

# CompHEP: developments and applications 2013-2016

**Speaker: Mikhail Dubinin**

SINP, Moscow State University

**CompHEP Collaboration:**

E. Boos, V. Bunichev, M. D., L. Dudko, V. Ilyin, A. Kryukov, V. Edneral, V. Savrin, A. Semenov, A. Sherstnev

<http://comphep.sinp.msu.ru>

## Outline

- **History and statistics**
- **Tools for BSM physics: combined global fits, operations with tables, subsidiary bosons**
- **Miscellaneous: batch modes, ROOT output, LHA formats, MCDB, nuclear PDF's,...**

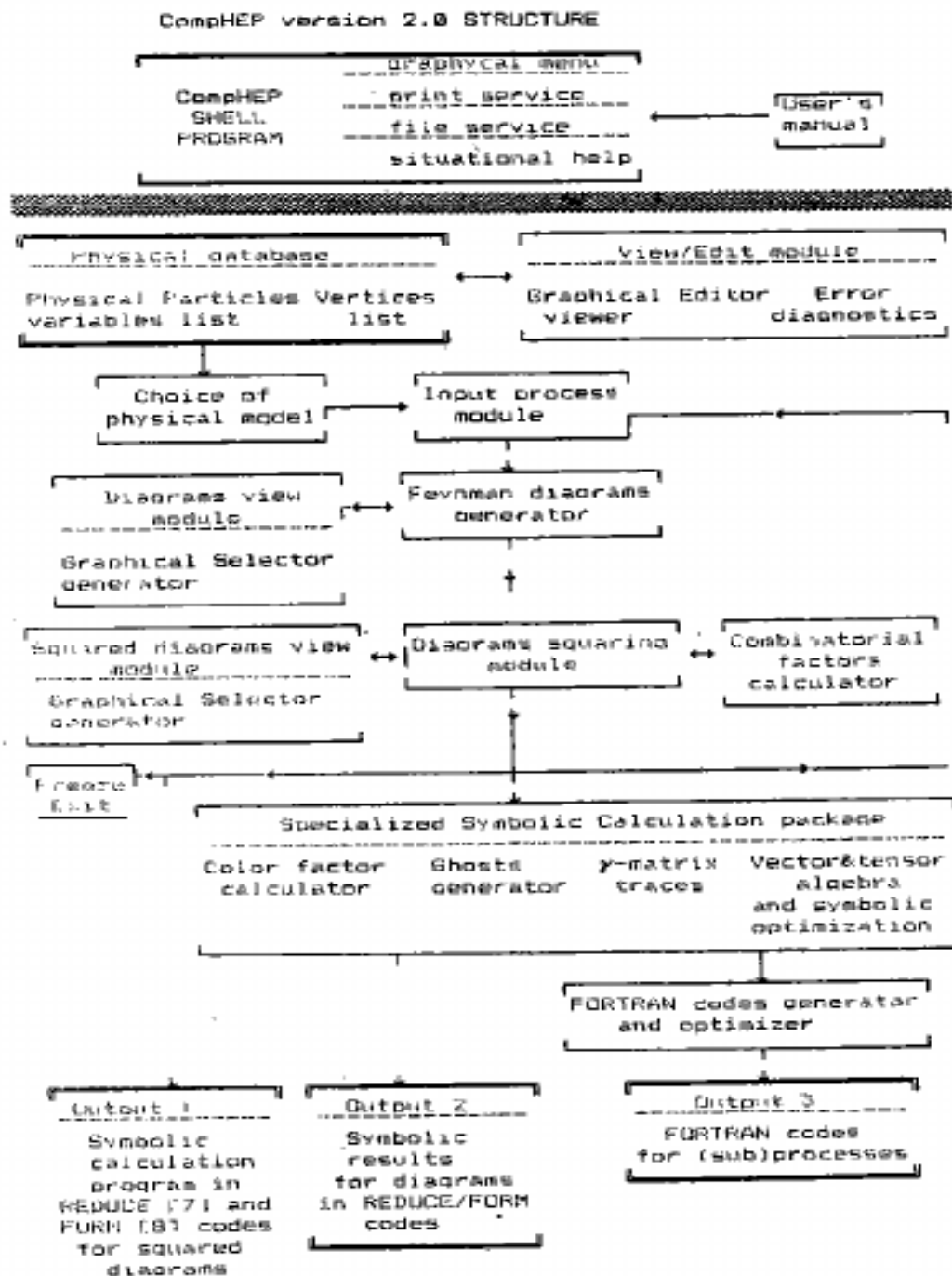
# 27 years of CompHEP project in 2016

Primary publication: 1989



