

New functionality of CompHEP 4.6 package

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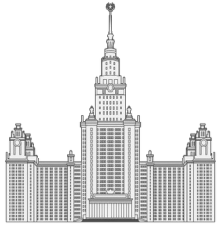
in collaboration with

E. Boos, M. Dubinin, L. Dudko, A. Kryukov, V. Edneral, V. Savrin

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University

QFTHEP-270 conference

CompHEP is a program for calculating the characteristics and modeling the processes of production and decay of elementary particles at colliders



CompHEP was created in 1998 by scientists of the SINP MSU.

A. Pukhov, V. Ilyin, E. Boos, V. Edneral, A. Kryukov, M. Dubinin, V. Savrin, A. Semenov, D. Kovalenko, S. Shichanin.

- Teaching Quantum Field Theory to MSU students
- User-friendly graphical interface and high level of automation

- Calculation of processes characteristics in symbolic and numerical form, construction of kinematic distributions

Model: SM, unitary gauge

List of (anti)particles

G(G)	A(A)	Z(Z)	Z boson
gluon	photon		
W+(W-)	W boson		
nm(Nm)	mu-neut		
l(L)	tau-lep		
c(C)	c-quark		
b(B)	b-quark		

Enter Final State:
Exclude diagrams w
Keep diagrams with

(sub)Process: u, b -> ne, E, d, b
Monte Carlo session: 1(begin)

#IT	Cross section [pb]	Error %	nCall	chi**2
1	5.4527E+00	3.40E-01	87480	
2	5.4623E+00	3.36E-01	87480	
3	5.4648E+00	3.33E-01	87480	
4	5.4946E+00	3.27E-01	87480	
5	5.4704E+00	3.27E-01	87480	
< >	5.4692E+00	1.49E-01	437400	0.7

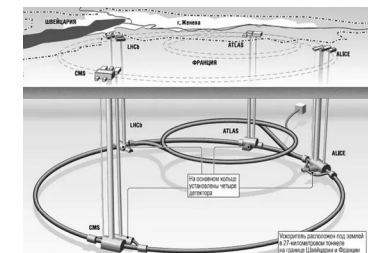
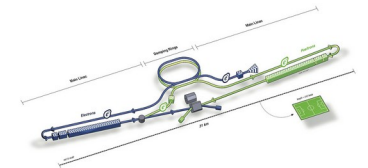
Numerical Session

Itmx = 5
nCall = 93312
Use Form Factor NO
Distributions
Start integration
Clear statistic
Clear grid
Generate events
All subprocess integr.
2 parameter dependence
1 parameter dependence

F1-He1p, F2-Man, PgUp, PgDn

F1-He1p F2-Man F4-Diagrams F5-Squared Diagrams F6-Results F9-Quit

- Creation of Monte Carlo generators for hadron and electron-positron colliders NICA, LHC, TEVATRON, FCC, HERA, LEP, ILC etc.



$$\frac{d\sigma_{SM}(\hat{s})_{ub \rightarrow db\nu e^+}}{d\epsilon \cdot d \cos \theta \cdot d\phi} = \frac{\alpha^2 \cdot V_{ud}^2 \cdot V_{tb}^2}{8 \cdot 3 \cdot \sin^4 \Theta_W \cdot m_W^2 \cdot (1 - r^2)^2 (1 + 2r^2)} \cdot \frac{(\hat{s} - m_t^2)^2}{\hat{s}(\hat{s} - m_t^2 + m_W^2)} \cdot (1 - \epsilon) \cdot \epsilon \cdot (1 + \cos \theta)$$

Modern requirements for the CompHEP package

- Due to the increased accuracy of modern collider experiments, there is a request for performing calculations of characteristics and modeling with a higher level of theoretical confidence in the next-to-leading order of perturbation theory with complicated form factors at the interaction vertices.
- Modern models of new physics have many new parameters whose values are not defined. Usually it is necessary to sort through the entire multidimensional set of such values, perform calculations with each of the defined sets of values and compare the results of calculations based on them with experimental data. The listed chain of actions is extremely resource-intensive and is associated with the risk of making errors. There is a need to automate this process.
- For a correct and theoretically justified comparison of simulation results with experimental data, it is necessary to apply modern statistical analysis methods to build confidence regions in the model parameter space and identify the most reliable values of these parameters.
- To improve the capabilities of theoretical analysis and search for the most sensitive characteristics, it is necessary to present the simulation results in a convenient graphical format in the form of one-dimensional, two-dimensional and three-dimensional graphs, which can be used for further analysis in the ROOT package.

