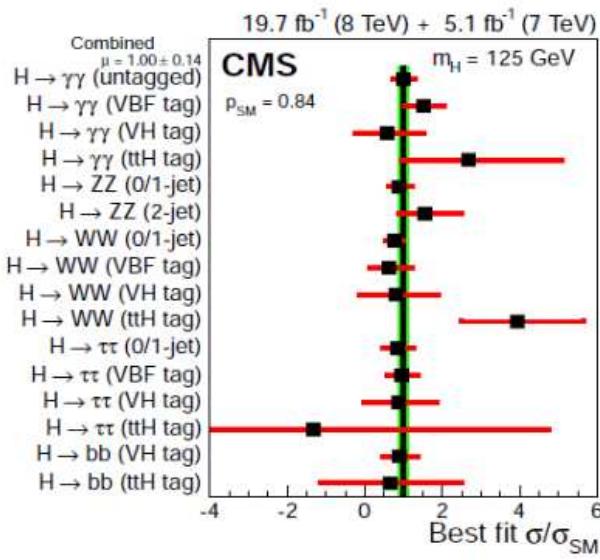


Figure 1. Signal strength and signal strength error for various groups of production channels. The best-fit σ/σ_{SM} for the overall combined analysis where combinations of channels grouped by the production mode and specific kinematics in the final state taken from [55] is indicated by vertical line. Horizontal bars indicate $\pm 1\sigma$ uncertainties in the best-fit σ/σ_{SM} values for individual channels, both statistical and systematic uncertainties are included. Combinations of channels are grouped by dominant decay modes when more than one decay mode contributes to the same final state. Tags in brackets indicate a specific production mechanism.

3. Global fits for the Higgs boson production channels

The method of exclusion contours reconstruction [57, 58, 59, 60] in the anomalous parameter space has been introduced to CompHEP version 4. Theoretical signal strengths in the infinitely small width approximation (ISW or production \times decay approximation) and for the complete gauge-invariant sets of diagrams are defined as

$$\mu_i^{ISW} = \frac{[\sum_j \sigma_{j \rightarrow h} Br(h \rightarrow i)]_{SME}}{[\sum_j \sigma_{j \rightarrow h} Br(h \rightarrow i)]_{SM}}; \quad \mu_i = \frac{\left[\sum_{j=1}^{N_{ch}} \sigma_{j \rightarrow H(\text{off-shell}) \rightarrow i} \right]_{SME}}{\left[\sum_{j=1}^{N_{ch}} \sigma_{j \rightarrow H(\text{off-shell}) \rightarrow i} \right]_{SM}}$$

where for ISW i is the number of Higgs boson decay channel and j is the number of Higgs production process for a given final state in the SM and in the SM extension (SME). If a signal strength $\hat{\mu}_i$ for an individual channel (see Fig.1) can be expressed using the observed cross section σ_{obs} , the background cross section σ_{backgr} and the SM signal cross section σ_{signal}^{SM} , then the global χ^2 for the signal strengths $\hat{\mu}_i$ is defined as

$$\hat{\mu}_i = \frac{\sigma_{obs,i} - \sigma_{backgr,i}}{\sigma_{signal,i}^{SM}}; \quad \chi^2(\mu_i) = \sum_i^{N_{ch}} \frac{(\mu_i - \hat{\mu}_i)^2}{\sigma_i^2}$$

for the number of production channels N_{ch} . Minimization of $\chi^2 \rightarrow \chi^2_{min}$ gives us 1σ , 2σ and 3σ regions $\chi^2 = \chi^2_{min} + \Delta\chi^2$ where $\Delta\chi^2$ is defined by cumulative distribution function. Assuming that the signal strengths of various channels have Gaussian distributions with the probability density functions (PDF's) having the expected values $\hat{\mu}_i$ and the dispersions σ_i normalized to one, combined PDF for a number of production channels can be found by multiplication of PDF's for the individual channels. The combined probability density function is also Gaussian characterized by μ_c and σ_c , $1/\sigma_c^2 = \sum_i^{N_{ch}} 1/\sigma_i^2$. The combined PDF allows one to determine, for example, 95% CL exclusion upper μ_U and lower μ_L limits on the signal strength parameter integrating the combined pdf from $\hat{\mu}$ to μ_U and from μ_L to $\hat{\mu}$, respectively, then equating the result to 0.95/2. If the SM is fully adequate, the values of μ_i are as close to one as allowed by experimental errors. Calculation of the $\Delta\chi^2$, see Fig.2, for the best fit defines a *given number \times CL* contours corresponding to the departure of the SM point (1, 1) from the best fit point in the (c_V, c_F) parameter plane. Contours in Fig.3 correspond to 65%, 90% and 99% best fit CL regions with $\Delta\chi^2$ less than 2.10, 4.61 and 9.21, respectively.