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

- 29 -



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

## **Main objectives**

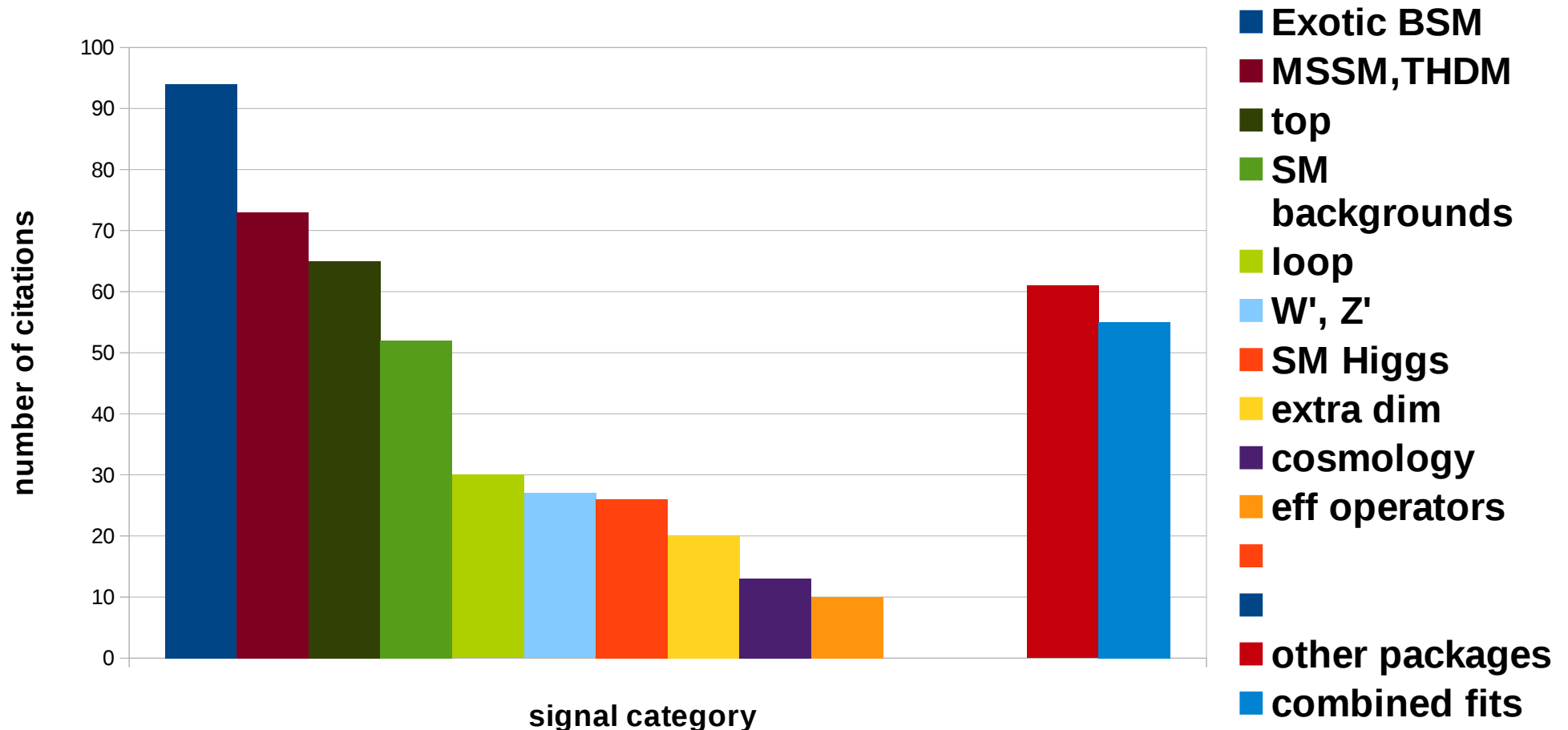
- **Automation of tree level diagram calculations**
- **“Unification” of symbolic and numerical calculation, unweighted event generation for detector simulation - a full computational chain for collider physics**
- **Interfacing to other generators (partonic showering, hadronization, masses and mixings)**
- **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>)**

