Status of CompHEP project and developments in 2013

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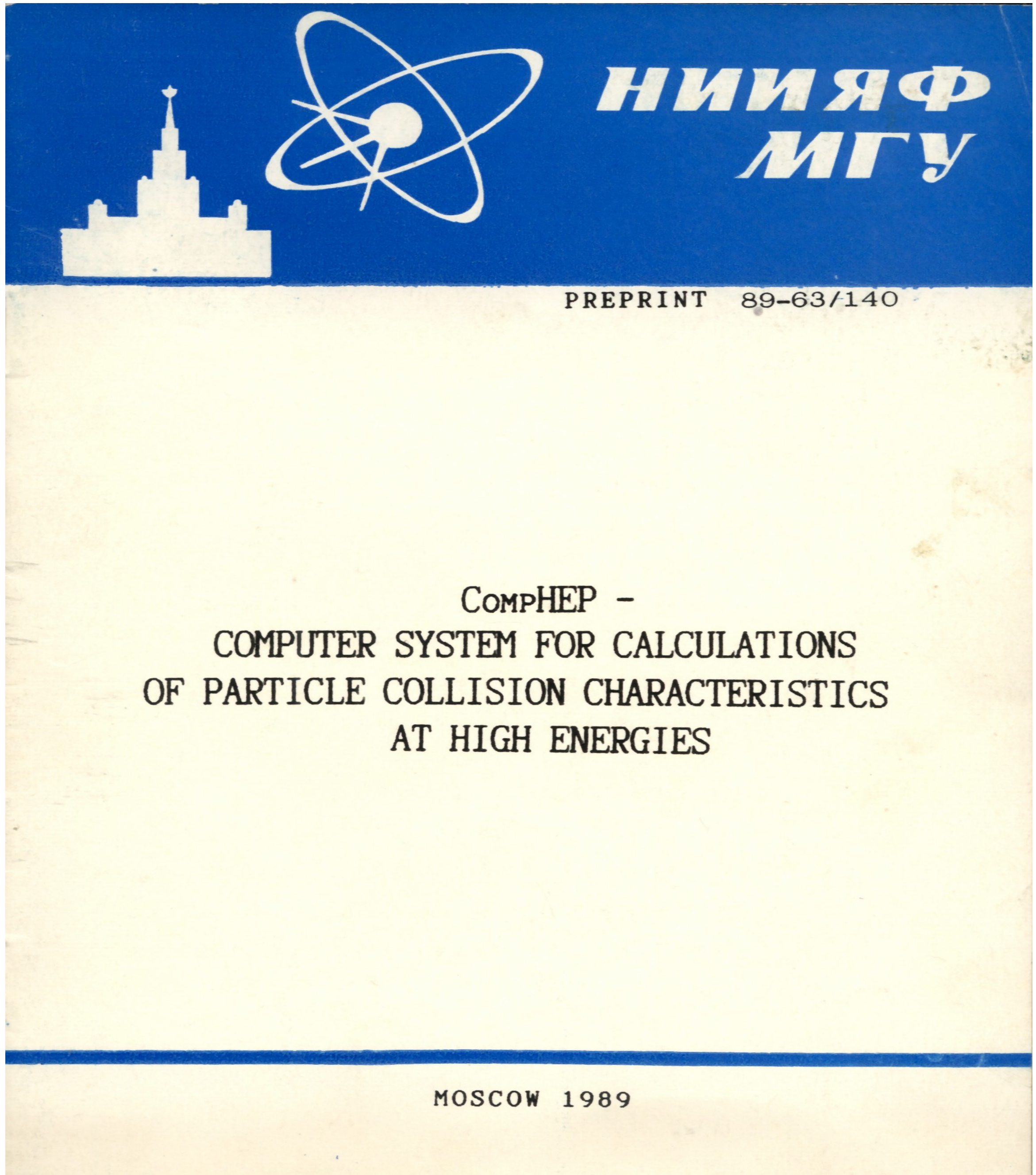
Outline

- **ROOT plots, batch modes, chain decays, LHA formats, etc.**
- **New feature: operations with tables**
- **SM extension by dim6 operators and combined global fits for Higgs boson production**

25 years of CompHEP project in 2014

Primary publication: 1989



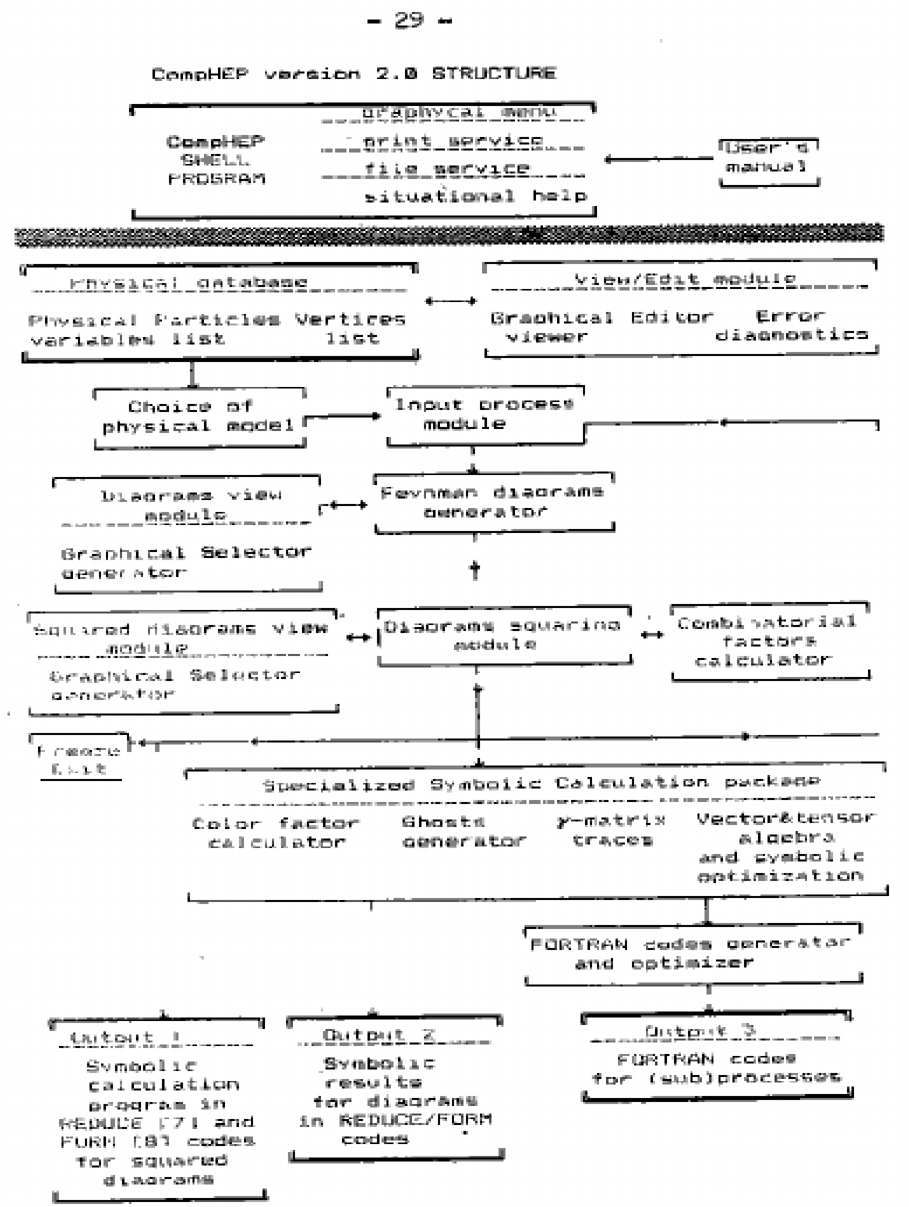
НИИЯФ МГУ

PREPRINT 89-63/140

CompHEP -
COMPUTER SYSTEM FOR CALCULATIONS
OF PARTICLE COLLISION CHARACTERISTICS
AT HIGH ENERGIES

MOSCOW 1989

CompHEP general structure
from SINP MSU preprint 91-9/213, 1991



Last stable version CompHEP 4.5.2 rc11,
download possible from http://comphep.sinp.msu.ru

Main objectives

- **Automation of tree level diagram calculations**
- **“Unification” of symbolical and numerical calculation, unweighted event generation – a full computational chain for phenomenologists**
- **Interfacing to other generators (for showering and hadronization) and further (full simulation)**
- **Interfacing to NLO codes: cross section calculators, mass spectrum calculators**

Features

- **Generation of complete gauge invariant sets of tree-level Feynman diagrams**
- **Symbolic calculation of squared diagrams**
- **Generation of binary for numerical integration by Monte-Carlo method and calculation of cross sections and distributions**
- **Unweighted events generation**
- **Convenient format of built-in models. CompHEP can work with 0,1/2,1-spin particles, Majorana and Dirac spinors, 3- and 4- vertices with fields, derivatives of fields, functions of model parameters**
- **User-friendly interface: GUI for both symbolic and numerical parts, comprehensive built-in help (F1), batch scripts**
- **Generation of models by means of LanHEP (see http://theory.sinp.msu.ru/~semenov/lanhep.html)**

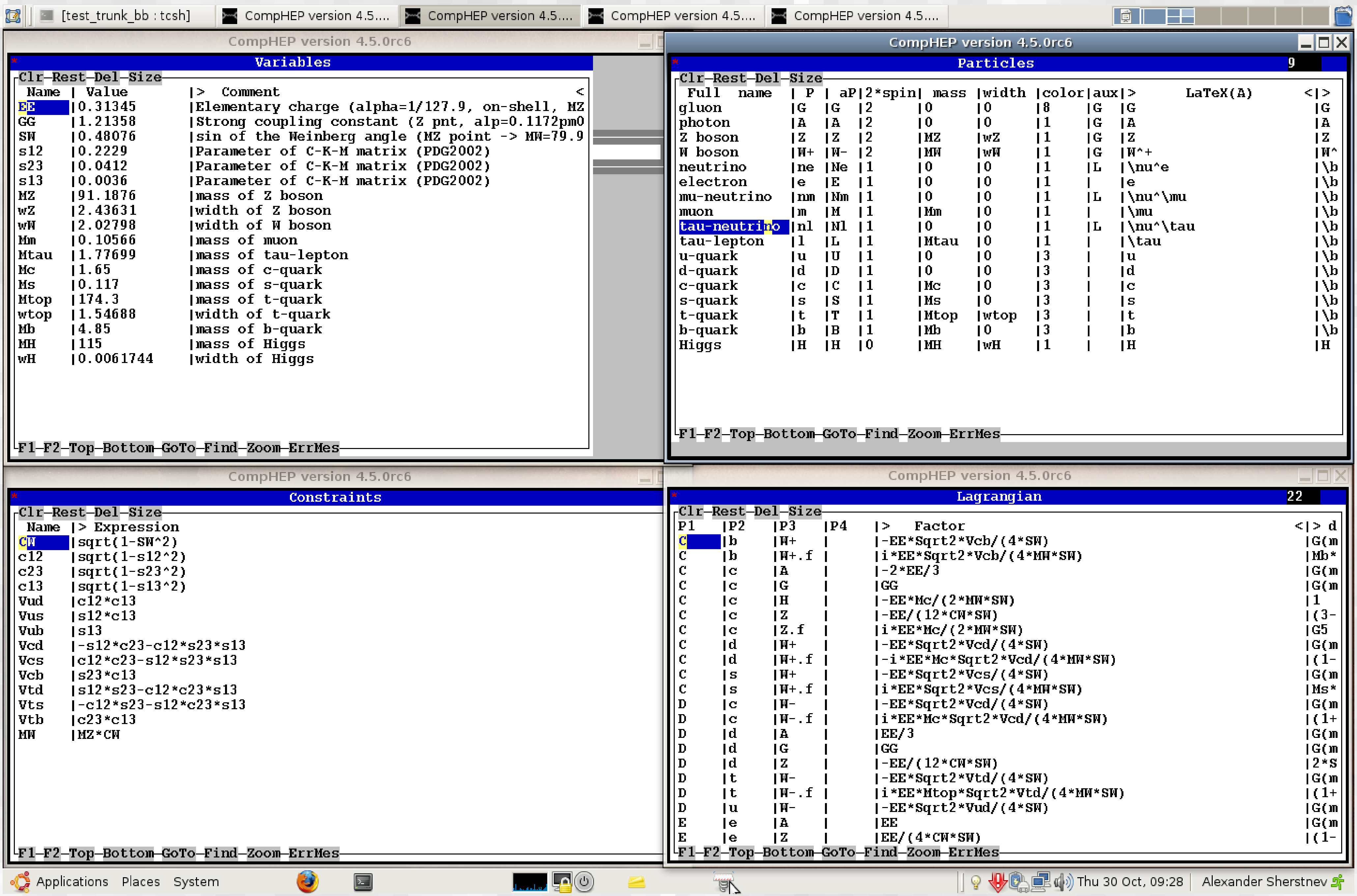
Basic and user-defined CompHEP models

- Simple instructive models: QED, 4-fermion interaction
- SM in the unitary and t 'Hooft-Feynman gauges. 'Flavour diagonal' model for up- and down- quarks (#-model)
- SUSY Models: unconstrained MSSM; SUGRA model; GMSB model

Generation of user-defined models

- Either add new particles/params/vertices 'by hand' OR
- For more complicated models: use LanHEP – a program for generation of Feynman rules from the Lagrangian
  - Generates model files in CompHEP format (also FeynArts and LaTeX format)
  - Works with super-multiplets and superpotential
  - Checks charge conservation, diagonalization of mass matrices, BRST invariance, etc.