Besides the model-independent analyses described above, extensive model-dependent theoretical studies involving the package LanHEP [61, 62] for automatic generation of Feynman rules from the Lagrangian were performed for the MSSM two-doublet Higgs sector [63]-[69].

4. Separation of anomalous contributions to the single top production. Subsidiary fields.

In the situation when several anomalous couplings (AC) coming from different effective operators of higher dimension contribute to some particular production channel at the same time, experimental reconstruction of BSM effects in the multidimensional anomalous coupling space is technically difficult. Moreover, analyses of fancy anomalous mixtures in BSM amplitudes where the Breit-Wigner propagators are also dependent on the several AC are not meaningful with the straightforward calculation. Various anomalous contributions should be separated on the stage of unweighted events generation for the following detector simulation of the event samples which are dependent on an individual AC. Separation of congenerous contributions (e.g. of $\sim 1/\Lambda^2$ leading terms) in the events samples for experimental reconstruction is of major interest. Let us consider an example with the anomalous Wtb vertex, see Eq.(1), which includes three anomalous couplings (AC) beyond the SM. Besides the right-handed vector current coupling

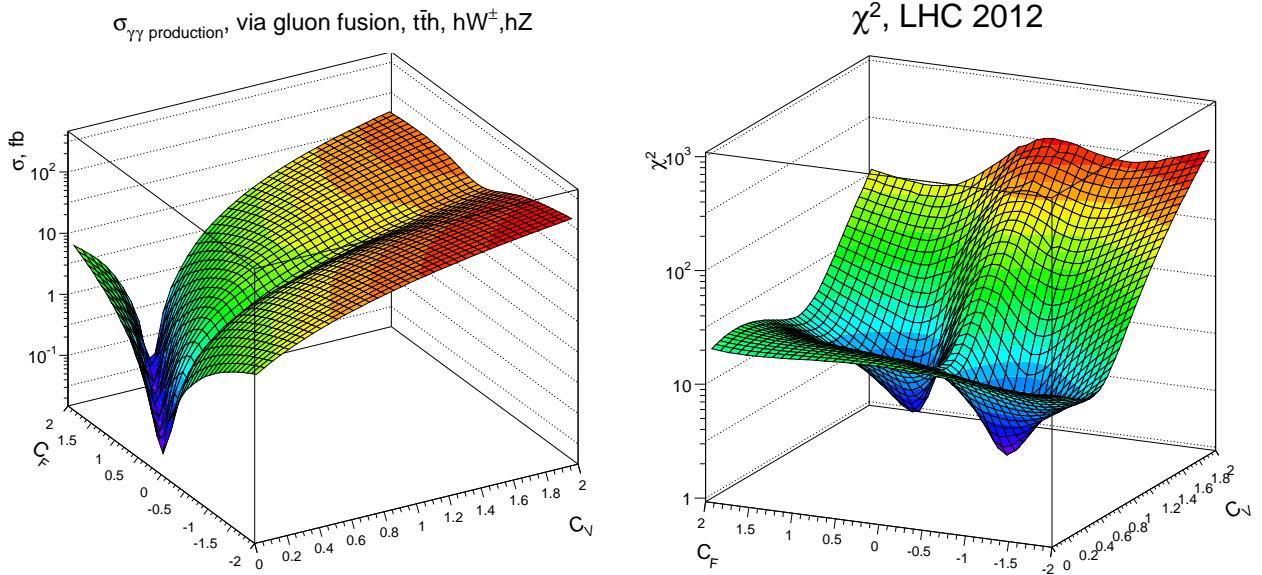


Figure 2. Three-dimensional plots in the (c_V, c_F) parameter space: (a) total cross section for $\gamma\gamma$ production processes at the LHC, $\sqrt{s} = 8$ TeV; (b) three-dimensional plot of χ^2 as a function of (c_V, c_F) , LHC $\sqrt{s} = 8$ TeV - all channels