Calculations with complicated form factors. Option 1

The model vertices use complicated form factors that depend on the momenta of the incoming particles, which arise from calculations in the next-to-leading order of perturbation theory.

$$F_W = -(2 + 3y_W + 3y_W(2 - y_W)f(y_W)),$$

$$F_t = y_t(1 + (1 - y_t)f(y_t)), \quad y_i = 4m_i^2/(2p_1 \cdot p_2),$$

$$f(z) = \begin{cases} \left[\sin^{-1} \left(\frac{1}{\sqrt{z}} \right) \right]^2, & z \geq 1 \\ -\frac{1}{4} \left[\log \frac{1+\sqrt{1-z}}{1-\sqrt{1-z}} - i\pi \right]^2, & z < 1. \end{cases}$$

First possibility: Call the user-defined form factor function in a CompHEP **symbolic session**, in the model's list of functional expressions.

The image shows two windows from the CompHEP software. The top window is the 'Constraints' window, which lists various parameters and their expressions. The 'myfunc3(yW, 2)' entry is highlighted in blue. The bottom window is a C code editor showing the implementation of the 'myfunc3' function. The function takes two arguments, 'ym' and 'keyp', and returns a 'double' result. The code uses 'asin' and 'log' functions to calculate the form factor.

These form factors are used in the vertex functions of the model.

The names «myfunc1, myfunc2, myfunc3,...» are reserved for these functions.

Calculations with complicated form factors. Option 2

Second possibility Call a user-defined form factor function in a CompHEP **numerical session** in the list of numerical procedures.

The image shows a screenshot of the CompHEP version 4.6 interface. The main window displays the following text:

```
(sub)Process: G,G -> A,A  
Monte Carlo session: 1(continue)
```

An inset window titled "userFactor.c" shows the following C code:

```
29 static double real_func(double ym, double keyp)  
30 {  
31     double result, Fym, as, sqr, logs;  
32  
33     as = asin(1./sqrt(fabs(ym)));  
34     sqr = sqrt(fabs(1.-ym));  
35     logs = log((1.+sqr)/(1.-sqr));  
36  
37  
38     if(ym >= 1.0) Fym = as*as;  
39     else         Fym = -0.25*(logs*logs-9.869587728);  
40  
41     if(keyp < 1.5) result = ym*(1.+(1.-ym)*Fym);  
42     else         result = -(2. + 3.*ym + 3.*ym*(2.-ym)*Fym);  
43  
44     return result;  
45 }  
46  
47 static double im_func(double ym, double keyp)  
48 {  
49     double result, Fym, as, sqr, logs;  
50
```

A "Numerical Session" dialog box is open, showing the following configuration:

```
Itmx = 5  
nCall = 100000  
Use Form Factor YES  
Distributions  
Start integration  
Clear statistic  
Clear grid  
Generate events  
All subprocess integr.  
2 parameter dependence  
1 parameter dependence
```

An arrow points from the "Use Form Factor YES" line in the dialog box to the corresponding code in the "userFactor.c" window.

This form factor is used as a common multiplier of the full process matrix element.

Using table-defined functions in model parameter expressions. Option 1

Call the user-defined function specified as a table of values and defined in the file "width1.txt" in the CompHEP **numerical session** in the list of functional expressions of the model.

The image shows three overlapping windows from the CompHEP version 4.6 software:

- Model Window:** Displays the model name `_H_R_mix_complex` and an abstract describing the package's purpose for calculating decay and collision processes. It includes an "Edit Model" button and a menu with options like Variables, Constraints, Particles, Lagrangian, and Composite.
- Constraints Window:** A table listing various parameters and their corresponding expressions. The entry for `wR` is `width2(MR, sint)`, which is highlighted with a blue selection bar. Other entries include `koeff`, `wH`, `c`, `b`, `yt`, `yW`, `loopt`, `loopW`, `Im1t`, `Im1W`, `RFF`, `HFF`, `Ranom`, `Hanom`, `RGG`, `ImRGG`, `HGG`, `ImHGG`, `RAA`, `ImRAA`, `HAA`, and `ImHAA`.
- width1.txt Window:** A text file containing a table of numerical values. The data is as follows:

Column 1	Column 2	Column 3
1.000000E+02	-7.071070E-01	9.265819E-04
1.000000E+02	-6.788227E-01	1.013980E-03
1.000000E+02	-6.505384E-01	1.099670E-03
1.000000E+02	-6.222542E-01	1.183458E-03
1.000000E+02	-5.939699E-01	1.265209E-03
1.000000E+02	-5.656856E-01	1.344767E-03
1.000000E+02	-5.374013E-01	1.422014E-03
1.000000E+02	-5.091170E-01	1.496865E-03
1.000000E+02	-4.808328E-01	1.569201E-03
1.000000E+02	-4.525485E-01	1.638916E-03
1.000000E+02	-4.242642E-01	1.705987E-03
1.000000E+02	-3.959799E-01	1.770256E-03
1.000000E+02	-3.676956E-01	1.831733E-03
1.000000E+02	-3.394114E-01	1.890312E-03
1.000000E+02	-3.111271E-01	1.945908E-03
1.000000E+02	-2.828428E-01	1.008526E-02

The names «width1.txt, width2.txt, width3.txt,...» are reserved for these functions.