CompHEP Standard Model



CompHEP version 4.5.0rc6

Variables

Clr-Rest-Del-Size

Name	Value	Comment
EE	0.31345	Elementary charge (alpha=1/127.9, on-shell, MZ
GG	1.21358	Strong coupling constant (Z pnt, alp=0.1172pm0
SW	0.48076	sin of the Weinberg angle (MZ point -> MW=79.9
s12	0.2229	Parameter of C-K-M matrix (PDG2002)
s23	0.0412	Parameter of C-K-M matrix (PDG2002)
s13	0.0036	Parameter of C-K-M matrix (PDG2002)
MZ	91.1876	mass of Z boson
wZ	2.43631	width of Z boson
wW	2.02798	width of W boson
Mm	0.10566	mass of muon
Mtau	1.77699	mass of tau-lepton
Mc	1.65	mass of c-quark
Ms	0.117	mass of s-quark
Mtop	174.3	mass of t-quark
wtop	1.54688	width of t-quark
Mb	4.85	mass of b-quark
MH	115	mass of Higgs
wH	0.0061744	width of Higgs

F1-F2-Top-Bottom-GoTo-Find-Zoom-ErrMes

CompHEP version 4.5.0rc6

Particles 9

Clr-Rest-Del-Size

Full name	P	aP	2*spin	mass	width	color	aux	LaTeX(A)	
gluon	G	G	2	0	0	8	G	G	G
photon	A	A	2	0	0	1	G	A	A
Z boson	Z	Z	2	MZ	wZ	1	G	Z	Z
W boson	W+	W-	2	MW	wW	1	G	W^+	W^
neutrino	ne	Ne	1	0	0	1	L	\nu^e	\b
electron	e	E	1	0	0	1		e	\b
mu-neutrino	nm	Nm	1	0	0	1	L	\nu^\mu	\b
muon	m	M	1	Mm	0	1		\mu	\b
tau-neutrino	nl	Nl	1	0	0	1	L	\nu^\tau	\b
tau-lepton	l	L	1	Mtau	0	1		\tau	\b
u-quark	u	U	1	0	0	3		u	\b
d-quark	d	D	1	0	0	3		d	\b
c-quark	c	C	1	Mc	0	3		c	\b
s-quark	s	S	1	Ms	0	3		s	\b
t-quark	t	T	1	Mtop	wtop	3		t	\b
b-quark	b	B	1	Mb	0	3		b	\b
Higgs	H	H	0	MH	wH	1		H	H

F1-F2-Top-Bottom-GoTo-Find-Zoom-ErrMes

CompHEP version 4.5.0rc6

Constraints

Clr-Rest-Del-Size

Name	Expression
CW	sqrt(1-SW^2)
c12	sqrt(1-s12^2)
c23	sqrt(1-s23^2)
c13	sqrt(1-s13^2)
Vud	c12*c13
Vus	s12*c13
Vub	s13
Vcd	-s12*c23-c12*s23*s13
Vcs	c12*c23-s12*s23*s13
Vcb	s23*c13
Vtd	s12*s23-c12*c23*s13
Vts	-c12*s23-s12*c23*s13
Vtb	c23*c13
MW	MZ*CW

F1-F2-Top-Bottom-GoTo-Find-Zoom-ErrMes

CompHEP version 4.5.0rc6

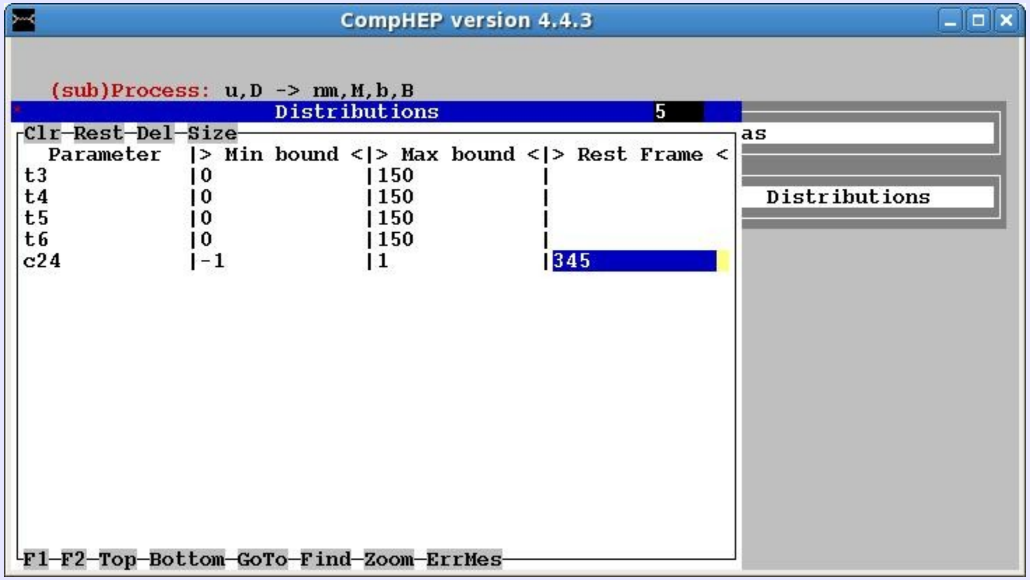
Lagrangian 22

Clr-Rest-Del-Size

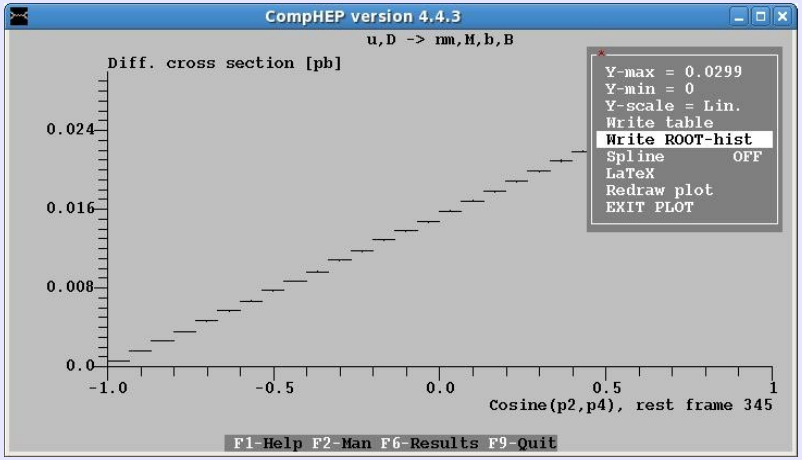
P1	P2	P3	P4	Factor	d
C	b	W+		-EE*Sqrt2*Vcb/(4*SW)	G(m
C	b	W+.f		i*EE*Sqrt2*Vcb/(4*MW*SW)	Mb*
C	c	A		-2*EE/3	G(m
C	c	G		GG	G(m
C	c	H		-EE*Mc/(2*MW*SW)	1
C	c	Z		-EE/(12*CW*SW)	(3-
C	c	Z.f		i*EE*Mc/(2*MW*SW)	G5
C	d	W+		-EE*Sqrt2*Vcd/(4*SW)	G(m
C	d	W+.f		-i*EE*Mc*Sqrt2*Vcd/(4*MW*SW)	(1-
C	s	W+		-EE*Sqrt2*Vcs/(4*SW)	G(m
C	s	W+.f		i*EE*Sqrt2*Vcs/(4*MW*SW)	Ms*
D	c	W-		-EE*Sqrt2*Vcd/(4*SW)	G(m
D	c	W-.f		i*EE*Mc*Sqrt2*Vcd/(4*MW*SW)	(1+
D	d	A		EE/3	G(m
D	d	G		GG	G(m
D	d	Z		-EE/(12*CW*SW)	2*S
D	t	W-		-EE*Sqrt2*Vtd/(4*SW)	G(m
D	t	W-.f		i*EE*Mtop*Sqrt2*Vtd/(4*MW*SW)	(1+
D	u	W-		-EE*Sqrt2*Vud/(4*SW)	G(m
E	e	A		EE	G(m
E	e	Z		EE/(4*CW*SW)	(1-

F1-F2-Top-Bottom-GoTo-Find-Zoom-ErrMes

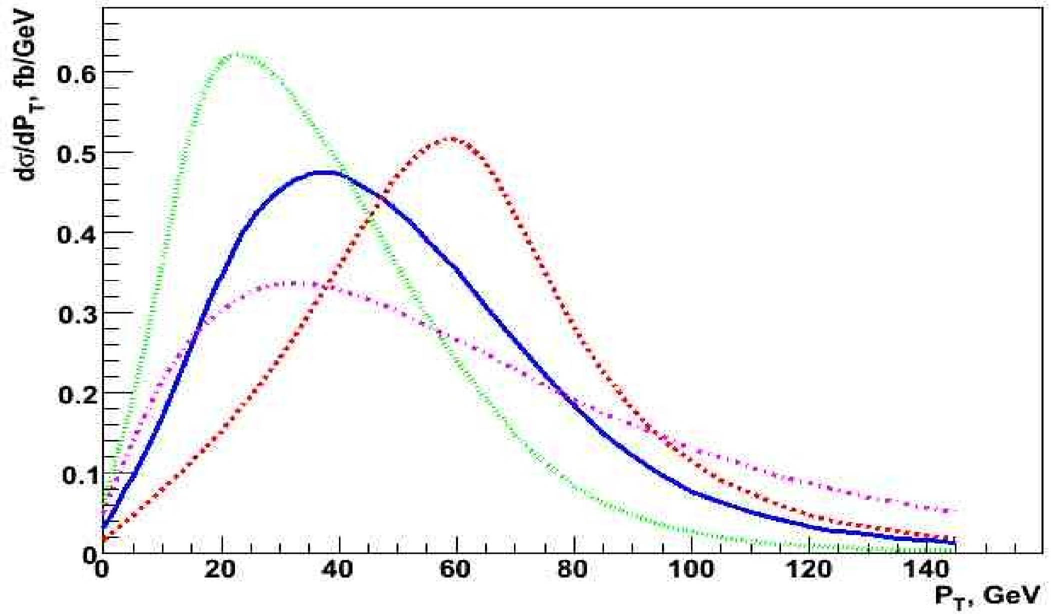
Distributions in CompHEP (ROOT interface)

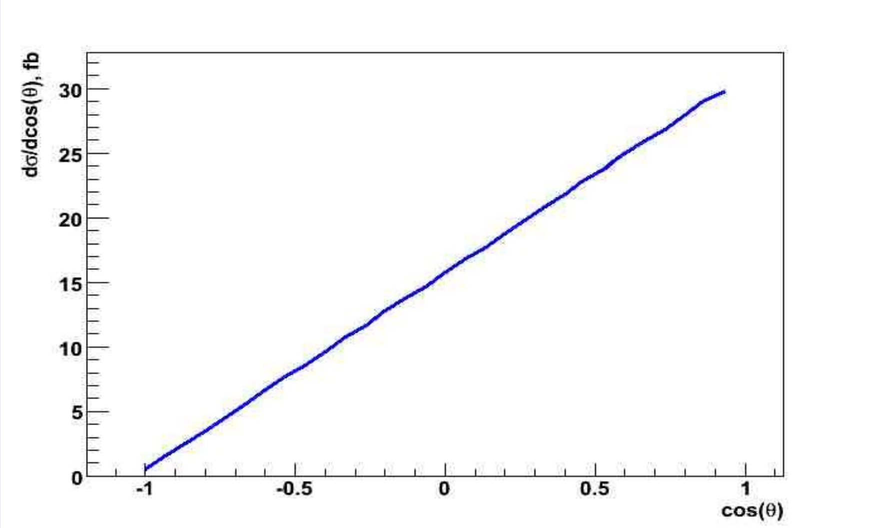


New option in the numerical menu - "write root histogram"



Pt distributions for all final particles

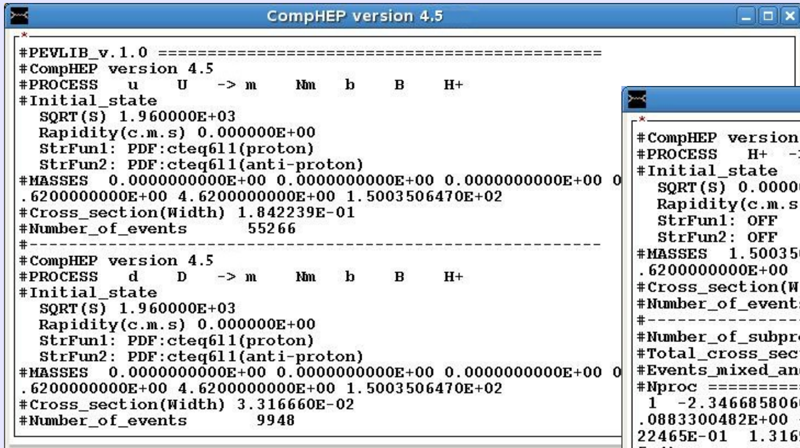




In "vegas" integration menu new submenu "combine histograms" for superimposing ROOT-histograms