# Distribution of citations: theory

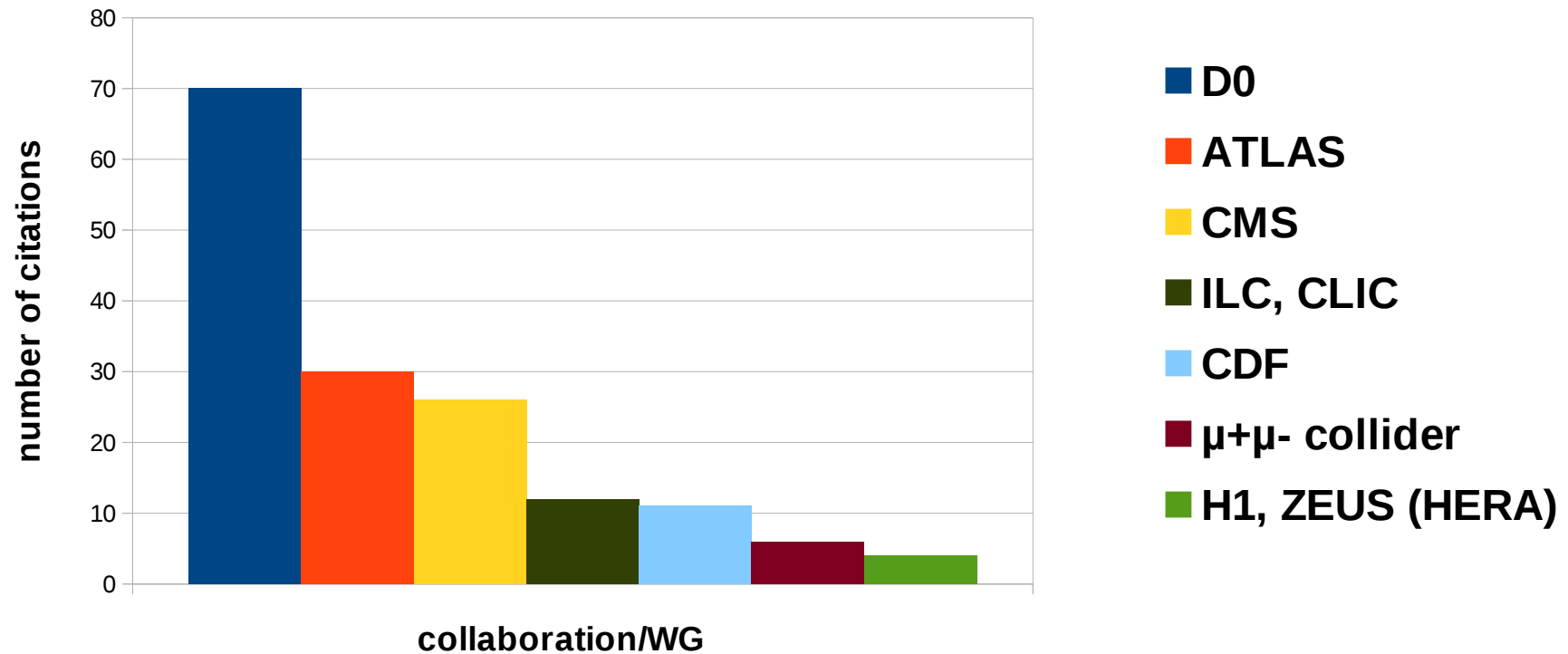
CompHEP, NIM, A534 (2004) 250, 560 citations (period 2005 - june 2016)



**Exotic BSM  $\Rightarrow$  scalar and vector leptoquarks, leptons and quarks of 4th generation, dileptons, mirror fermions, invisible H, little H, strong EW SB, color in the SB sector...**