Using table-defined functions in model parameter expressions. Option 2

Multiplication of any part of the square of the amplitude modulus by a function specified as a table of values and defined in the file "koeff1.txt" in the CompHEP **symbolic session** in the list of functional expressions of the model.

The image shows two windows from the CompHEP version 4.6 software. The left window, titled "Constraints", displays a list of parameters and their expressions. The right window, titled "Delete, On/off, Restore, Latex, Ghosts", shows a diagram editor with two diagrams and a red label "koeff" pointing to a specific part of the diagram.

Name	Expression
koeff	koeff1(MR,sint)
wH	width1(MR,sint)
wR	width2(MR,sint)
c	width3(MR,sint)
b	b1*c
yt	myfunc2(Mtop)
yW	myfunc2(MW)
loopt	myfunc3(yt,1)
loopW	myfunc3(yW,2)
Im1t	myfunc4(yt,1)
Im1W	myfunc4(yW,2)
RFF	-(b1*cost-b*sint-sint/v)
HFF	-(b1*sint+b*cost+cost/v)
Ranom	b1*cost-b*sint
Hanom	b1*sint+b*cost
RGG	7*Ranom+loopt*(-RFF)
ImRGG	Im1t*(-RFF)
HGG	7*Hanom+loopt*(-HFF)
ImHGG	Im1t*(-HFF)
RAA	-11/(3)*Ranom+(loopW+8/(3)*loopW)*(-RFF)
ImRAA	(Im1W+8/(3)*Im1t)*(-RFF)
HAA	-11/(3)*Hanom+(loopW+8/(3)*loopW)*(-HFF)
ImHAA	(Im1W+8/(3)*Im1t)*(-HFF)

The diagram editor shows two diagrams. The top diagram is a tree-level process with external lines G, H, A, A, H, G and internal lines H, A, A. The bottom diagram is a tree-level process with external lines G, R, A, A, R, G and internal lines R, A, A. A red label "koeff" is placed below the top diagram, with a blue arrow pointing to it from the "koeff" entry in the constraints list.

The names «koeff1.txt, koeff2.txt, koeff3.txt,...» are reserved for these functions.

Calculating an array of decay width values depending on multidimensional array of model parameter values

In the decay width calculation menu in the CompHEP **numerical session**.

The sequence of screenshots illustrates the workflow in CompHEP 4.6:

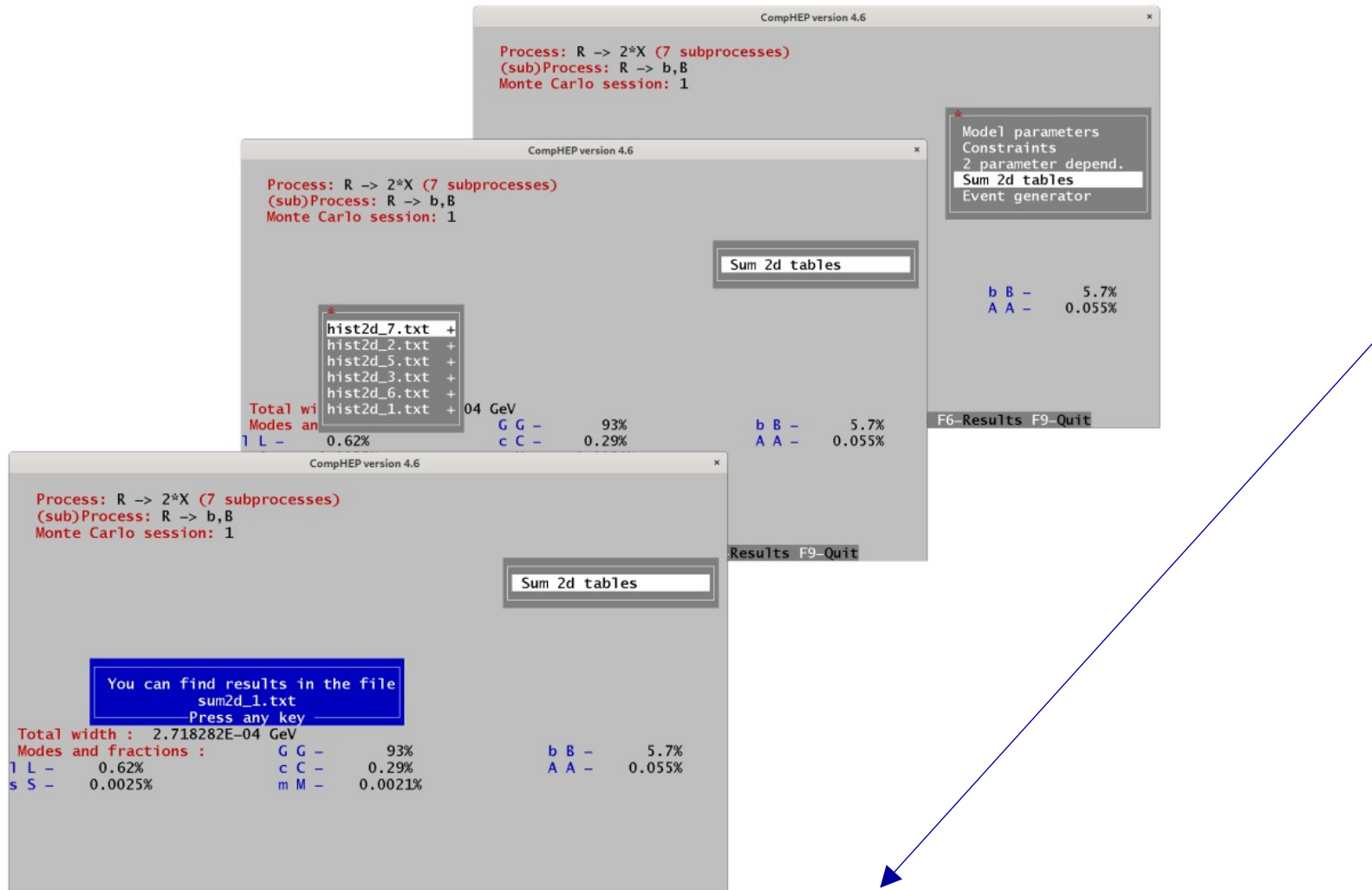
- Top-left screenshot:** Shows the main menu with options: Model parameters, Constraints, 2 parameter depend., Sum 2d tables, and Event generator. The '2 parameter depend.' option is highlighted.
- Top-right screenshot:** Shows the '2 parameter depend.' dialog box with a blue box around the text 'Enter second parameter' and 'Press any key'.
- Middle-right screenshot:** Shows the 'Choose parameter' dialog box with a list of parameters: b1= 0.00033, sint= 0, KG= 1.2076, KA= 0.93551, Kb= 0.6373, Kc= 0.419, Ks= 0.55, Km= 0.983, Ktau= 0.9933, GG= 1.2136, and Dummy= 0.
- Bottom-left screenshot:** Shows the 'Run table calculations?' dialog box with a red box around the text '(Y / N ?)'.
- Bottom-right screenshot:** Shows the final results table with the following data:

Total width : 2.718282E-04 GeV	
Modes and fractions :	
L - 0.62%	G G - 93%
S - 0.0025%	c C - 0.29%
	m M - 0.0021%
	b B - 5.7%
	A A - 0.055%

The table of width values is written to the file "width_N.txt".