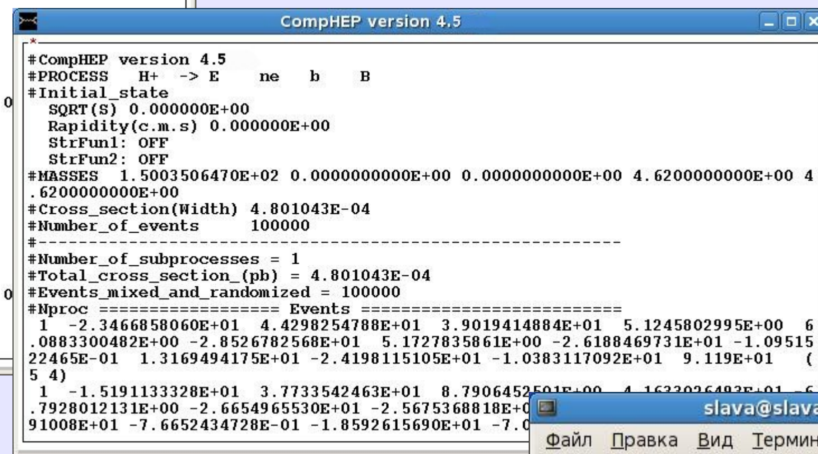
Simulation of cascade decay in CompHEP

1. Generate production events


CompHEP version 4.5

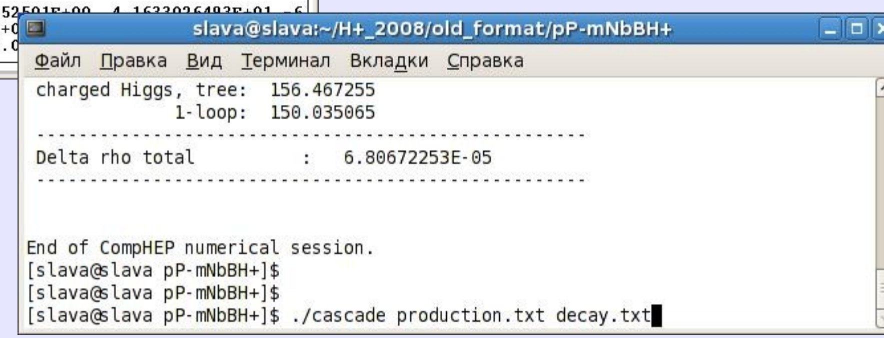
```
#PEVLIB_v.1.0 ============================================
#CompHEP version 4.5
#PROCESS   u    U   -> m     Nm    b     B     H+
#Initial_state
  SQRT(S) 1.960000E+03
  Rapidity(c.m.s) 0.000000E+00
  StrFun1: PDF:cteq6l1(proton)
  StrFun2: PDF:cteq6l1(anti-proton)
#MASSES  0.0000000000E+00 0.0000000000E+00 0.0000000000E+00 0
.6200000000E+00 4.6200000000E+00 1.5003506470E+02
#Cross_section(Width) 1.842239E-01
#Number_of_events      55266
#----------------------------------------------------------
#CompHEP version 4.5
#PROCESS   d    D   -> m     Nm    b     B     H+
#Initial_state
  SQRT(S) 1.960000E+03
  Rapidity(c.m.s) 0.000000E+00
  StrFun1: PDF:cteq6l1(proton)
  StrFun2: PDF:cteq6l1(anti-proton)
#MASSES  0.0000000000E+00 0.0000000000E+00 0.0000000000E+00 0
.6200000000E+00 4.6200000000E+00 1.5003506470E+02
#Cross_section(Width) 3.316660E-02
#Number_of_events       9948
```

2. Generate decay events


CompHEP version 4.5

```
#CompHEP version 4.5
#PROCESS    H+  -> E     ne    b     B
#Initial_state
  SQRT(S) 0.000000E+00
  Rapidity(c.m.s) 0.000000E+00
  StrFun1: OFF
  StrFun2: OFF
#MASSES  1.5003506470E+02 0.0000000000E+00 0.0000000000E+00 4.6200000000E+00 4
.6200000000E+00
#Cross_section(Width) 4.801043E-04
#Number_of_events     100000
#----------------------------------------------------------
#Number_of_subprocesses = 1
#Total_cross_section_(pb) = 4.801043E-04
#Events_mixed_and_randomized = 100000
#Nproc ================= Events ==========================
 1  -2.3466858060E+01  4.4298254788E+01  3.9019414884E+01  5.1245802995E+00  6
.0883300482E+00 -2.8526782568E+01  5.1727835861E+00 -2.6188469731E+01 -1.09515
22465E-01  1.3169494175E+01 -2.4198115105E+01 -1.0383117092E+01  9.119E+01   (
5 4)
 1  -1.5191133328E+01  3.7733542463E+01  8.7906452
.7928012131E+00 -2.6654965530E+01 -2.5675368818E+0
91008E+01 -7.6652434728E-01 -1.8592615690E+01 -7.0
```

3. Run command “cascade”

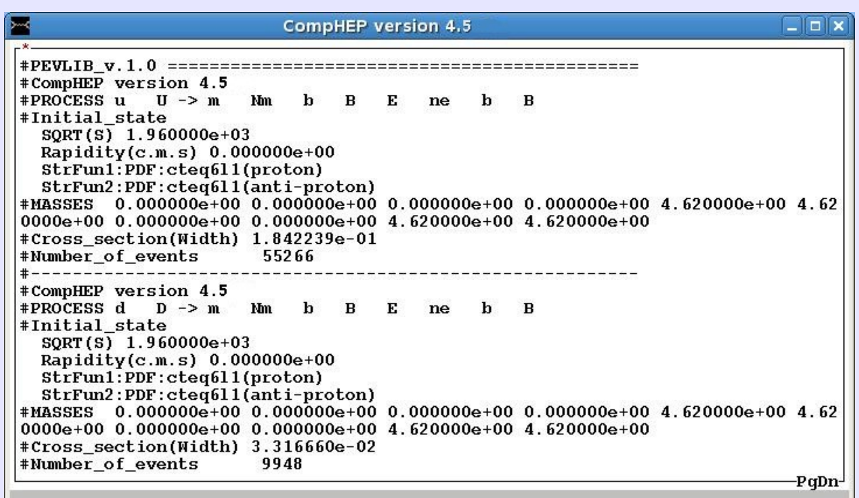

slava@slava:~/H+_2008/old_format/pP-mNbBH+

Файл Правка Вид Терминал Вкладки Справка

```
 charged Higgs, tree:  156.467255
             1-loop:  150.035065
 ---------------------------------------------------
 Delta rho total          :   6.80672253E-05
 ---------------------------------------------------


End of CompHEP numerical session.
[slava@slava pP-mNbBH+]$
[slava@slava pP-mNbBH+]$
[slava@slava pP-mNbBH+]$ ./cascade production.txt decay.txt
```

File with glued events


CompHEP version 4.5

```
#PEVLIB_v.1.0 ============================================
#CompHEP version 4.5
#PROCESS u    U -> m    Nm    b    B    E    ne    b    B
#Initial_state
  SQRT(S) 1.960000e+03
  Rapidity(c.m.s) 0.000000e+00
  StrFun1:PDF:cteq6l1(proton)
  StrFun2:PDF:cteq6l1(anti-proton)
#MASSES  0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 4.620000e+00 4.62
0000e+00 0.000000e+00 0.000000e+00 4.620000e+00 4.620000e+00
#Cross_section(Width) 1.842239e-01
#Number_of_events      55266
#----------------------------------------------------------
#CompHEP version 4.5
#PROCESS d    D -> m    Nm    b    B    E    ne    b    B
#Initial_state
  SQRT(S) 1.960000e+03
  Rapidity(c.m.s) 0.000000e+00
  StrFun1:PDF:cteq6l1(proton)
  StrFun2:PDF:cteq6l1(anti-proton)
#MASSES  0.000000e+00 0.000000e+00 0.000000e+00 0.000000e+00 4.620000e+00 4.62
0000e+00 0.000000e+00 0.000000e+00 4.620000e+00 4.620000e+00
#Cross_section(Width) 3.316660e-02
#Number_of_events      9948
                                                                    PgDn
```

Batch system in CompHEP

Both symbolic & numerical parts of the package have batch scripts: symb_batch.pl and num_batch.pl (in Perl)

Useful in the cases

- Computations of many (of the order of 100) subprocesses for LHC analyses
- **Remote calculations:** GUI not convenient
- **Support of parallel calculations**: very helpful for multi-CPU machines/computer clusters (pbs/lsf is available; grid in progress)

Les Houches Agreements

LHEF, LHAPDF, SUSY LHA, BSM LHA

- **LHA I** is implemented in CompHEP-Interfaces
- **LHEF** - the format adopted by many developer groups (hep-ph/060917). Now CompHEP supports 3 event formats: cpyth-1, cpyth-2 (for experiments, where the formats are used), and LHEF with HepML header. There is a special option - Generator (LHEF format) - in the event menu in n_comphep
- All modern PDFs are available via **LHAPDF**: CTEQ, MRST, Alekhin PDF, etc. Both options, LHAPDF and internal PDF, are available in CompHEP 4.5 with the same functionality in both regimes
- **SUSY LHA** The SLHA interface is implemented in SUGRA and GMSB models of CompHEP. By default, the slhaScript file invokes SUSPECT
- **BSM LHA**

HepML

- Unified XML format of MC event files metadata
  - to keep comprehensive information on event
  - to store generator input parameters and setup
  - an effort to fix a unified extensible way of MC events description
  - the LHEF standard permits XML code in event file headers
- Main purposes:
  - to unify MC event files description (parton and particle levels of MC simulation)
  - to facilitate passing information from Matrix Element generators to Shower generators
  - to simplify MC generators tuning and testing
- Contributors
  - CEDAR http://www.cedar.ac.uk
  - LCG MCDB http://mcdb.cern.ch
- Homepage https://twiki.cern.ch/twiki/bin/view/Main/HepML

CompHEP–FORM interface

Implementation of FORM in parallel to the standard CompHEP symbolic calculator for full compatibility.

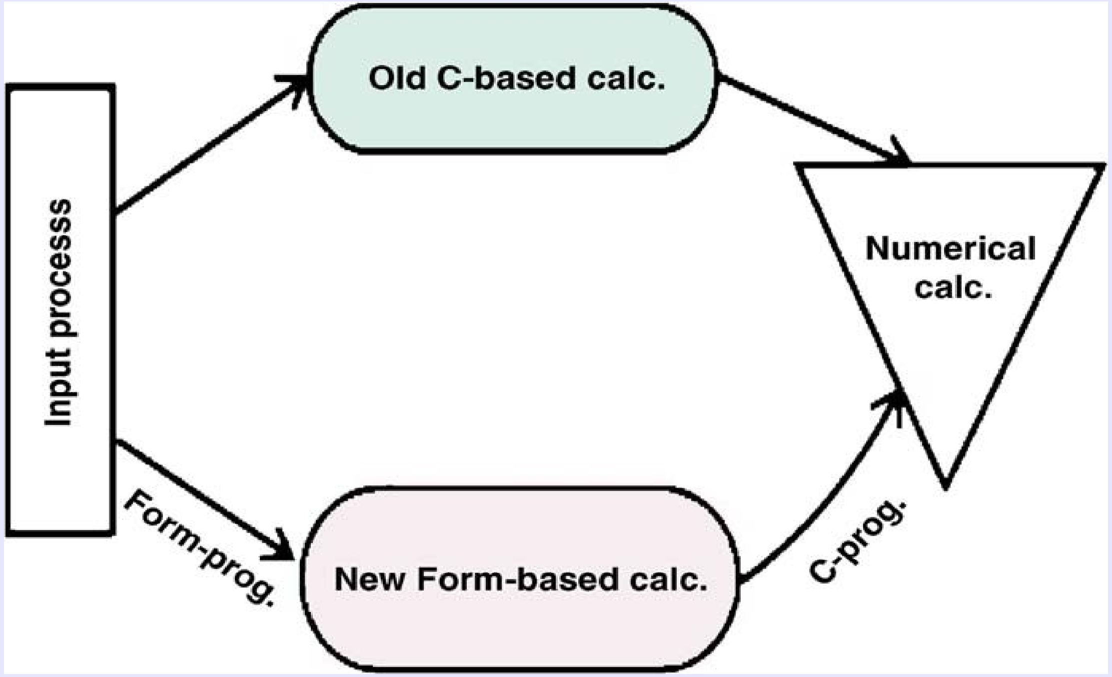
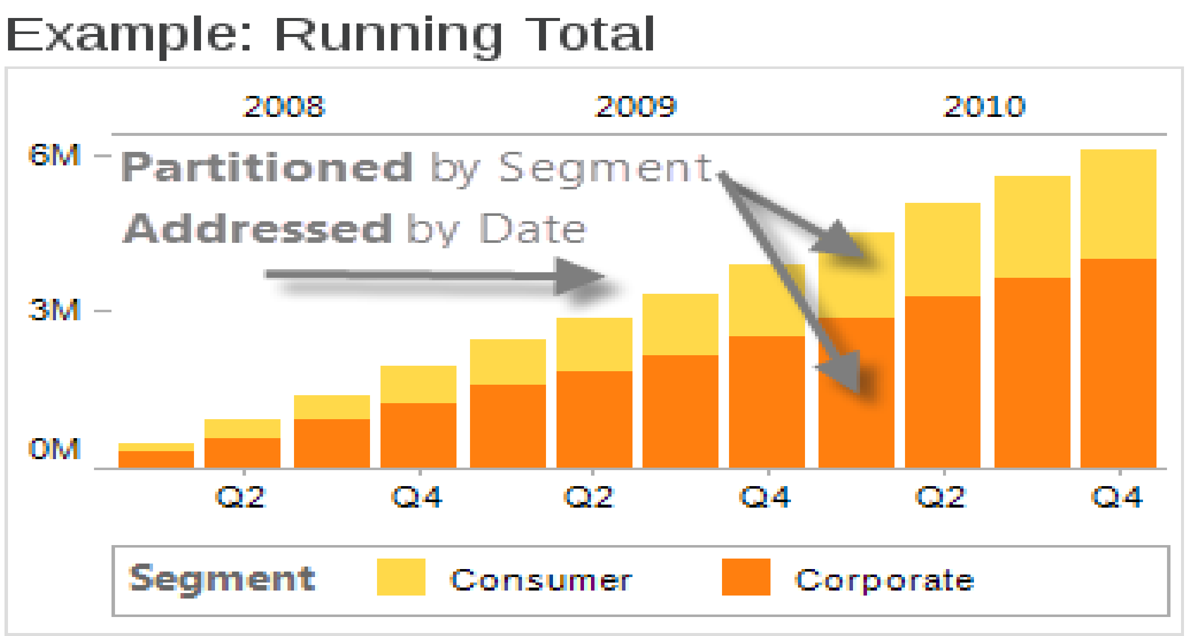


Table calculations with CompHEP

Example of table calculations: running total of sales



In the case of Higgs production at a given point of the anomalous coupling space signal events are addressed by the production channel and partitioned by the decay channel

Table calculations menu

Basic object: χ^2 measure in the anomalous coupling space. Global fits to μ in (a,c) plane are performed. Dispersion matrix of the observables convoluted with vector differences between the observed and calculated μ values defines χ^2. The minimum of χ^2 is found and 65%,90% and 99% best fit CL regions in the (a,c) space are defined by deviations from χ^2_min less than 2.1,4.6 and 9.2, respectively.