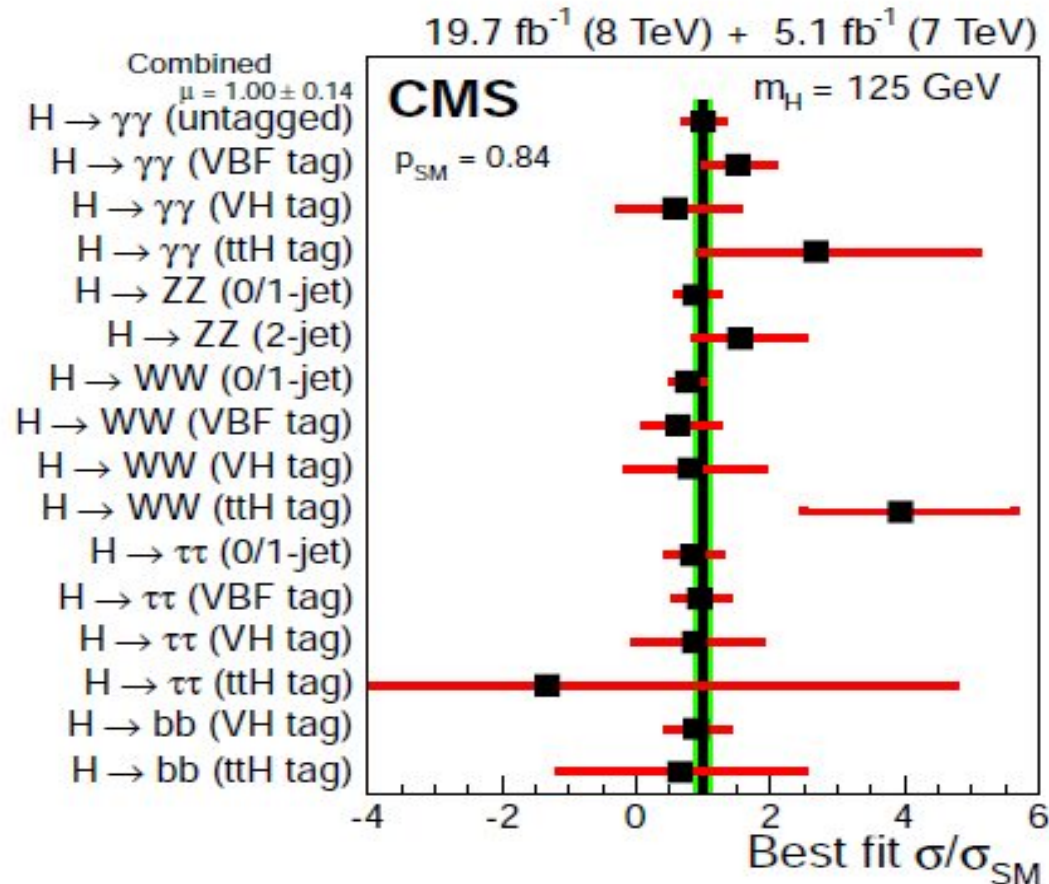
# Distribution of citations: experimental analyses and simulations

CompHEP, NIM, A534 (2004) 250, 560 citations (period 2005 - june 2016)



# Global fits

The signal strength and the signal strength error for various groups of Higgs boson production channels



Overall signal strength – all channels

$$1.00^{+0.14}_{-0.13} \left[ \pm 0.09(\text{stat.})^{+0.08}_{-0.07}(\text{theo.}) \pm 0.07(\text{syst.}) \right]$$



# Signal strength and exclusion contours in the SME (Standard Model Extension) parameter space

$$(1) \quad \mu_i = \frac{\left[ \sum_{j=1}^{N_{\text{ch}}} \sigma_{j \rightarrow H} \text{Br}(H \rightarrow i) \right]_{\text{SME}}}{\left[ \sum_{j=1}^{N_{\text{ch}}} \sigma_{j \rightarrow H} \text{Br}(H \rightarrow i) \right]_{\text{SM}}} \quad (2) \quad \mu_i = \frac{\left[ \sum_{j=1}^{N_{\text{ch}}} \sigma_{j \rightarrow H(\text{off-shell}) \rightarrow i} \right]_{\text{SME}}}{\left[ \sum_{j=1}^{N_{\text{ch}}} \sigma_{j \rightarrow H(\text{off-shell}) \rightarrow i} \right]_{\text{SM}}}$$