Summation of arrays of partial decay width values

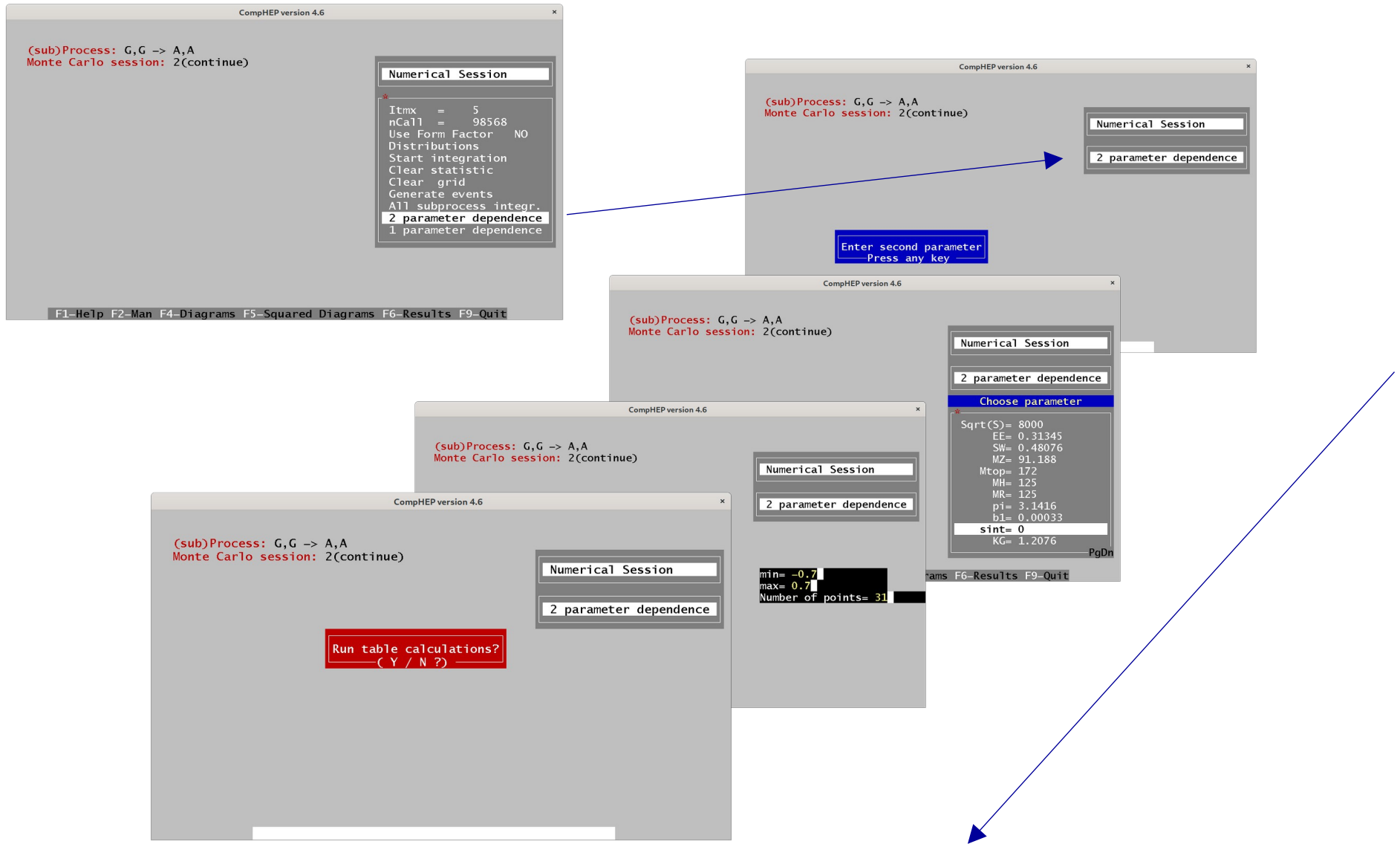
In the decay width calculation menu in the CompHEP **numerical session**.



The table of summed partial width values is written to the file "sum2d_N.txt".
This file can be renamed to "width_N.txt" and used as a table-defined function in the model.

Calculating an array of scattering cross-section values depending on multidimensional arrays of model parameter values (**Interactive mode**)

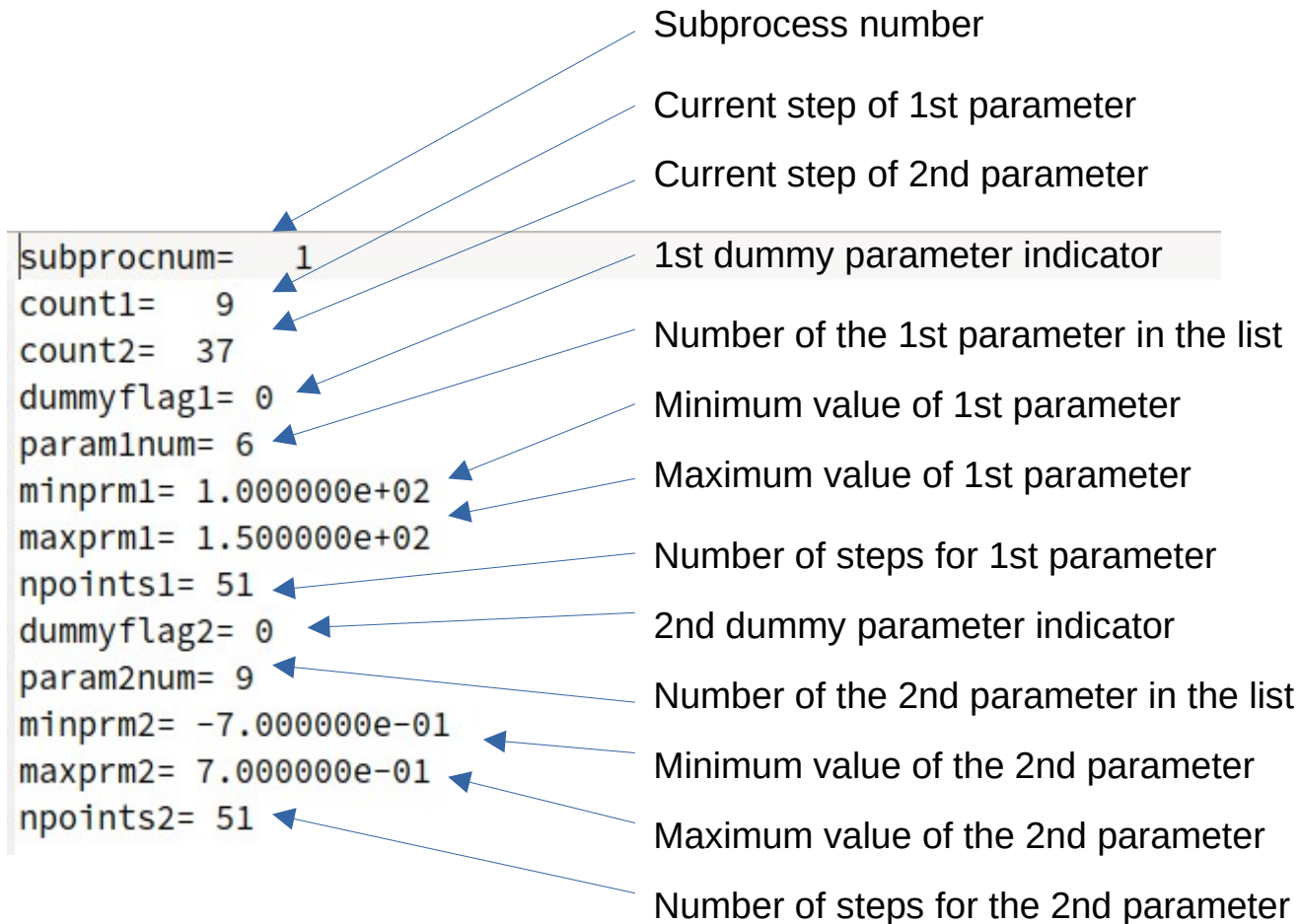
In the scattering cross-section calculation menu in the CompHEP **numerical session**.