Higgs signal strength and exclusion contours in the anomalous couplings space

$$\mu_i = \frac{[\sum_j \sigma_{j\to h} Br(h\to i)]_{obs}}{[\sum_j \sigma_{j\to h} Br(h\to i)]_{SM}}$$

- signal strength in the production decay approximation (or infinitely small width approximation);

$$\hat{\mu}_i = \frac{N_{obs,i} - N_{backgr,i}}{N^{SM}_{signal,i}}$$

- best fit value of a signal strength for the number of observed signal events N_{OBS}, the number of observed background events N_{BACKGR} and the number of signal events evaluated in the SM N^{SM}_{SIGNAL};

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

- the global χ^2 for the number of production channels N_{CH};

Summary tables of the signal strength for various Higgs production channels from J.R.Espinosa et al, arXiv:12023697v2: 2011 data (upper) and post-Moriond 2012 data (lower)

Channel [Exp]	m_h[GeV] (Local Significance)	μ (μ_L)	Scaling to SM
$pp \to \gamma\gamma$ [ATLAS]	126.5 ± 0.7 ($2.8\,\sigma$) [26]	$2^{+0.9}_{-0.7}$ [27] (2.6)	$\sim c^2\,\mathrm{Br}_{\gamma\gamma}[a,c]$
$pp \to Z\,Z^* \to \ell^+\ell^-\ell^+\ell^-$ [ATLAS]	$126\pm \sim 2\%$ ($2.1\,\sigma$) [26]	$1.2^{+1.2}_{-0.8}$ [27] (4.9)	$\sim c^2\,\mathrm{Br}_{ZZ}[a,c]$
$pp \to W\,W^* \to \ell^+\nu\,\ell^-\bar\nu$ [ATLAS]	$126\pm \sim 20\%$ ($1.4\,\sigma$) [26]	$1.2^{+0.8}_{-0.8}$ [27] (3.4)	$\sim c^2\,\mathrm{Br}_{WW}[a,c]$
$pp \to \gamma\gamma jj$ [CMS]	$124 \pm 3\%$ [10, 11]	$3.7^{+2.5}_{-1.8}$ [11]	$\sim a^2\,\mathrm{Br}_{\gamma\gamma}[a,c]$
$pp \to \gamma\gamma$[CMS, b, $R_9^{\rm min} > 0.94$]	$124 \pm 3\%$ [10, 11]	$1.5^{+1.1}_{-1.0}$ [11]	$\sim c^2\,\mathrm{Br}_{\gamma\gamma}[a,c]$
$pp \to \gamma\gamma$[CMS, b, $R_9^{\rm min} < 0.94$]	$124 \pm 3\%$ [10, 11]	$2.1^{+1.5}_{-1.4}$ [11]	$\sim c^2\,\mathrm{Br}_{\gamma\gamma}[a,c]$
$pp \to \gamma\gamma$[CMS, e, $R_9^{\rm min} > 0.94$]	$124 \pm 3\%$ [10, 11]	$0.0^{+2.9}$ [11]	$\sim c^2\,\mathrm{Br}_{\gamma\gamma}[a,c]$
$pp \to \gamma\gamma$[CMS, e, $R_9^{\rm min} < 0.94$]	$124 \pm 3\%$ [10, 11]	$4.1^{+4.6}_{-4.1}$ [11]	$\sim c^2\,\mathrm{Br}_{\gamma\gamma}[a,c]$
$pp \to Z\,Z^* \to \ell^+\ell^-\ell^+\ell^-$ [CMS]	$126 \pm 2\%$ ($1.5\,\sigma$) [11, 28]	$0.5^{+1.0}_{-0.7}$ [10] (2.7)	$\sim c^2\,\mathrm{Br}_{ZZ}[a,c]$
$pp \to W\,W^* \to \ell^+\nu\,\ell^-\bar\nu$ [CMS]	$126 \pm 20\%$ [10, 29]	$0.7^{+0.4}_{-0.6}$ [10] (1.8)	$\sim c^2\,\mathrm{Br}_{WW}[a,c]$
$pp \to b\bar b$ [CMS]	$124 \pm 10\%$ [10]	$1.2^{+1.4}_{-1.7}$ [10] (4.1)	$\sim a^2\,\mathrm{Br}_{b\bar b}[a,c]$
$pp \to \tau\bar\tau$ [CMS]	$124 \pm 20\%$[10]	$0.8^{+1.2}$[illegible] [10] (3.3)	$\sim c^2\,\mathrm{Br}_{\tau\bar\tau}[a,c]$

Channel [Exp]	$\hat\mu_{119.5}$ ($\mu^L_{119.5}$)	$\hat\mu_{124}$ (μ^L_{124})	$\hat\mu_{125}$ (μ^L_{125})
$pp \to \gamma\gamma$ [ATLAS]	$0.0^{+0.6}_{-0.8}$ (1.5)	$0.8^{+0.8}_{-0.7}$ (2.6)	$1.6^{+0.9}_{-0.8}$ (3.9)
$pp \to Z\,Z^* \to \ell^+\ell^-\ell^+\ell^-$ [ATLAS]	-0.5^{+1} (5.1)	$1.6^{+1.4}_{-0.8}$ (4.7)	$1.4^{+1.3}_{-0.8}$ (4.1)
$pp \to W\,W^* \to \ell^+\nu\,\ell^-\bar\nu$ [ATLAS]	$0.0^{+1.2}_{-1.3}$ (2.4)	$0.1^{+0.7}_{-0.7}$ (1.6)	$0.1^{+0.7}_{-0.6}$ (1.4)
$pp \to \gamma\gamma$ [CMS]	$-1.1^{+0.6}_{-0.6}$ (1.3)	$1.5^{+0.7}_{-0.7}$ (3.5)	$1.6^{+0.7}_{-0.6}$ (3.0)
$pp \to Z\,Z^* \to \ell^+\ell^-\ell^+\ell^-$ [CMS]	$2.0^{+1.6}_{-1.1}$ (5.2)	$0.5^{+1.1}_{-0.7}$ (2.7)	$0.6^{+0.9}_{-0.6}$ (2.5)
$pp \to W\,W^* \to \ell^+\nu\,\ell^-\bar\nu$ [CMS]	$0.9^{+0.8}_{-0.7}$ (2.5)	$0.6^{+0.7}_{-0.7}$ (1.8)	$0.4^{+0.6}_{-0.6}$ (1.5)
$pp \to b\bar b$ [CMS]	$0.4^{+1.8}_{-1.6}$ (4.1)	$1.2^{+1.9}_{-1.8}$ (5.0)	$1.2^{+2.1}_{-1.7}$ (5.2)
$pp \to \tau\bar\tau$ [CMS]	$0.2^{+0.9}_{-1.1}$ (3.6)	$0.4^{+1.0}_{-1.2}$ (3.9)	$0.6^{+1.1}_{-1.2}$ (4.1)
$pp \to \tau\bar\tau$ [ATLAS]	$-0.9^{+1.7}_{-1.7}$ (2.9)	$-0.1^{+1.7}_{-1.7}$ (3.4)	$0.1^{+1.7}_{-1.8}$ (3.5)
$p\bar p \to b\bar b$ [CDF&D$\emptyset$]	$1.5^{+0.6}_{-0.5}$ (2.5)	$1.9^{+0.8}_{-0.6}$ (3.1)	$2.0^{+0.8}_{-0.7}$ (3.2)
$p\bar p \to W^+W^-$ [CDF&D$\emptyset$]	$1.63^{+1.46}_{-1.12}$ (4.5)	$0.03^{+1.22}_{-0.03}$ (2.4)	$0.03^{+1.22}_{-0.03}$ (2.4)

- Up to which degree the SM Higgs boson is consistent with the available data?
- Deviations from the SM are introduced in the form of effective operators *O*. Anomalous couplings *C* parametrize the deviations

$$L_{eff}^{(6)} = \frac{1}{\Lambda^2} \sum_{k=V,F} C_{\Phi k} O_{\Phi k}$$

Global fit in the anomalous coupling space is performed and exclusion contours reconstructed

Sector by sector extension of the SM by dimension 5 and 6 effective operators

W.Buchmuller, D.Wyler, Nucl.Phys. B268 (1986) 621

Recent two-parametric global fits – nonlinear chiral realization of the SM gauge symmetry (alternative)

J.R. Espinosa, C. Grojean, M. Muhlleitner, M. Trott, JHEP 1205, 097 (2012) (arXiv:1202.3697 [hep-ph]), JHEP 1212, 045 (2012) (arXiv:1207.1717 [hep-ph])

- *scalar-gauge boson sector*

$$O_{\Phi G} = \frac{1}{2}(\Phi^\dagger\Phi - \frac{v^2}{2})G^a_{\mu\nu}G^{a\mu\nu} \qquad O_{\Phi \tilde{G}} = \frac{1}{2}(\Phi^\dagger\Phi - \frac{v^2}{2})G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

$$O_{\Phi B} = \frac{1}{2}(\Phi^\dagger\Phi - \frac{v^2}{2})B_{\mu\nu}B^{\mu\nu} \qquad O_{\Phi \tilde{B}} = \frac{1}{2}(\Phi^\dagger\Phi - \frac{v^2}{2})B_{\mu\nu}\tilde{B}^{\mu\nu}$$

$$O_{\Phi W} = \frac{1}{2}(\Phi^\dagger\Phi - \frac{v^2}{2})W^i_{\mu\nu}W^{i\mu\nu} \qquad O_{\Phi \tilde{W}} = \frac{1}{2}(\Phi^\dagger\Phi - \frac{v^2}{2})W^i_{\mu\nu}\tilde{W}^{i\mu\nu}$$

$$O_{\Phi}^{(1)} = (\Phi^\dagger\Phi - \frac{v^2}{2})D_\mu\Phi^\dagger D^\mu\Phi$$

- *scalar-fermion sector*

$$O_{t\Phi} = (\Phi^\dagger\Phi - \frac{v^2}{2})(\bar{Q}_L\Phi^c t_R)$$

$$O_{b\Phi} = (\Phi^\dagger\Phi - \frac{v^2}{2})(\bar{Q}_L\Phi b_R)$$

$$O_{\tau\Phi} = (\Phi^\dagger\Phi - \frac{v^2}{2})(\bar{L}_L\Phi \tau_R)$$

$$\tilde{F}_{\mu\nu} = \epsilon_{\mu\nu\gamma\delta}F_{\gamma\delta}.$$

List of authors and papers 2012-2013

T. Corbett, O.J.P. Eboli, J. Gonzalez-Fraile, M.C. Gonzalez-Garcia
P. Giardino, K. Kannike, M. Raidal, A. Strumia
Tianjin Li, Xia Wan, You-kai Wang, Shou-hua Zhu
J. Ellis, T. You
A. Azatov, R. Contino, D. Del Re, J. Galloway, M. Grassi, S. Rahatlou
M. Klute, R. Lafaye, T. Plehn, M. Rauch, D. Zerwas
I. Low, J. Lykken, G. Shaughnessy
P. Giardino, K. Kannike, M. Raidal, A. Strumia
M. Montull, F. Riva
D. Carmi, A. Falkowski, E. Kuflik, T. Volansky, J. Zupan
S. Banerjee, S. Mukhopadhyay, B. Mukhopadhyaya
F. Bonnet, T. Ota, M. Rauch, W. Winter
T. Plehn, M. Rauch
A. Djouadi
B. Batell, S. Gori, Lian-Tao Wang
G. Cacciapaglia, A. Deandrea, G. Drieu La Rochelle, J.-B. Flament
E. Masso, V. Sanz
G. Belanger, B. Dumont, U. Ellwanger, J.F. Gunion, S. Kraml
Kingman Cheung, J. S. Lee, Po-Yan Tseng
S. Dittmaier, M. Schumacher
G.F. Guidice, C. Grojean, A. Pomarol, R. Ratazzi
R. Contino, C. Grojean, M. Moretti, F. Piccinini, R. Ratazzi
J.R. Espinosa, C. Grojean, M. Muhlleitner, M. Trott
... ...

Effective triple vertices in the Buchmueller-Wyler basis (LanHEP calculation). Effective couplings C (Wilson coefficients) are multiplicative factors in front of O_{ij}

Effective operators	Triple vertices	Feynman rules
$O_{t\Phi} = (\Phi^\dagger\Phi - \frac{v^2}{2})(-\lambda_t)(\bar{Q_L}\Phi^c t_R)$	$\bar{t}$ t H	$-M_t \cdot \frac{v}{\Lambda^2} \cdot C_{t\Phi}$
$O_{b\Phi} = (\Phi^\dagger\Phi - \frac{v^2}{2})(-\lambda_b)(\bar{Q_L}\Phi b_R)$	$\bar{b}$ b H	$-M_b \cdot \frac{v}{\Lambda^2} \cdot C_{b\Phi}$
$O_{\tau\Phi} = (\Phi^\dagger\Phi - \frac{v^2}{2})(-\lambda_\tau)(\bar{L_L}\Phi\tau_R)$	$\bar{\tau}$ τ H	$-M_\tau \cdot \frac{v}{\Lambda^2} \cdot C_{\tau\Phi}$
$O_{\Phi G} = \frac{1}{2}(\Phi^\dagger\Phi - \frac{v^2}{2})G^a_{\mu\nu}G^{a\mu\nu}$	G_μ G_ν H	$-2 \cdot \frac{v}{\Lambda^2} \cdot C_{\Phi G} \cdot (g^{\mu\nu}p_1p_2 - p_1^\nu p_2^\mu)$
$O_{\Phi B} = \frac{1}{2}(\Phi^\dagger\Phi - \frac{v^2}{2})B_{\mu\nu}B^{\mu\nu}$	A_μ A_ν H	$-2 \cdot c_W^2 \cdot \frac{v}{\Lambda^2} \cdot C_{\Phi B} \cdot (g^{\mu\nu}p_1p_2 - p_1^\nu p_2^\mu)$
	A_μ Z_ν H	$+2 \cdot c_W \cdot s_W \cdot \frac{v}{\Lambda^2} \cdot C_{\Phi B} \cdot (g^{\mu\nu}p_1p_2 - p_1^\nu p_2^\mu)$
	Z_μ Z_ν H	$-2 \cdot s_W^2 \cdot \frac{v}{\Lambda^2} \cdot C_{\Phi B} \cdot (g^{\mu\nu}p_1p_2 - p_1^\nu p_2^\mu)$
$O_{\Phi W} = \frac{1}{2}(\Phi^\dagger\Phi - \frac{v^2}{2})W^i_{\mu\nu}W^{i\mu\nu}$	A_μ A_ν H	$-2 \cdot s_W^2 \cdot \frac{v}{\Lambda^2} \cdot C_{\Phi W} \cdot (g^{\mu\nu}p_1p_2 - p_1^\nu p_2^\mu)$
	A_μ Z_ν H	$-2 \cdot c_W \cdot s_W \cdot \frac{v}{\Lambda^2} \cdot C_{\Phi W} \cdot (g^{\mu\nu}p_1p_2 - p_1^\nu p_2^\mu)$
	Z_μ Z_ν H	$-2 \cdot c_W^2 \cdot \frac{v}{\Lambda^2} \cdot C_{\Phi W} \cdot (g^{\mu\nu}p_1p_2 - p_1^\nu p_2^\mu)$
	W^+_μ W^-_ν H	$-2 \cdot \frac{v}{\Lambda^2} \cdot C_{\Phi W} \cdot (g^{\mu\nu}p_1p_2 - p_1^\nu p_2^\mu)$
$O_\Phi^{(1)} = (\Phi^\dagger\Phi - \frac{v^2}{2})D_\mu\Phi^\dagger D^\mu\Phi$	W^+_μ W^-_ν H	$M_W^2 \cdot \frac{v}{\Lambda^2} \cdot C_\Phi^{(1)} \cdot g^{\mu\nu}$
	Z_μ Z_ν H	$M_Z^2 \cdot \frac{v}{\Lambda^2} \cdot C_\Phi^{(1)} \cdot g^{\mu\nu}$