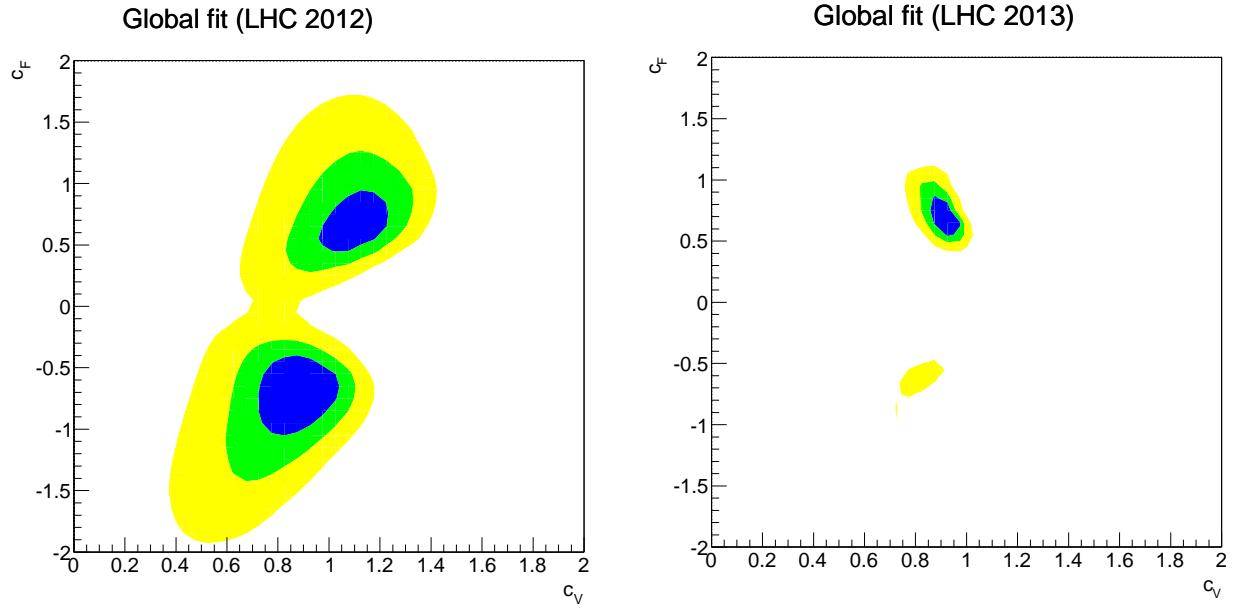


Figure 3. Left panel - three exclusion contours for the combined χ^2 fit in the (c_V, c_F) plane based on 2012 LHC data, right panel - the same based on 2013 LHC data. Blue, green and yellow areas correspond to $\Delta\chi^2 = 2.10, 4.61$ and 9.21 (CL of the fit is 65%, 90% and 99%), respectively. See [50] for details.

f_{1R} it is dependent on the couplings of anomalous magnetic moment type f_{2L} and f_{2R} . So we can write

$$\Gamma_\mu = \Gamma_\mu^{SM} + \Gamma_\mu^{NP_1} + \Gamma_\mu^{NP_2} + \Gamma_\mu^{NP_3}$$

and introduce three subsidiary bosons [70] in the CompHEP Lagrangian table

W boson SM	$\frac{g}{2\sqrt{2}}f_{1L}\gamma^\mu(1-\gamma_5)$
W boson subsidiary 1	$\frac{g}{2\sqrt{2}}f_{1R}\gamma^\mu(1+\gamma_5)$
W boson subsidiary 2	$\frac{g}{2m_W\sqrt{2}}f_{2L}\sigma^{\mu\nu}q_\nu(1+\gamma_5)$
W boson subsidiary 3	$\frac{g}{2m_W\sqrt{2}}f_{2R}\sigma^{\mu\nu}q_\nu(1-\gamma_5)$