The table of scattering cross-section values is written to the file "table2d_1.txt".

Calculating an array of scattering cross-section values depending on multidimensional arrays of model parameter values (**Batch mode**)

In command mode, edit the file "tablecalc.dat":



The image shows a text file named 'tablecalc.dat' with several parameters. Blue arrows point from descriptive text on the right to the corresponding values in the file. The parameters and their values are:

- subprocnum= 1 (Subprocess number)
- count1= 9 (Current step of 1st parameter)
- count2= 37 (Current step of 2nd parameter)
- dummyflag1= 0 (1st dummy parameter indicator)
- param1num= 6 (Number of the 1st parameter in the list)
- minprm1= 1.000000e+02 (Minimum value of 1st parameter)
- maxprm1= 1.500000e+02 (Maximum value of 1st parameter)
- npoints1= 51 (Number of steps for 1st parameter)
- dummyflag2= 0 (2nd dummy parameter indicator)
- param2num= 9 (Number of the 2nd parameter in the list)
- minprm2= -7.000000e-01 (Minimum value of the 2nd parameter)
- maxprm2= 7.000000e-01 (Maximum value of the 2nd parameter)
- npoints2= 51 (Number of steps for the 2nd parameter)

In command mode, run the command `./table_batch`.

Statistical processing of results and construction of confidence regions in the space of model parameters