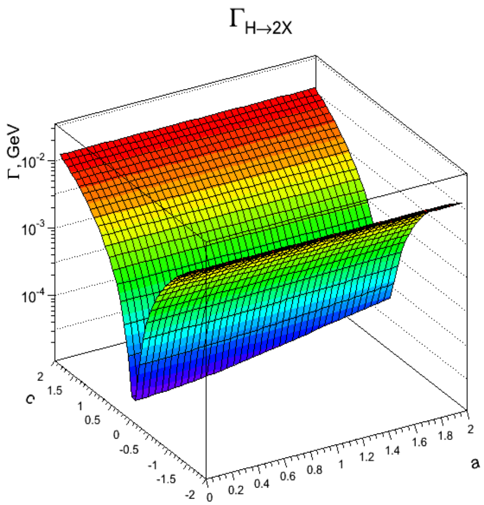
It is convenient to introduce (a,c) parametrization

$$
\begin{aligned}
c &= 1 + C_{t\Phi} \cdot \frac{v^2}{\Lambda^2} \\
a &= 1 + \frac{v^2}{2\Lambda^2} \cdot C_{\Phi}^{(1)} \\
c_G &= 1 + \frac{6\pi}{\alpha_s} \cdot C_{\Phi G} \cdot \frac{v^2}{\Lambda^2} \\
c_\gamma &= \frac{63a - 16c}{47} + \frac{9\pi}{4\alpha} \cdot (c_W^2 \cdot C_{\Phi B} + s_W^2 \cdot C_{\Phi W}) \cdot \frac{v^2}{\Lambda^2} \\
a_Z &= (s_W^2 \cdot C_{\Phi B} + c_W^2 \cdot C_{\Phi W}) \cdot \frac{v^2}{\Lambda^2} \\
a_W &= C_{\Phi W} \cdot \frac{v^2}{\Lambda^2}
\end{aligned}
$$

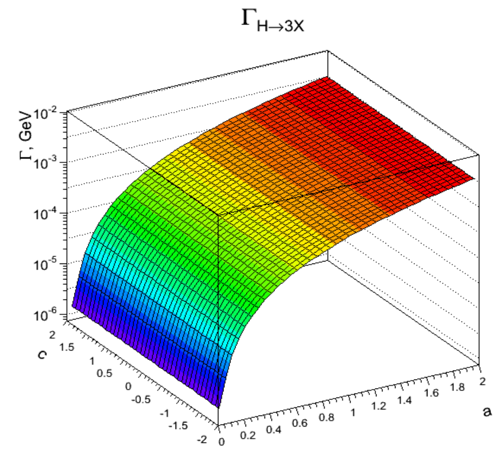
such that the SM limit [$a=1$, $c=c_G=c_\gamma=1$, $a_W=0, a_Z=0$] with the one-loop induced $H\to gg$, $H\to\gamma\gamma$ is clearly seen.

Effective triple vertices with the (a,c) parametrization

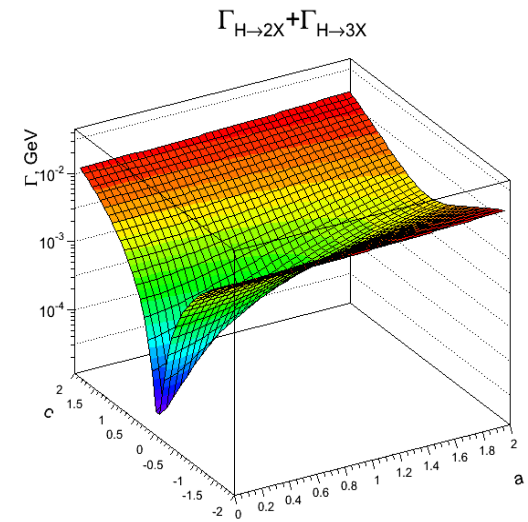
Triple vertices	Feynman rules
$\bar{t}\quad t\quad H$	$-\frac{M_t}{v}\cdot c$
$\bar{b}\quad b\quad H$	$-\frac{M_b}{v}\cdot c$
$\bar{\tau}\quad \tau\quad H$	$-\frac{M_\tau}{v}\cdot c$
$G_\mu\quad G_\nu\quad H$	$-\frac{2}{v}\cdot\frac{\alpha_s}{6\pi}\cdot c_G\cdot(g^{\mu\nu}p_1p_2-p_1^\nu p_2^\mu)$
$A_\mu\quad A_\nu\quad H$	$-\frac{2}{v}\cdot\frac{4\alpha}{9\pi}\cdot c_\gamma\cdot(g^{\mu\nu}p_1p_2-p_1^\nu p_2^\mu)$
$A_\mu\quad Z_\nu\quad H$	$+2\cdot c_W\cdot s_W\cdot(C_{\Phi B}-C_{\Phi W})\cdot\frac{v}{\Lambda^2}(g^{\mu\nu}p_1p_2-p_1^\nu p_2^\mu)$
$Z_\mu\quad Z_\nu\quad H$	$+\frac{2}{v}\cdot[M_Z^2\cdot a\cdot g^{\mu\nu}-a_Z\cdot(g^{\mu\nu}p_1p_2-p_1^\nu p_2^\mu)]$
$W_\mu^+\quad W_\nu^-\quad H$	$+\frac{2}{v}\cdot[M_W^2\cdot a\cdot g^{\mu\nu}-a_W\cdot(g^{\mu\nu}p_1p_2-p_1^\nu p_2^\mu)]$



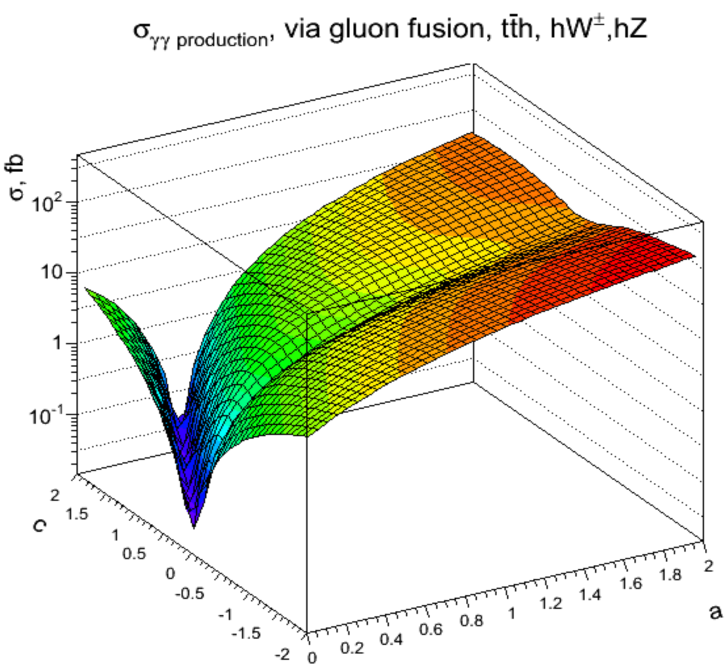
$\Gamma_{H\to 2X}$
Γ, GeV
c
a



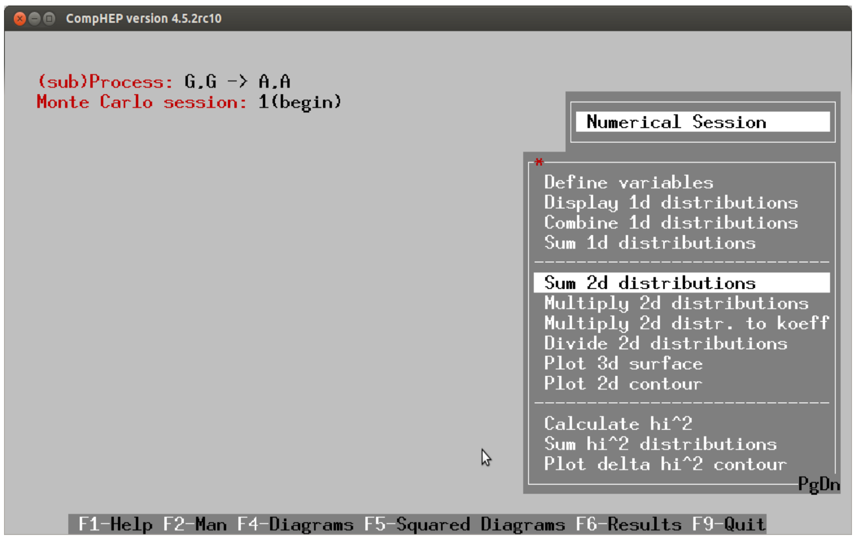
$\Gamma_{H\to 3X}$
Γ, GeV
c
a



$\Gamma_{H\to 2X}+\Gamma_{H\to 3X}$
Γ, GeV
c
a



$\sigma_{\gamma\gamma\ \mathrm{production}}$, via gluon fusion, $t\bar{t}h$, $hW^{\pm}$,hZ
σ, fb
c
a

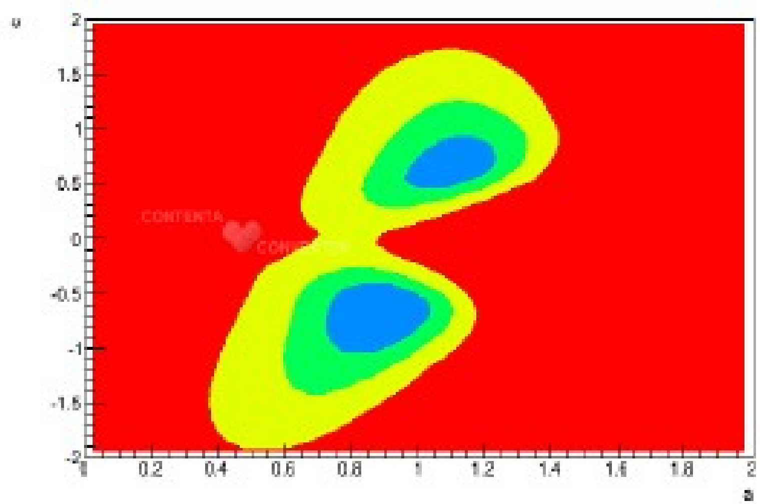


CompHEP version 4.5.2rc10
(sub)Process: G,G -> A,A
Monte Carlo session: 1(begin)
Numerical Session
Define variables
Display 1d distributions
Combine 1d distributions
Sum 1d distributions
Sum 2d distributions
Multiply 2d distributions
Multiply 2d distr. to koeff
Divide 2d distributions
Plot 3d surface
Plot 2d contour
Calculate hi^2
Sum hi^2 distributions
Plot delta hi^2 contour
PgDn
F1-Help F2-Man F4-Diagrams F5-Squared Diagrams F6-Results F9-Quit

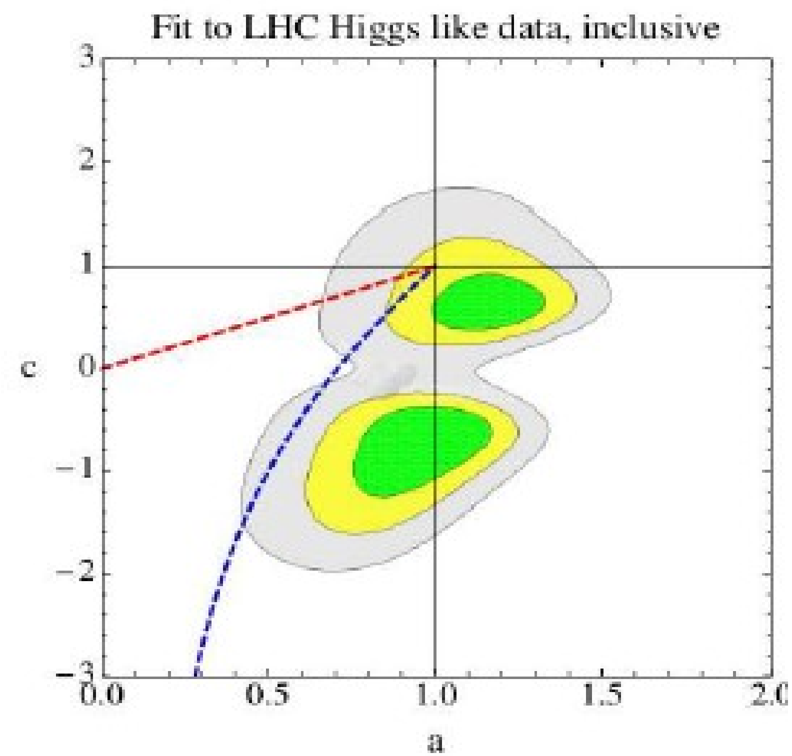
Combined global fits in the (a,c) plane for all channels ($\gamma\gamma$, WW+ZZ, bb+$\tau\tau$)