(1) signal strength in the production  $\times$  decay approximation

(narrow width approximation or infinitely small width approximation);

(2) signal strength for complete gauge invariant set

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

- best fit of the signal strength for the number of experimentally observed signal events  $N_{\text{OBS}}$ , the number of background events  $N_{\text{BACKGR}}$  and the number of Standard Model events  $N_{\text{SIGNAL}}^{\text{SM}}$ ;

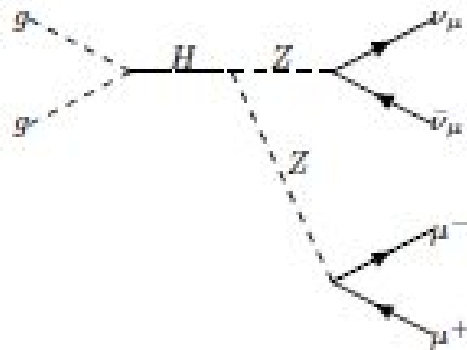
$$\chi_{N_{\text{ch}}}^2 = \sum_{i=1}^{N_{\text{ch}}} \frac{(\mu_i - \hat{\mu}_i)^2}{\sigma_i^2}$$

*MC* -  $\chi_{N_{\text{ch}}}^2$  distribution for the number of production channels  $N_{\text{CH}}$ ;

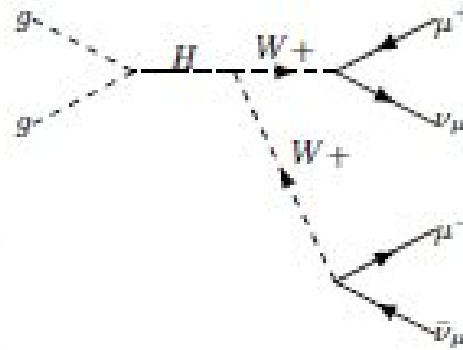
# Beyond the infinitely small width approximation

In a number of channels the interference terms are not small (especially for  $\gamma\gamma$ , 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  $\mu\mu\mu$ )

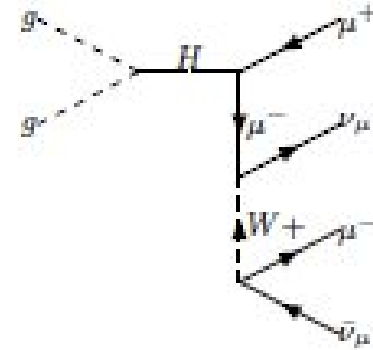
**Example:  $gg \rightarrow (W^*W^*, Z^*Z^*) \rightarrow \nu_\mu \nu_\mu \mu^+ \mu^-$**



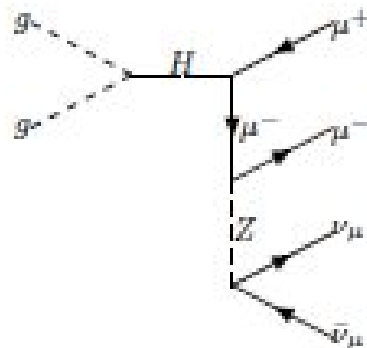
diagr.1



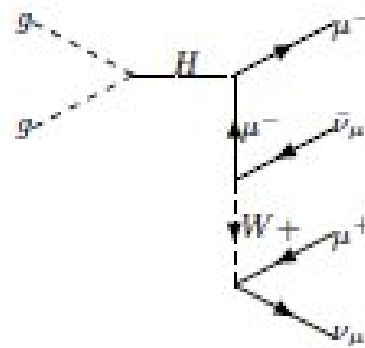
diagr.2



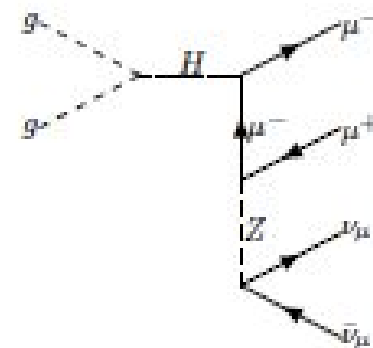
diagr.3



diagr.4



diagr.5



diagr.6

- **Up to which degree the SM Higgs boson is consistent with the available data? More than 200 production  $\otimes$  decay combinations and rearrangements are measured**
- **Structure of the couplings can be extracted correlating event rates from all channels**
- **Deviations from the SM are introduced in the form of effective operators  $O$ . Anomalous couplings  $C$  parametrize the deviations**