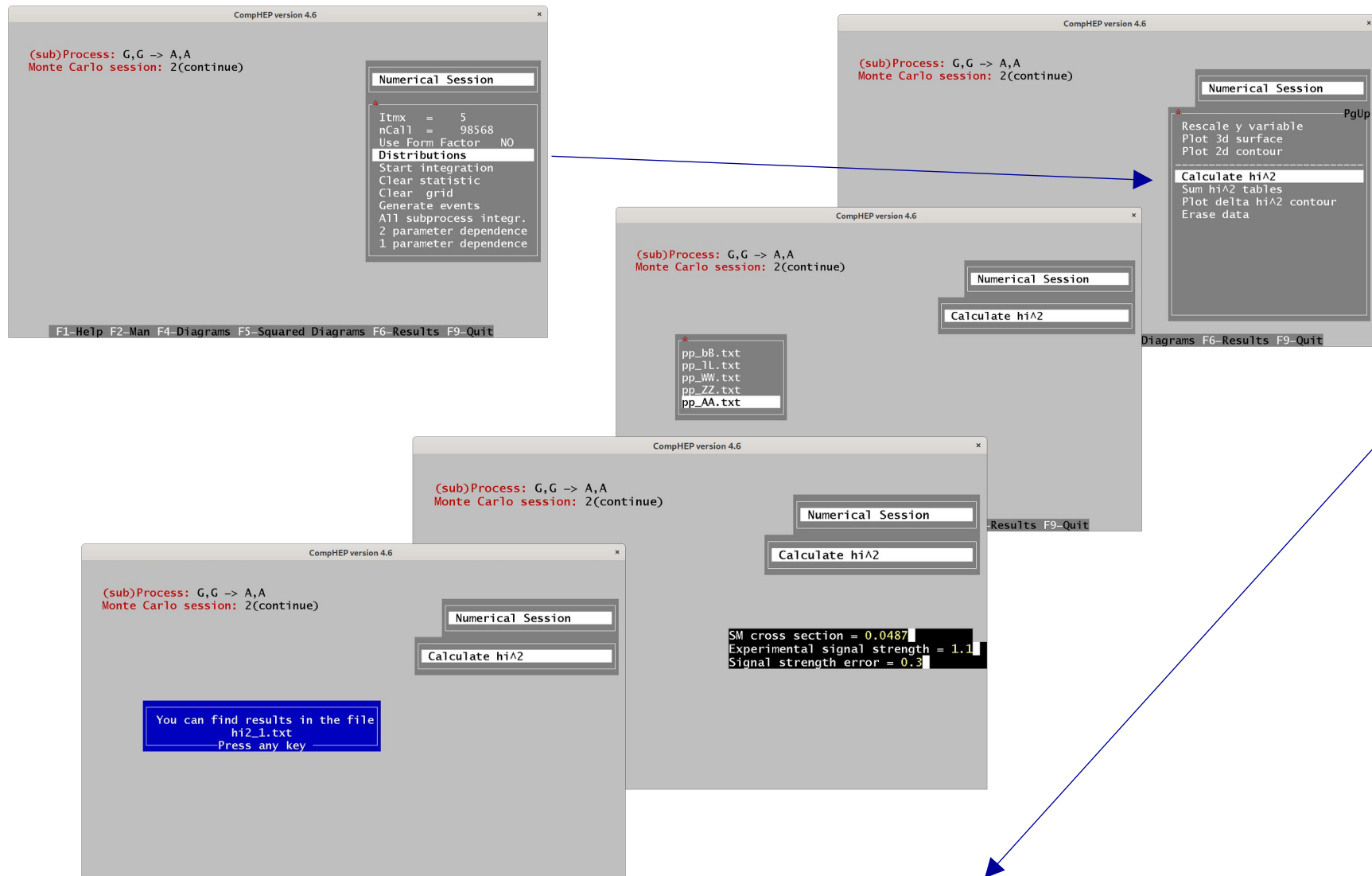
Confidence regions of parameters are determined by searching for the minimum of the function χ^2 :

$$\chi^2(\mu_i) = \sum_i^{N_{ch}} \frac{(\mu_i - \hat{\mu}_i)^2}{\sigma_i^2}$$

- where **ch** - is the number of channels for the production of a new particle, μ_i - theoretical (fitting) value of signal strength for a given channel, $\hat{\mu}_i$ - experimental value of signal strength for a given channel, σ_i - ошибка измерения экспериментальной силы сигнала для данного канала.
- The fitted value of the signal strength μ_i is defined as the value of the process cross-section predicted by the new model divided by the value of the cross-section predicted by the Standard Model:
$$\mu_i = \sigma_{bsm,i} / \sigma_{sm,i}$$
- The experimental value of signal strength is calculated as:
$$\hat{\mu}_i = \frac{N_{obs,i} - N_{backgr,i}}{N_{signal,i}^{SM}}$$
- where $N_{obs,i}$ - total observed number of events, $N_{obs,i}$ - number of background events, $N_{obs,i}$ - the number of events predicted by the Standard Model.
- Finding the minimum of the function χ^2 allows us to determine **1 σ , 2 σ , 3 σ** - confidence regions of the parameters using the formula:
$$\chi^2 = \chi^2_{min} + \Delta\chi^2$$
- where $\Delta\chi^2$ - is a quantile and is determined by the cumulative distribution function.

Calculating an array of χ^2 function values depending on multidimensional arrays of model parameter values

In the distribution construction menu in the CompHEP **numerical session**.



The table of scattering cross-section values is written to the file "hi2_1.txt".

New CompHEP functions for data processing and graphical presentation of results

In the distribution construction menu in the CompHEP **numerical session**.

CompHEP version 4.6

(sub)Process: G,G -> A,A
Monte Carlo session: 2(continue)

Numerical Session

- Define variables
- Display 1d distributions
- Combine 1d distributions
- Sum 1d distributions

- Sum 1d tables
- Plot 1d table
- Construct 2d distribution

- Sum 2d tables**
- Add constant to table terms
- Multiply 2d tables
- Multiply 2d table to koeff.
- Divide 2d tables
- Rescale x variable
- Rescale y variable
- Plot 3d surface
- Plot 2d contour