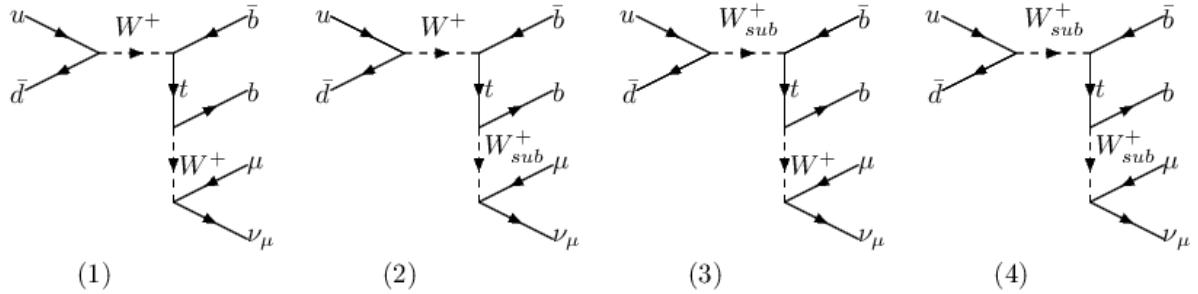


Figure 4. Diagrams (2), (3) and (4) include intermediate vector boson subsidiary fields W_{sub} .

Diagrams for the four-fermion production process $u\bar{d} \rightarrow b\bar{b}\mu^+\nu_\mu$, where anomalous Wtb vertices contribute to the production part and to the decay part of each diagram taken in the infinitely small width approximation, are shown in Fig.4. Diagrams (2),(3) and (4) include the intermediate subsidiary bosons $W_{1,2,3}$. If only f_{1R} coupling is not equal to zero in the Lagrangian Eq.(1), then the structure of matrix element squared for the sum of the four diagrams can be written in the form

$$\begin{aligned} |\mathbf{M}|^2 &\sim \frac{1}{\Gamma(f_{1L}, f_{1R})} [(f_{1L})^2 P_1 + (f_{1R})^2 P_2] \times [(f_{1L})^2 D_1 + (f_{1R})^2 D_2] \\ &\sim \frac{1}{\Gamma(f_{1L}, f_{1R})} [(f_{1L})^4 P_1 D_1 + (f_{1L})^2 (f_{1R})^2 P_1 D_2 + (f_{1L})^2 (f_{1R})^2 P_2 D_1 + (f_{1R})^4 P_2 D_2] \end{aligned}$$

where P_1 and P_2 denote the production functions dependent on the four-momenta products and D_1 and D_2 denote the decay functions. Apparently the term $P_1 D_2$ and the term $P_2 D_1$ are of the order of Λ^{-2} while the term $P_2 D_2$ is of the order of Λ^{-4} . They can be easily separated after generation of all squared diagrams by the CompHEP and then omitting diagrams with the two subsidiary bosons W_{sub} . The unweighted event samples are generated for restricted sets of squared diagrams. Using a schematic denomination $(f_{1L}f_{1R}00) \leftrightarrow f_{1L}(1000)$ for an event sample where, for example, only f_{1R} anomalous coupling is taken to be non-zero, we can write

$$(f_{1L}f_{1R}00) \Leftrightarrow (f_{1L})^4 \otimes (1000) \oplus (f_{1L})^2 (f_{1R})^2 \otimes (1100)_{sub} \oplus (f_{1R})^4 \otimes (0100)_{sub}^{sub}.$$

where (0100) event sample coming from diagrams with the two subsidiary bosons does not participate in the simulation.

Data and model comparison of Bayesian Neural Network discriminant (BNN) for the LHC physics analysis of the single top quark production based on the $(f_{1L}0f_{2L}0)$ event samples (left weak current SM contribution and the left anomalous tensor contribution) are shown in Fig.5. Exclusion contours in the (f_{1L}, f_{1R}) plane generated for the case $(f_{1L}f_{1R}00)$ of the right vector coupling are shown in Fig.6.