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

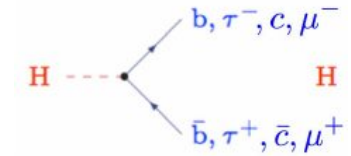
- **Global fit in the anomalous coupling space is performed combining all production channels**

**E.Boos, V.Bunichev, M.D.,Y.Kurihara Phys.Rev.D 2014, Phys.Lett.B 2014**

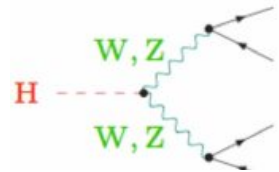
**Uses signal strength definition (2) – complete gauge invariant sets**

**(a,c) parametrization.**

**a rescales the VVH, c rescales the FFH**

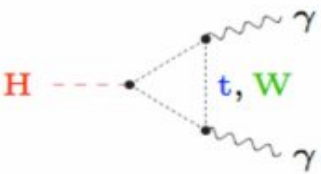


$$c_F = 1 + C_{t\Phi} \cdot \frac{v^2}{\Lambda^2}$$



$$c_V = 1 + \frac{v^2}{2\Lambda^2} \cdot C_{\Phi}^{(1)}$$

$$c_G = c_F + \frac{6\pi}{\alpha_s} \cdot C_{\Phi G} \cdot \frac{v^2}{\Lambda^2}$$



$$c_{\gamma} = \frac{63c_F - 16c_V}{47} + \frac{9\pi}{4\alpha} \cdot (c_w^2 \cdot C_{\Phi B} + s_w^2 \cdot C_{\Phi W}) \cdot \frac{v^2}{\Lambda^2}$$

$$c_Z = (s_w^2 \cdot C_{\Phi B} + c_w^2 \cdot C_{\Phi W}) \cdot \frac{v^2}{\Lambda^2}$$