CompHEP infinitely small width approximation

Espinosa et al, arXiv:1202.3697v2

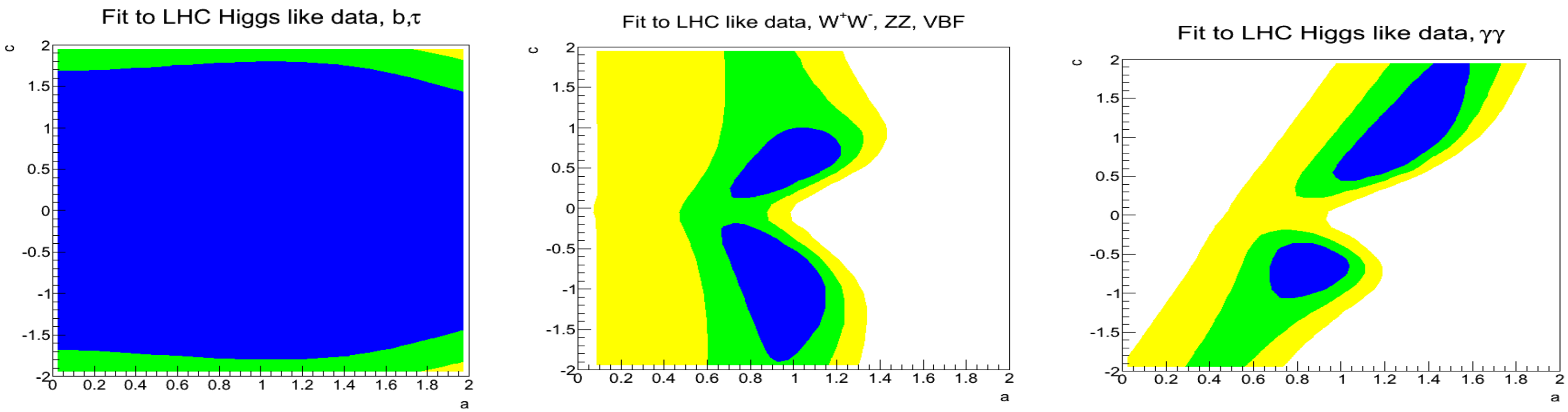


(a)

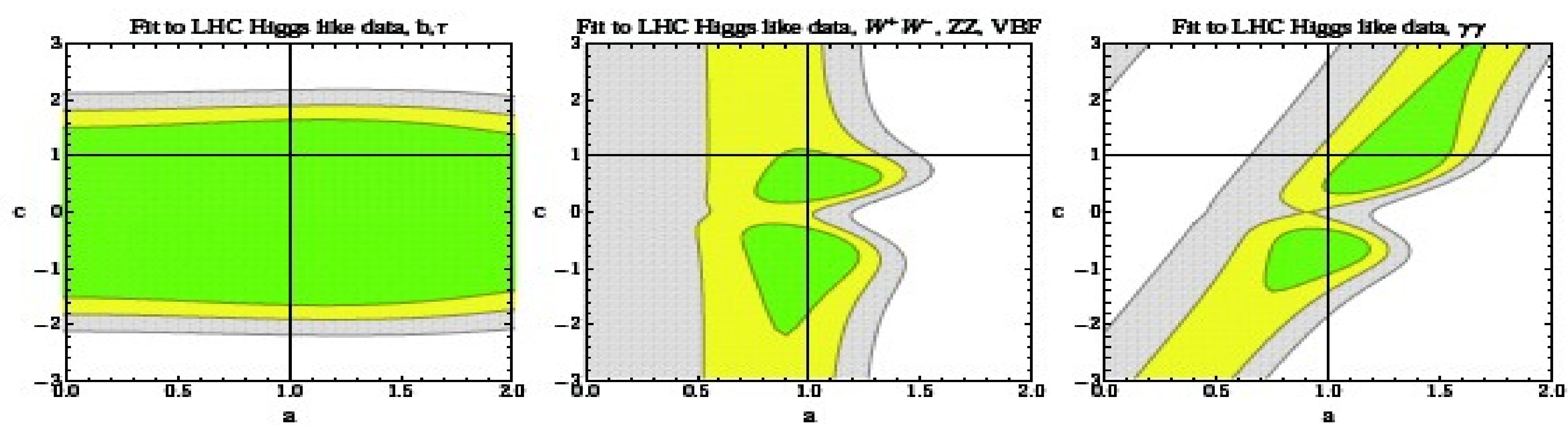


(b)

Combined fits in the (a,c) plane for $\gamma\gamma$, WW+ZZ, bb+$\tau\tau$ separately



CompHEP infinitely small width approximation



J.Espinosa et al, arXiv:1202.3697v2

Beyond the infinitely small width approximation

In a number of channels the interference terms are not small (especially for γγ, WW and ZZ exchange diagrams). Individual contributions of t-channel and subleading s-channel diagrams are usually small, but the number of such diagrams can be of the order of 100 (especially μμμμ)

Example 1

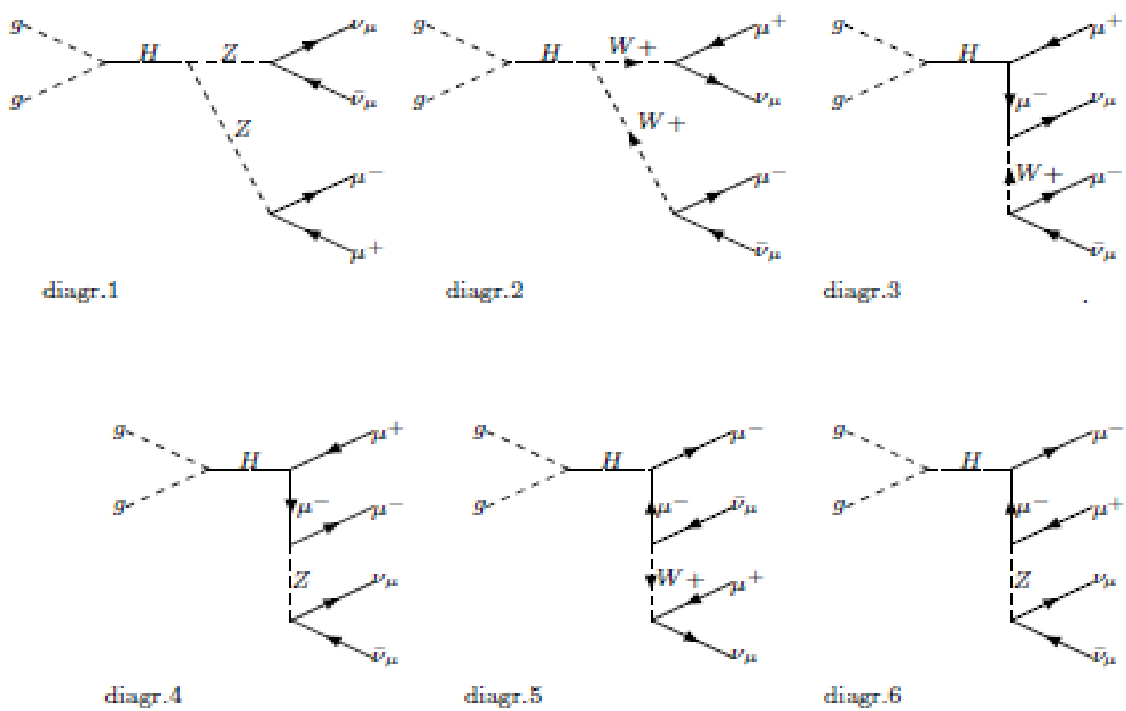


Figure 1: Signal diagrams for the process $e^- e^+ \to WW \to \nu_e \bar{\nu}_e e^+ e^-$

Example 2

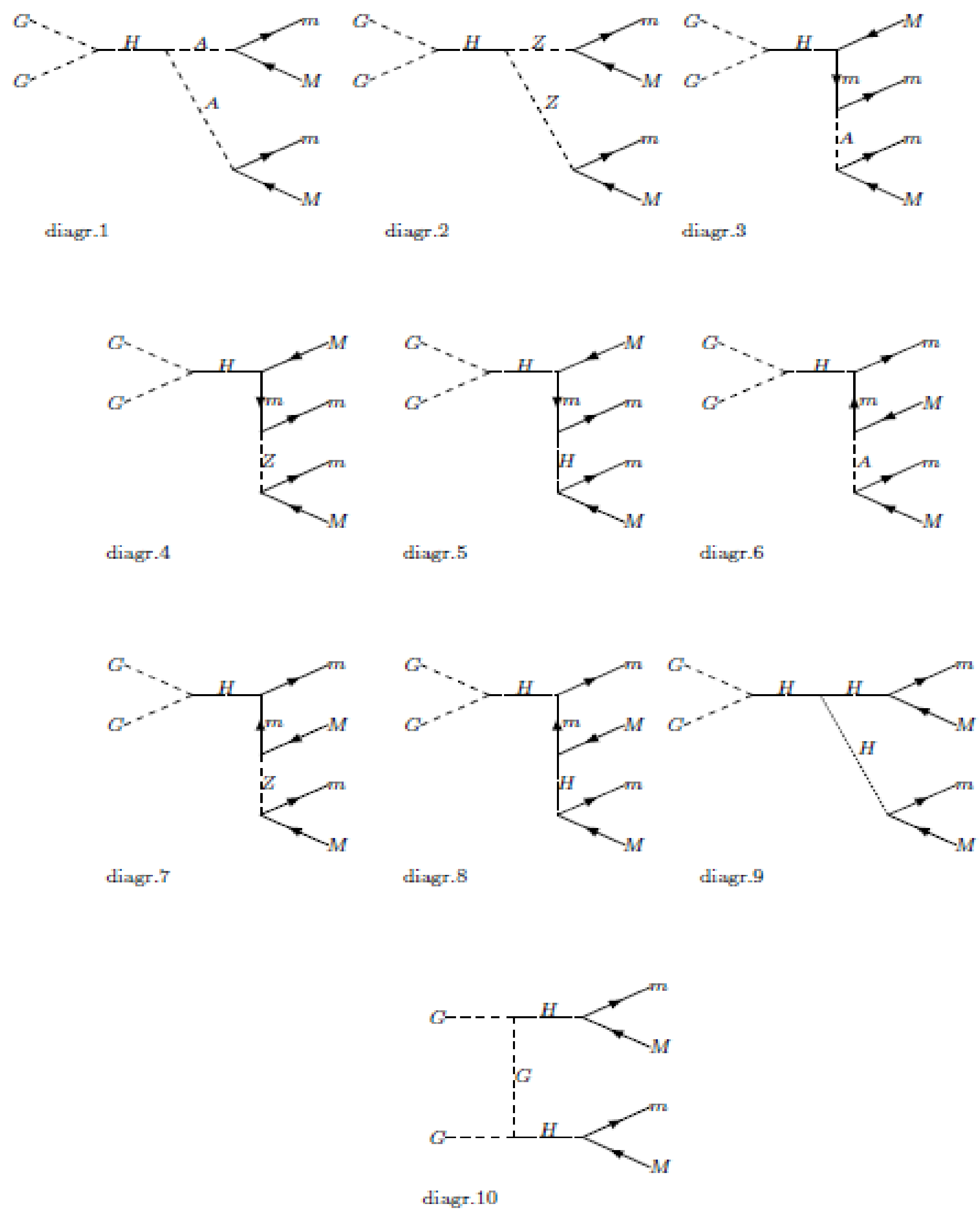
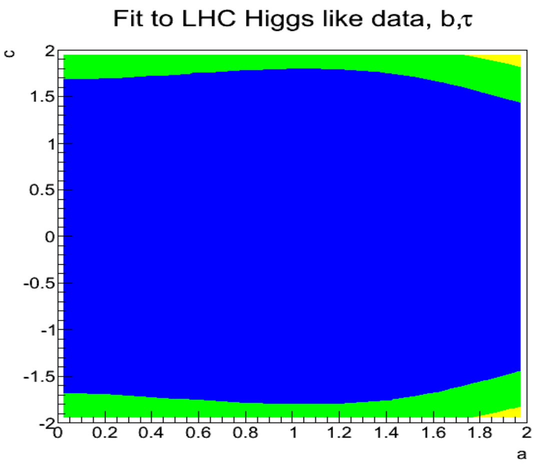
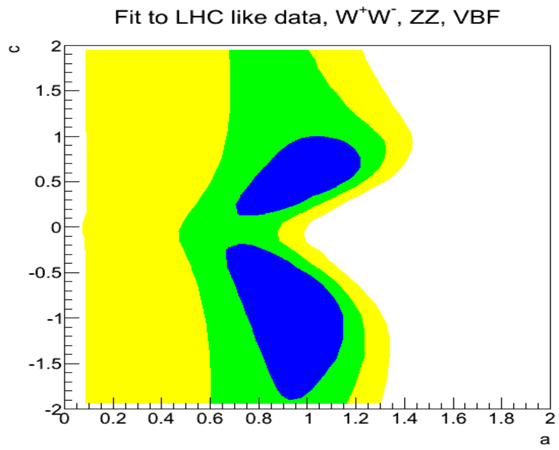
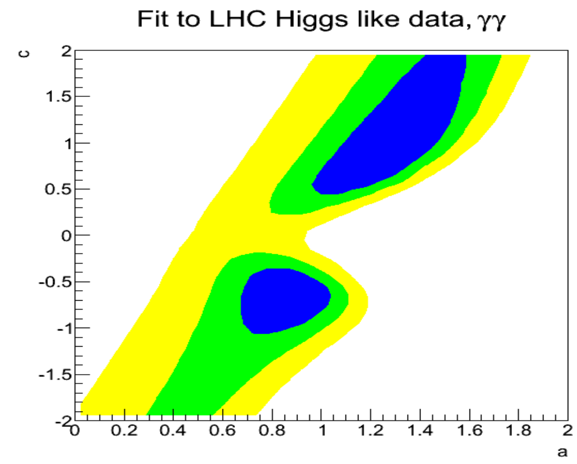