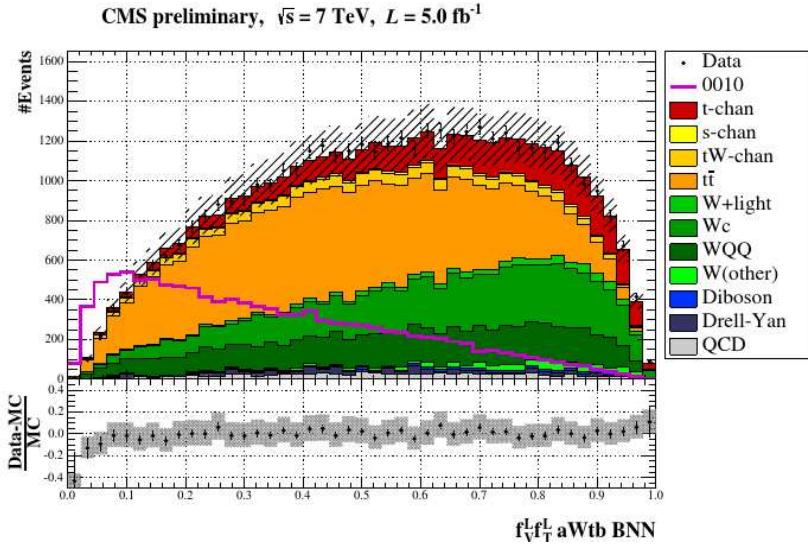


Figure 5. Data and model comparison of BNN discriminant for anomalous Wtb coupling in the case ($f_{1L}f_{1R}00$), see more details in [71]. The BNN discriminant was trained to separate the SM events and possible events with f_{2L} coupling in the anomalous Wtb vertex. The hashed band corresponds to systematic uncertainty.

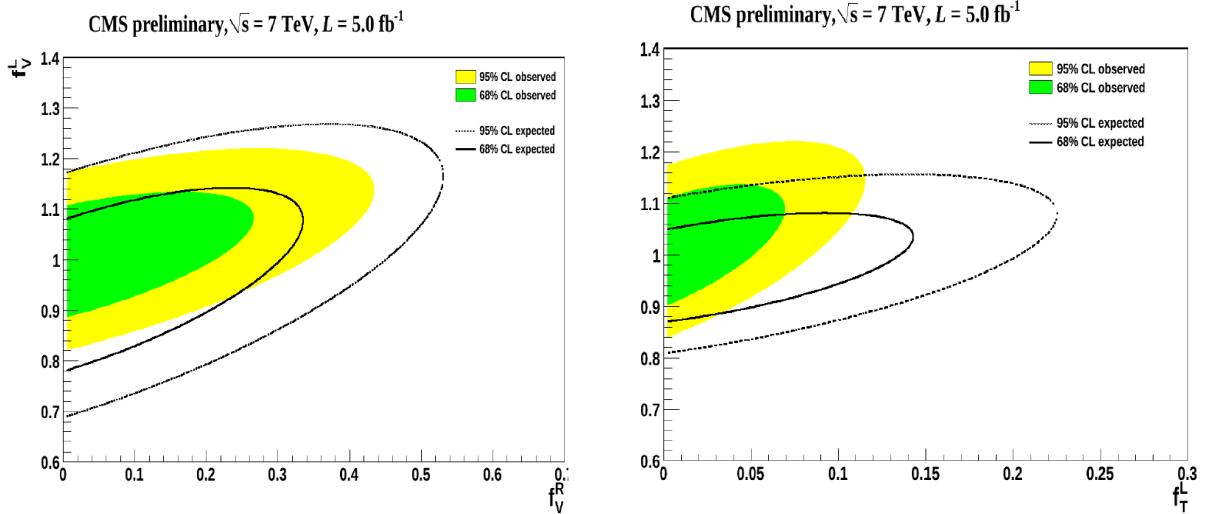


Figure 6. Exclusion contours for the top quark anomalous couplings f_{1L}, f_{1R} (left panel) and f_{2L}, f_{2R} (right panel) taken from [71].

5. New features of GUI

New features of the CompHEP Graphics User Interface (GUI) useful for generation of global fits and exclusion contours are introduced in version 4.6

- Implementation of external functions in the CompHEP Constraints Model Table
- Multiplication of selected squared diagrams on an external function
- Table calculations and algebraic operations with tables cross section/width vs parameters
- ROOT code generation to draw table functions (3D surfaces or 2D contours)
- Generation of the 3D plots for phase space distributions dependent on a model parameter

Table calculations and algebraic operations with tables are needed in the BSM analyses when the total width in the Breit-Wigner propagator of an intermediate particle depends on a number of anomalous couplings. In this case multidimensional total width table is generated in the anomalous coupling space for all partial decay channels which are then summed and used