- Calculate hi^2
- Sum hi^2 tables
- Plot delta hi^2 contour
- Erase data

Combine 1D distributions on one graph

Sum corresponding values of several 1D tables

Sum corresponding values of several 2D tables

Add a constant to all table values

Multiply the corresponding values of several 2D tables

Multiply all values in the 2D table by a number

Divide the corresponding values of 2 tables by each other

Rescale the values of the 1st parameter in the table

Rescale the values of the 2nd parameter in the table

Draw a 3D surface based on a table of values

Draw 2D contours based on a table of values

Draw 2D exclusion contours based on chi-square table

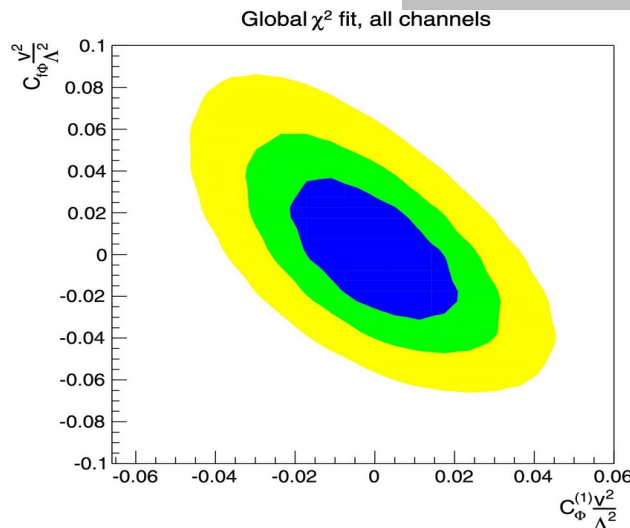
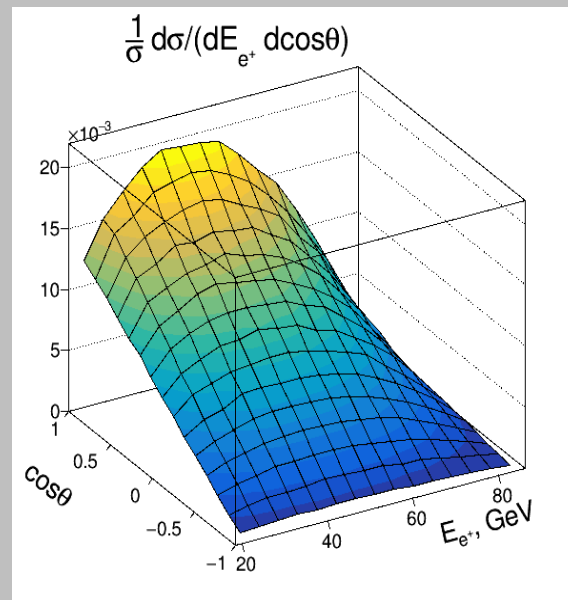
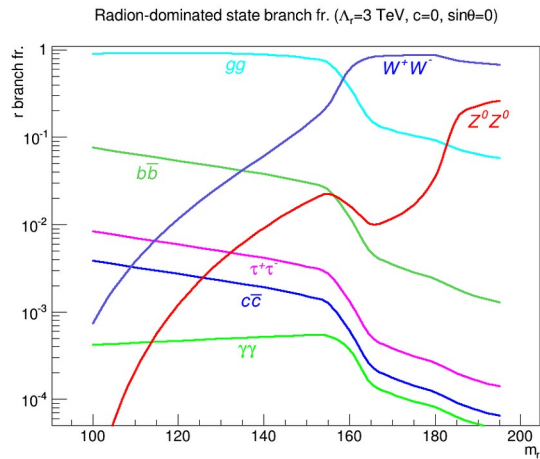
F1-Help F2-Man F4-Diagrams F5-Squared Diagrams F6-Results F9-Quit

Examples of the new CompHEP functions for graphical presentation of results

CompHEP version 4.6

(sub)Process: $G,G \rightarrow A,A$
 Monte Carlo session: 2(continue)

Numerical Session



Define variables
 Display 1d distributions
 Combine 1d distributions
 Sum 1d distributions

Sum 1d tables
 Plot 1d table
 Construct 2d distribution

Sum 2d tables

Add constant to table terms
 Multiply 2d tables
 Multiply 2d table to coeff.
 Divide 2d tables
 Rescale x variable
 Rescale y variable
 Plot 3d surface
 Plot 2d contour

Calculate $hi\Lambda^2$
 Sum $hi\Lambda^2$ tables
 Plot delta $hi\Lambda^2$ contour
 Erase data

The functionality of the CompHEP software package has been extended:

- The CompHEP package has been extended to handle complicated form factors, allowing the calculation of decay widths and scattering cross sections in next-to-leading order of perturbation theory.
- A module of the CompHEP package has been developed for automatic sequential calculations of arrays of decay width and scattering cross-section values depending on multidimensional arrays of model parameter values.
- A module of the CompHEP package has been developed for statistical processing of results and construction of confidence regions in the space of model parameters.
- A module of the CompHEP package has been developed for extended graphical presentation of results: construction of one-dimensional, two-dimensional and three-dimensional graphs in the ROOT package format.

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