$$c_W = C_{\Phi W} \cdot \frac{v^2}{\Lambda^2}$$

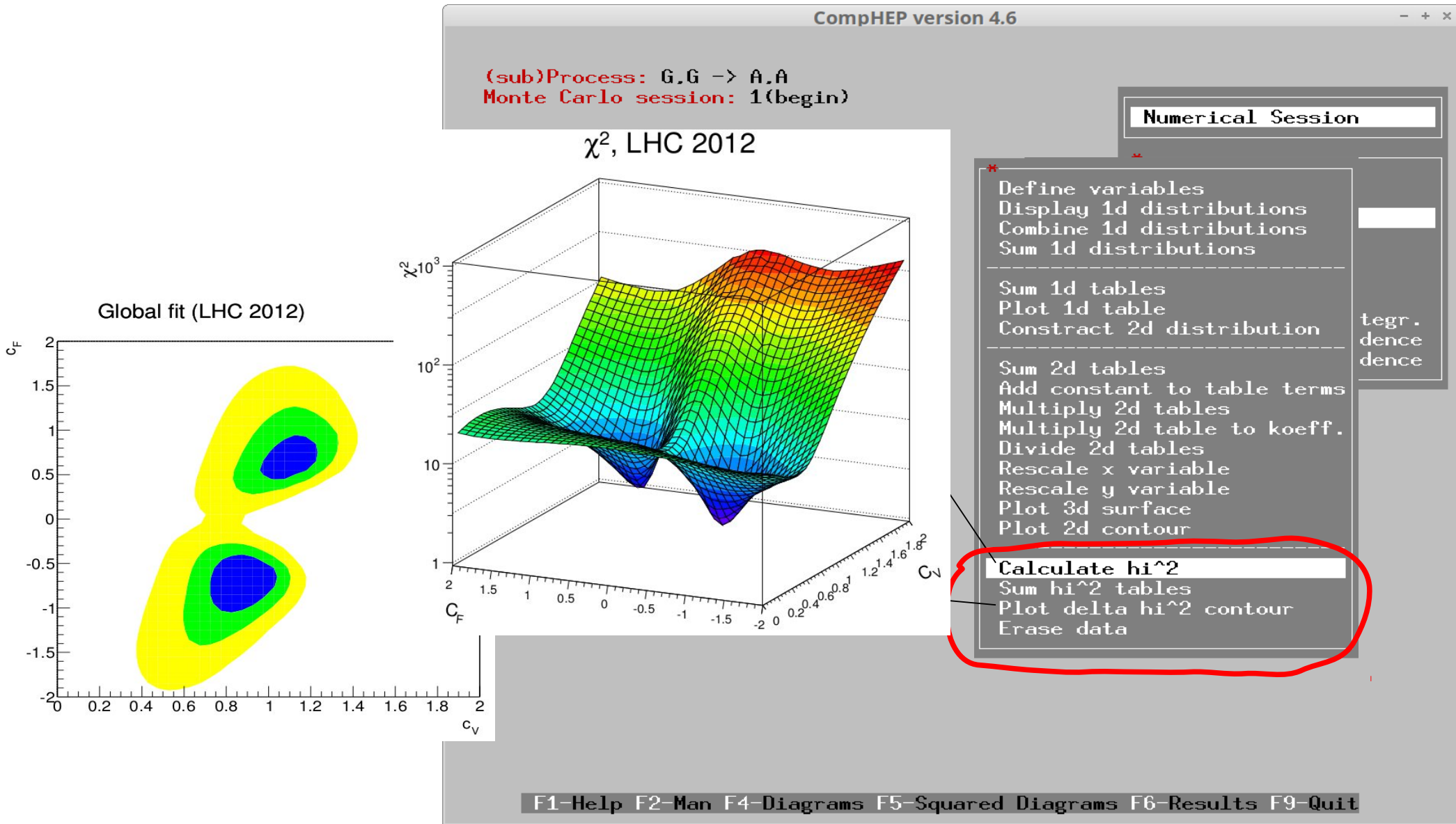
**the SM limit [a=1, c=c<sub>G</sub>=c<sub>γ</sub>=1, a<sub>W</sub>=0, a<sub>Z</sub>=0]**

**with the one-loop induced H→gg, H→γγ is clearly seen.**

## Effective triple vertices with the $(c_F, c_V)$ parametrization

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

**Basic object:  $\chi^2$  measure in the anomalous coupling space.**  
**Global fits to  $\mu$  in (cF,cV) plane are performed. Dispersion matrix of the observables convoluted with vector differences between the observed and calculated  $\mu$  values defines  $\chi^2$ . The minimum of  $\chi^2$  is found and 65%,90% and 99% best fit CL regions in the (cF,cV) space are defined by deviations from  $\chi^2_{\min}$  less than 2.1,4.6 and 9.2, respectively.**



## **New features of CompHEP v. 4.6 useful for generation of global fits**

**Implementation of external functions in the 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 3-DIM phase space distributions dependent on a model parameter**

# CompHEP Standard Model

The screenshot displays the CompHEP version 4.5.0rc6 interface, divided into four main panels:

- Variables:** A table listing physical constants and parameters. The selected row is 'EE' (Elementary charge).
- Particles:** A table listing particles with their properties. The selected row is 'tau-neutrino'.
- Constraints:** A table listing mathematical constraints. The selected row is 'CW'.
- Lagrangian:** A table listing terms in the Lagrangian. The selected row is 'P1'.

**Variables Panel:**

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	

**Particles Panel:**

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

**Constraints Panel:**

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	

**Lagrangian Panel:**

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



# Using external functions in the Constraints Model Table

*Any model parameter and vertex form-factor may be represented in the form of «c»-function that depends on other model parameters and on 4-momenta of particles*