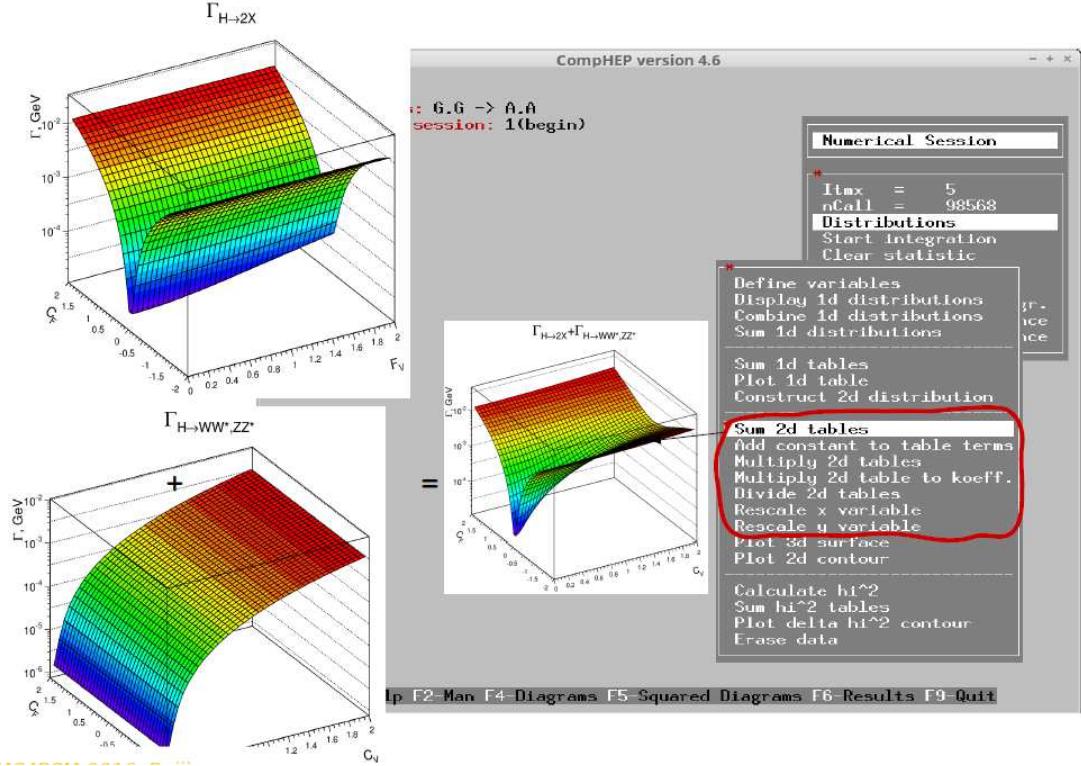


Figure 7. An example of CompHEP GUI for operation with tables for the decay width $H \rightarrow 2X$ dependent on the anomalous couplings c_V and c_F .

in the squared amplitude calculation for the signal. An example of GUI for the Higgs boson decay $H \rightarrow \gamma\gamma$ in the (c_V, c_F) coupling space (see Section 2) is depicted in Fig.7. An example of ROOT code generation for the sub-process $u\bar{d} \rightarrow t\bar{d}$ can be found in Fig.8 where the 3D t -quark distribution is generated for different values of an anomalous parameter.

6. Summary

The ideology of automatic generation of amplitudes, corresponding to the full set of Feynman rules for a given BSM Lagrangian, symbolic calculations and precise Monte Carlo integration of the complete tree-level diagram sets with subsequent generation of unweighted events demonstrated over the last two decades its efficiency for calculation of signal and background reactions at LEP2, HERA, NLC and simulation of processes for the Tevatron and the LHC.

The initial goal of the CompHEP project discussed in 1988 [1], was the establishment of an effective tool for automatic calculation of the SM signals and backgrounds at UNK (IHEP, Serpukhov) and LEP2. Although the UNK project was terminated and real practical applications started from the LEP2 physics and have been continued for linear colliders and the LHC, it is interesting to what extent the created product was the original intent. Below we reconstruct distributions of 560 citations to the NIM paper (see [33]) in the period 2004-2016, see Fig.9. Distributions of citations over a specific scientific topics and over applications by experimental collaborations are based on the INSPIRE database. Note that the package was used not in the way it had been expected. Most theoretical publications are considering extensions of the SM.