Figure 2: Signal diagrams for the process $e^- e^+ \to ZZ \to \mu^+ \mu^- \mu^+ \mu^-$

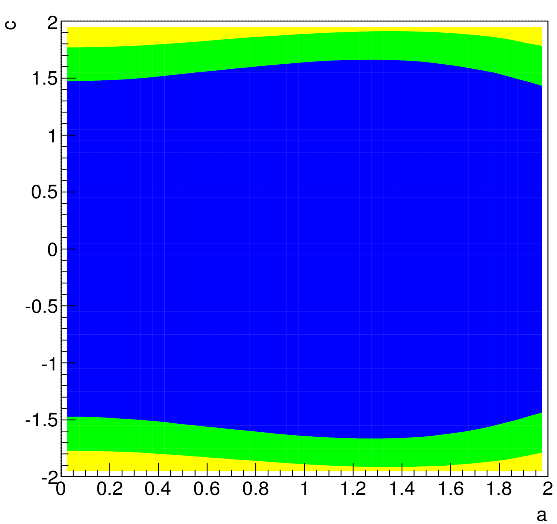
Combined fits in the anomalous coupling (a,c) plane for γγ , bb+ττ separately

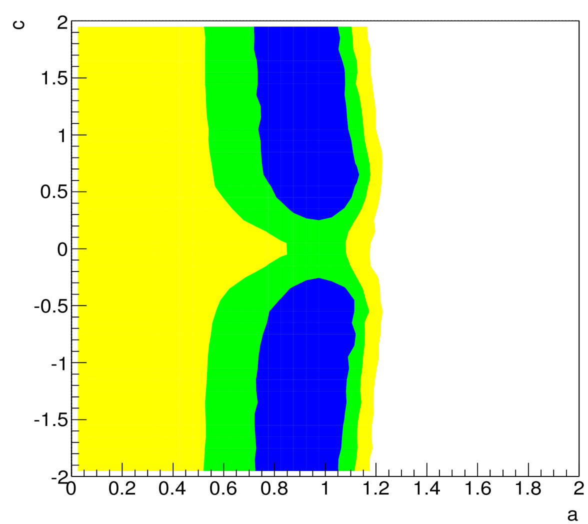


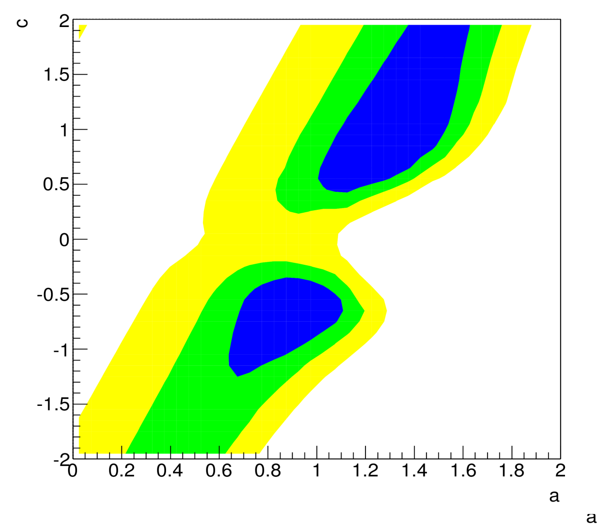




CompHEP infinitely small width approximation

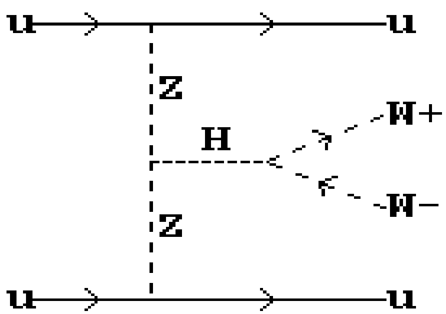


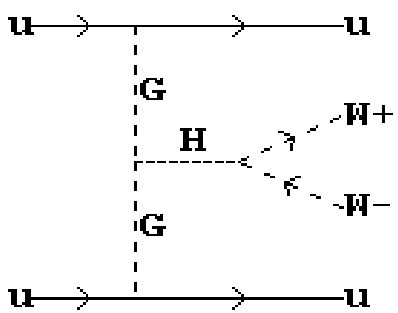


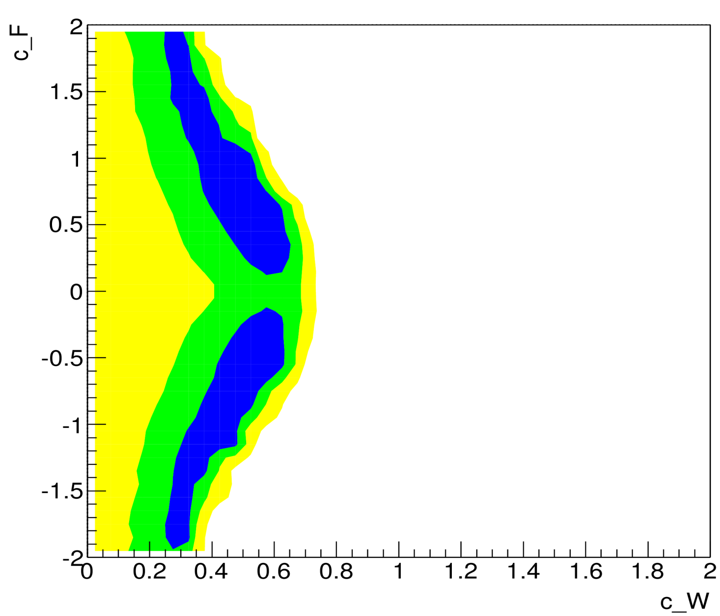


CompHEP complete tree-level sets

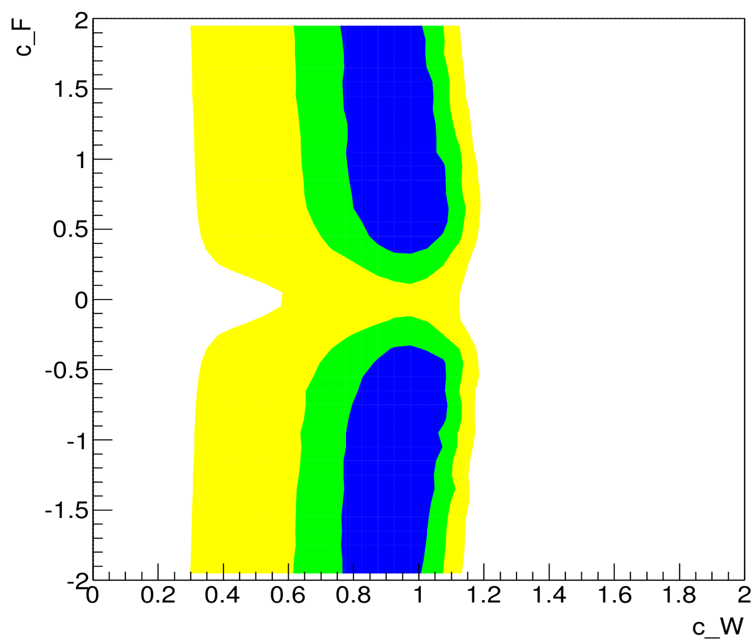
High sensitivity to gg fusion in the pp → 4 leptons VBF







With gg VBF



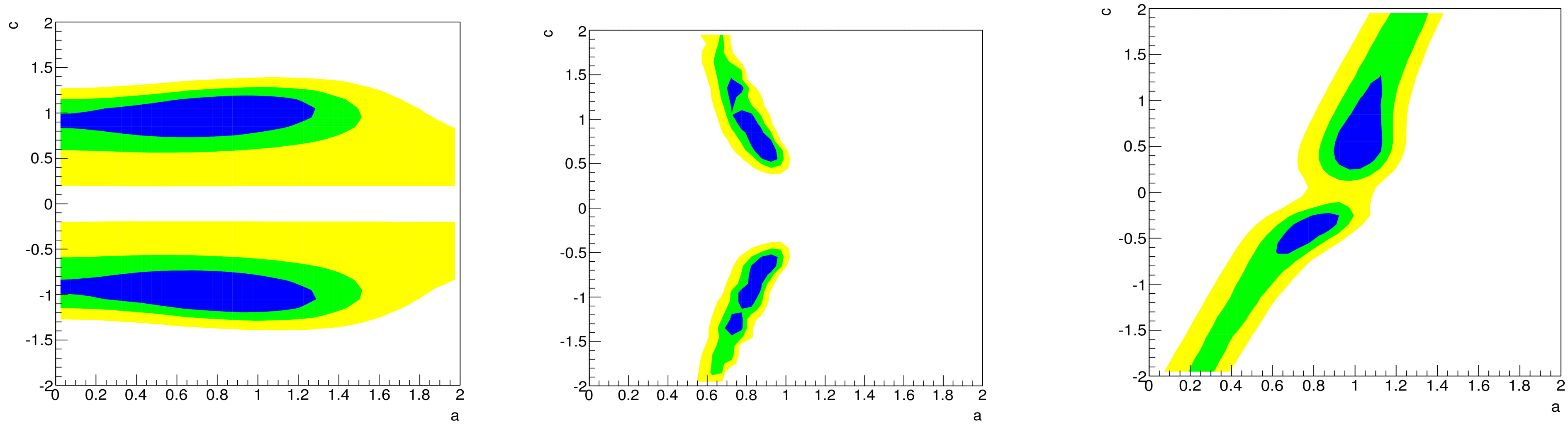
No gg VBF

The signal strength and the signal strength error from LC 2013 27-31 May, DESY, A.Zanzi (ATLAS), V.Savin (CMS)

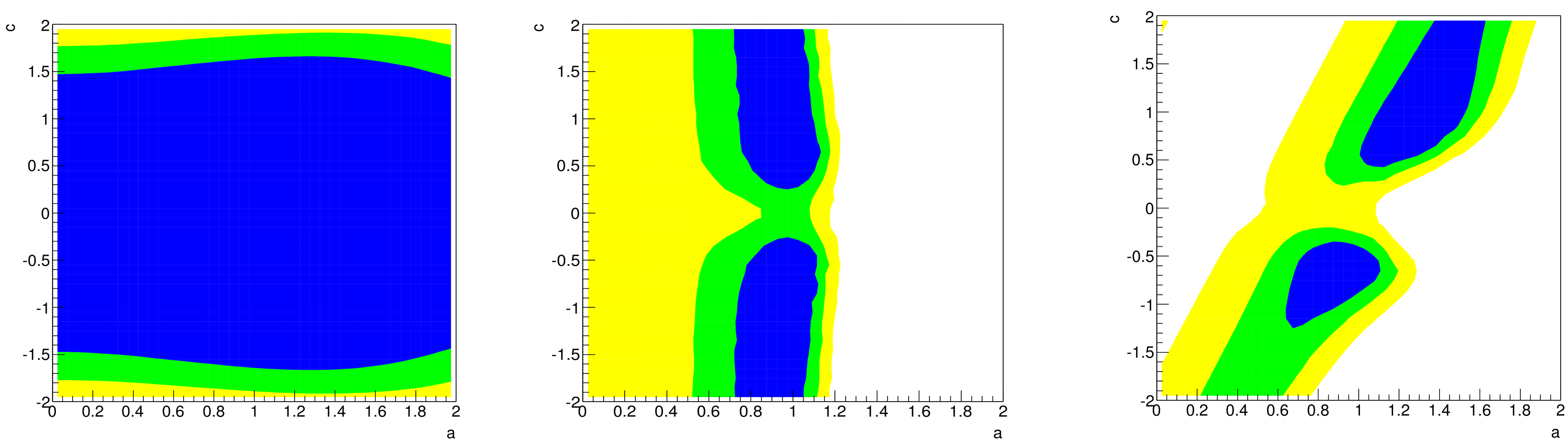
Significant improvements in the bb, tau tau channel have been reported.

channel	ATLAS	CMS
$VH \to Vb\bar{b}$	-0.4±1.0	1.15±0.62
$H \to \tau^+\tau^-$	0.8±0.7	1.10±0.41
$H \to WW^*$	1.0±0.3	0.68±0.20
$H \to ZZ^*$	1.5±0.4	0.92±0.28
$H \to \gamma\gamma$	1.6±0.3	0.77±0.27

Combined fits in the (a,c) plane
for bb+ττ, WW+ZZ and γγ separately

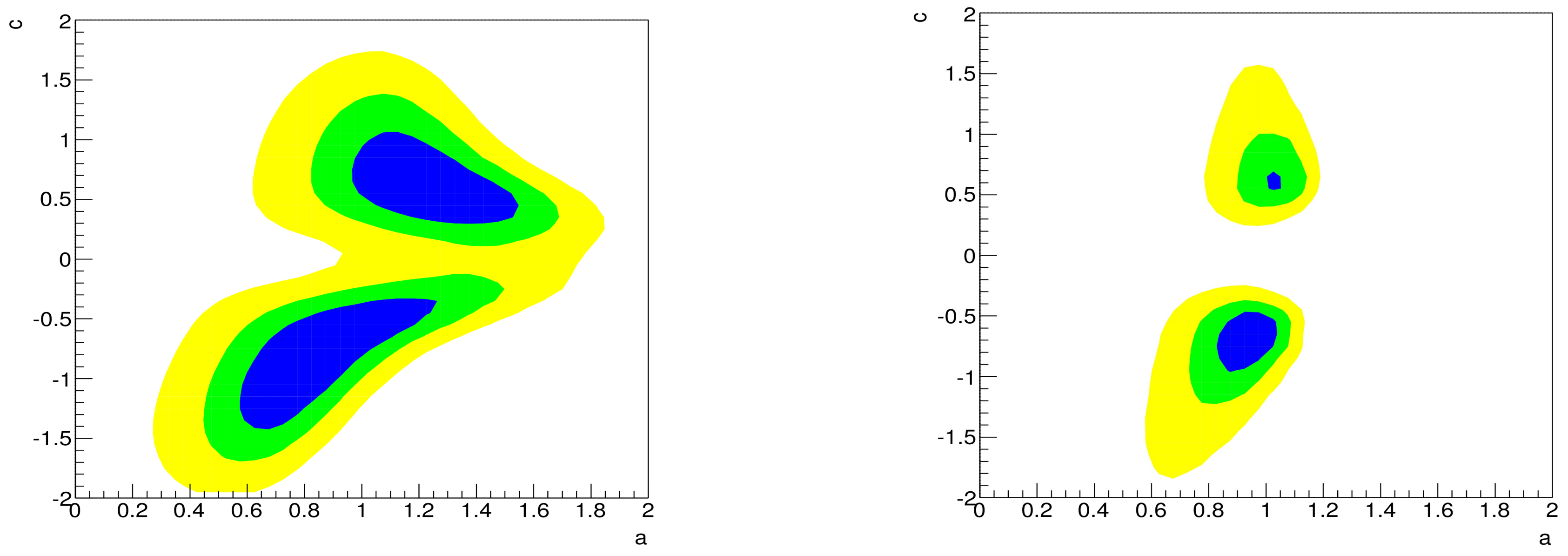


LC 2013 data (preliminary)