Number of studies for various extensions of the Standard Model in the CompHEP format, published by users of the package, is impressively large despite of the fact that beyond the

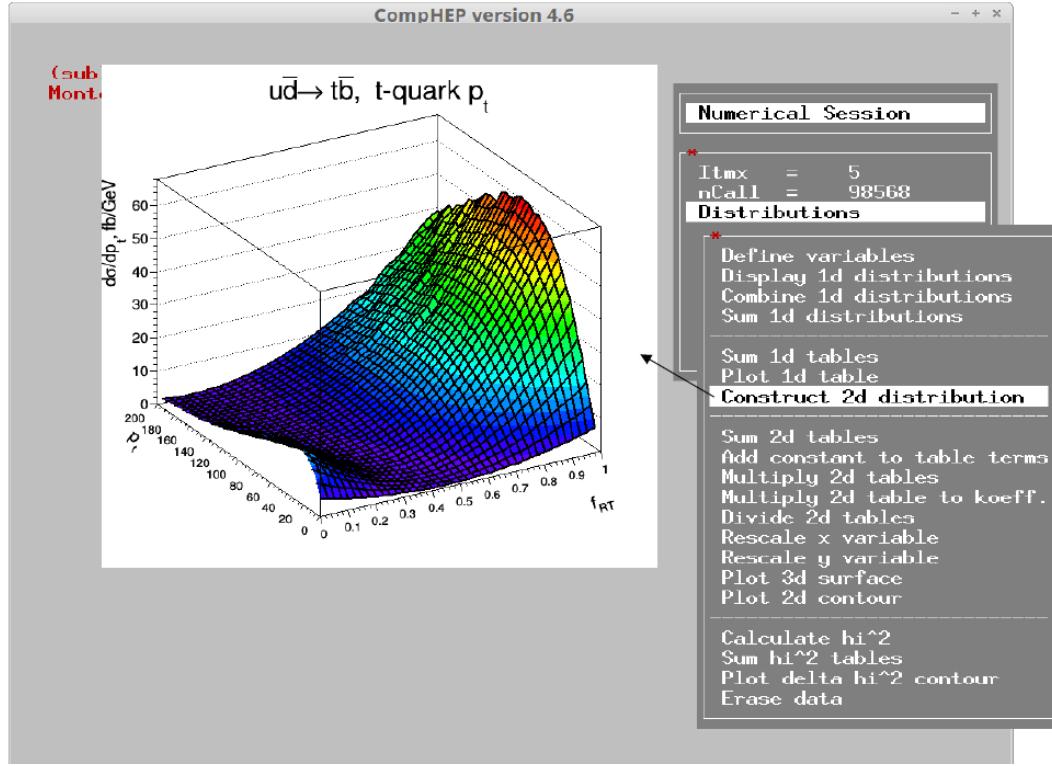


Figure 8. An example of CompHEP GUI for the ROOT code generation when the phase space distribution over p_T is dependent on an anomalous coupling.

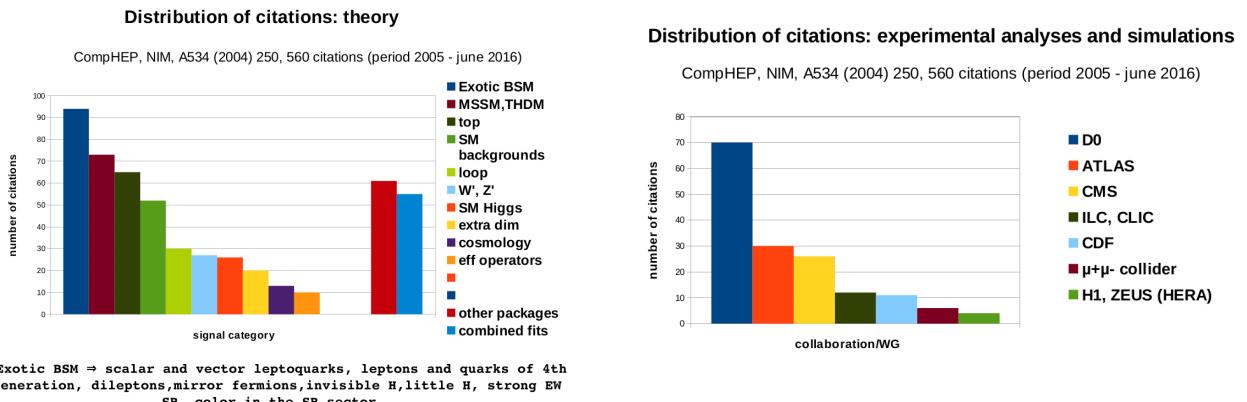


Figure 9. Distributions of theoretical and experimental citations.

'proliferation' of chiral $SU(2)$ multiplets and singlets of fundamental fermions, CompHEP version 4 provides rather restricted possibilities for work with models of higher-rank gauge symmetry groups. Rich possibilities are going to be implemented in version 5 of CompHEP, which includes the symbolic calculation kernel based on FORM [72, 73].

6.1. Acknowledgments

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