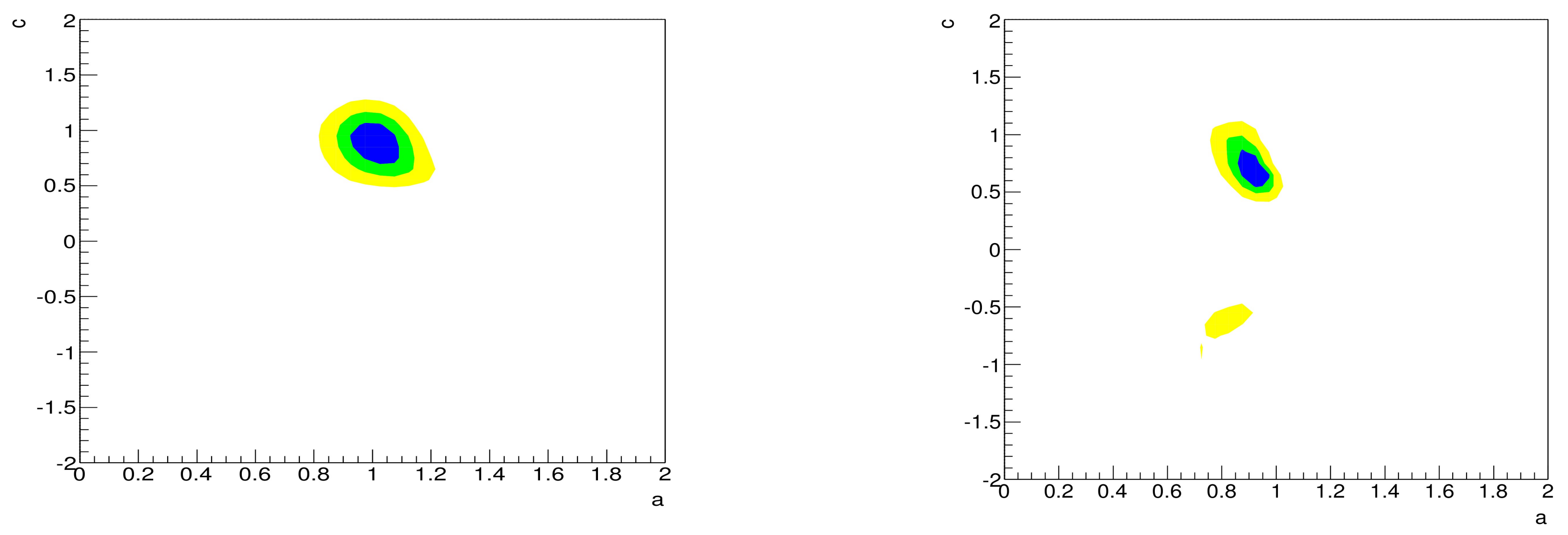


Post-Moriond 2012 data

Combined γγ,WW,ZZ,bb,ττ, post-Moriond 2012



Combined γγ,WW,ZZ,bb,ττ, LC 2013 (preliminary)

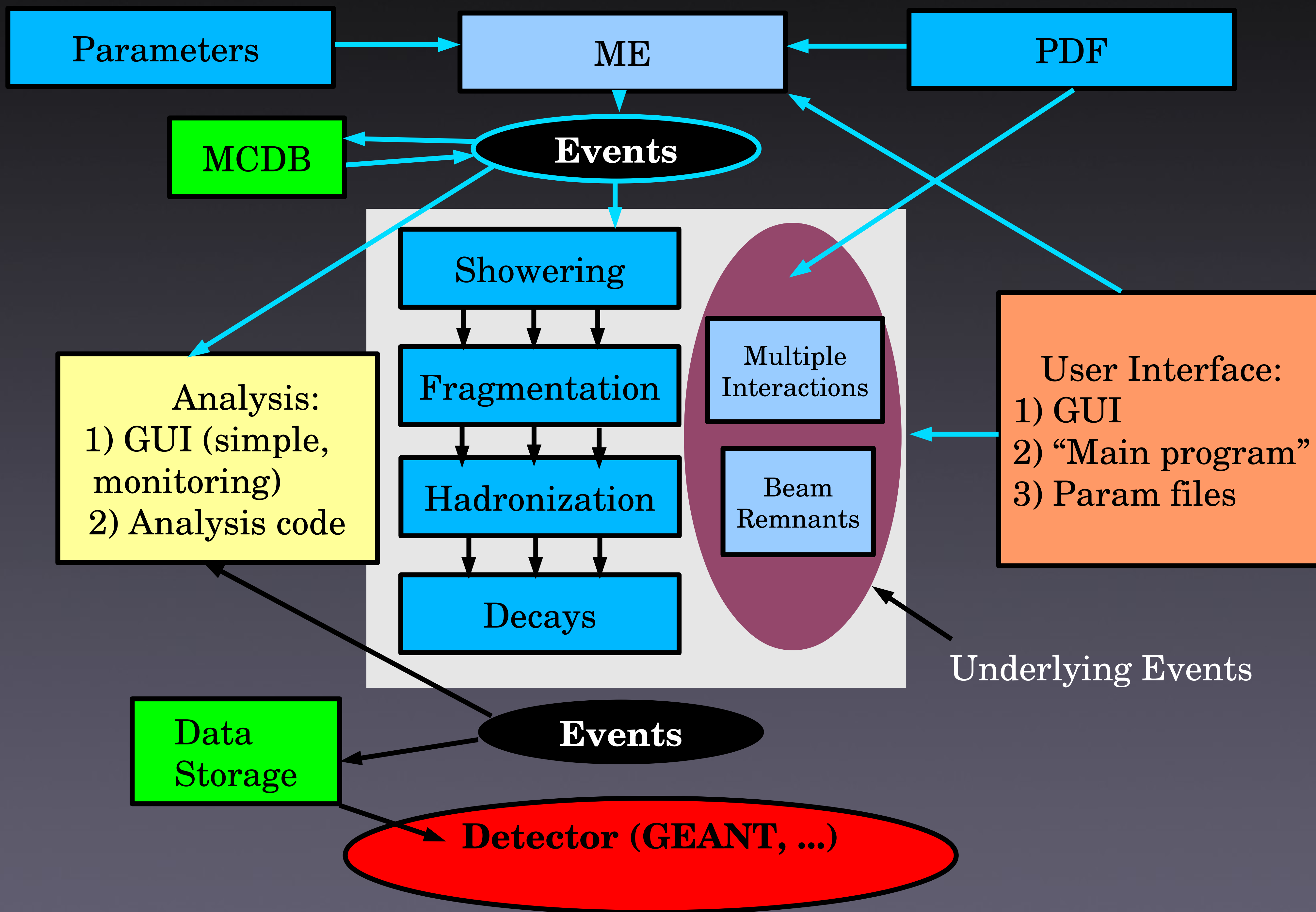


Summary

- CompHEP developments in 2011-2013 have been motivated mainly by experimental analyses of CMS and D0 collaborations. Interfaces, visualization and batch modes significanltly improved.
- Operations with cross section/Br tables and generation of CL contours are introduced to work in BSM multiparameter space.
- Relevant issue of Higgs boson production in the SM extension by dim6 effective operators is analysed beyond the production ⊗ decay approximation.
- A degree of sensitivity of the exclusion contours to theoretical uncertainties is demonstrated to be rather low, dominated by the VBF amplitudes.

Backup slides

Modern Monte-Carlo Chain



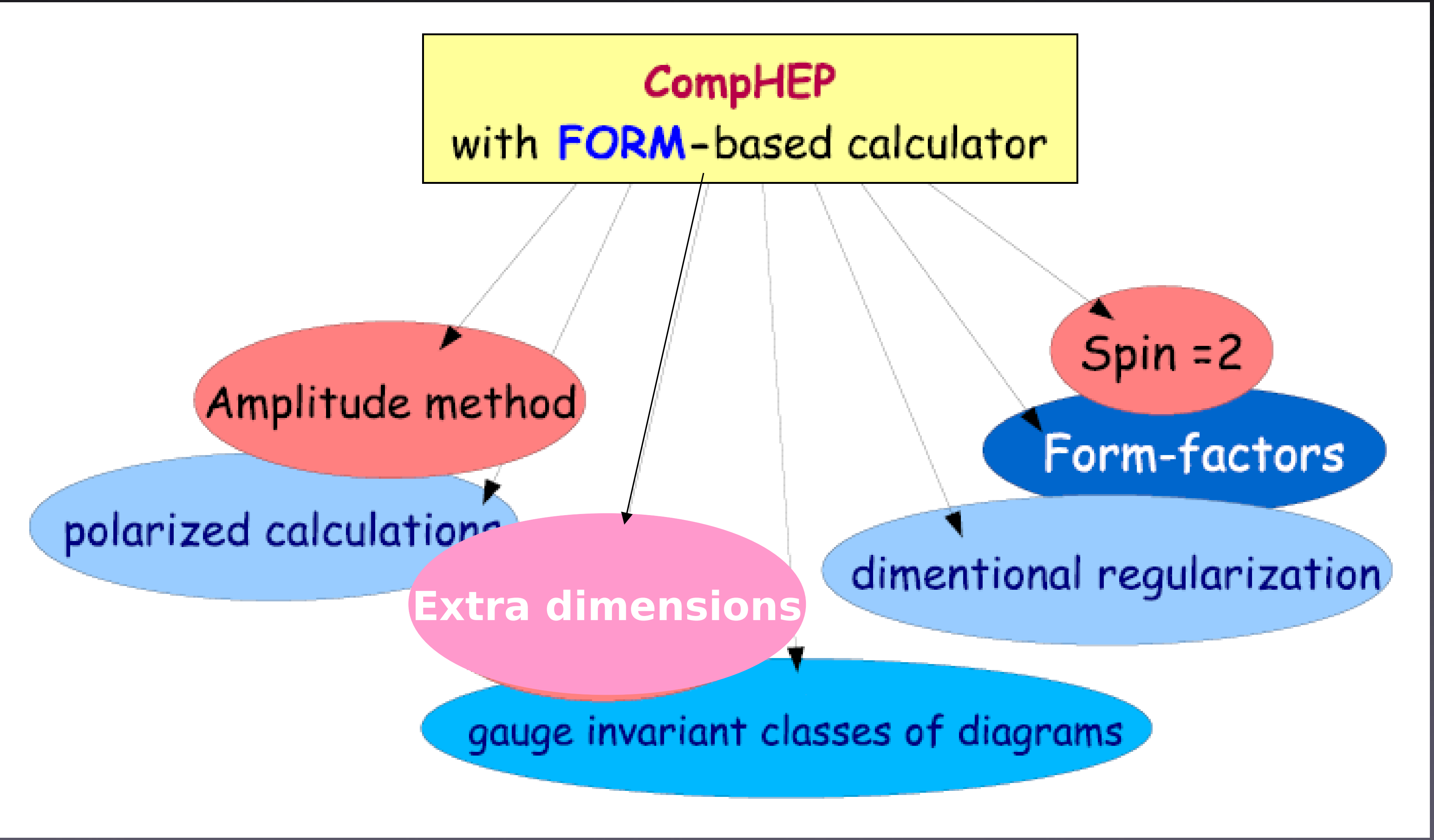
Les Houches Agreements

There are many MC generators with their own advantages and application areas. Often we are forced to use several generators for reliable calculations:

Problems:

- Interfacing some MC codes (ME and SH generators): Les Houches Accord 1, Les Houches Event format
- Les Houches Accord 2: uniform interface to different PDF sets (LHAPDF package)
- Les Houches Accord 3: Interfacing SUSY codes to MC generators for parameters, spectrum, decays (SPA).
- BSM Les Houches Accord: fixing of parameter record for BSM
- Matching ME (LO/NLO) and SR(NL): CKKW, MC@NLO, Mrenna-Richardson, MLM, ...

Two symbolic passes in CompHEP: standard and FORM based



Not publicly available yet

General information and references

- CompHEP collaboration: E. Boos, V. Bunichev, M. Dubinin, L. Dudko, V. Ilyin, A. Kryukov, V. Edneral, V. Savrin (Moscow State), A. Semenov (JINR, Dubna), A.Sherstnev
- CompHEP homepage: http://comphep.sinp.msu.ru
- References:
    - CompHEP 4.5 Status Report. E.Boos et al. arXiv:0901.4757
  - CompHEP: E. Boos et al., Nucl.Inst.Meth. A534:250 (2004) [hep-ph/0403123]
  - LanHEP: A. Semenov, Nucl.Inst.Meth. A393:293 (1997) [hep-ph/0403123]; 0805.0555 (hep-ph)
  - CompHEP-Interfaces: A.Belyaev et al., hep-ph/0101232