CompHEP version 4.6

Constraints 17

Name	Expression
coeff	coeff1(MR,sint)
wH	lwidth1(MR,sint)
wR	lwidth2(MR,sint)
c	lwidth3(MR,sint)
b	lb1*c
yt	lmyfunc2(Mtop)
yW	lmyfunc2(MW)
loopt	lmyfunc3(yt,1)
loopW	lmyfunc3(yW,2)
Imlt	lmyfunc4(yt,1)
ImlW	lmyfunc4(yW,2)
RFF	l-(b1*cos+ b*sint-sint/v)
HFF	l-(b1*sint+ b*cos+ cost/v)
Ranom	lb1*cos- b*sint
Hanom	lb1*sint+ b*cos
RGG	l7*Ranom+loopt*(-RFF)
ImRGG	lImlt*(-RFF)
HGG	l7*Hanom+loopt*(-HFF)
ImHGG	lImlt*(-HFF)
RAA	l-11/(3)*Ranom+(loopW+8/(3)*loopt)*(-RFF)
ImRAA	l(ImlW+8/(3)*Imlt)*(-RFF)
HAA	l-11/(3)*Hanom+(loopW+8/(3)*loopt)*(-HFF)
ImHAA	l(ImlW+8/(3)*Imlt)*(-HFF)

F1 F2 Top Bottom GoTo Find Zoom ErrMes

```
myfunc.c
double myfunc3 (double ym, double keyp)
{
    double result, Fym, as, sqr, logs;

    as = asin(1./sqrt(fabs(ym)));
    sqr = sqrt(fabs(1.-ym));
    logs = log((1.+sqr)/(1.-sqr));

    if(ym >= 1.0) Fym = as*as;
    else Fym = -0.25*(logs*logs-9.869587728);

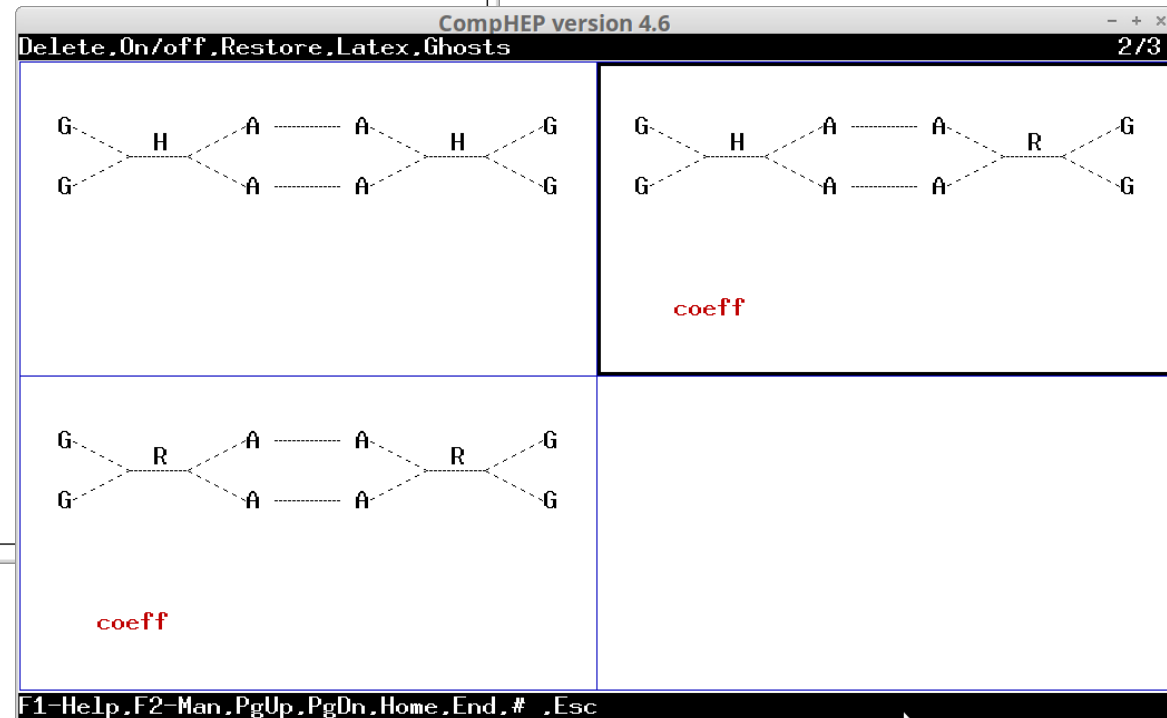
    if(keyp < 1.5) result = ym*(1.+(1.-ym)*Fym);
    else result = -(2. + 3.*ym + 3.*ym*(2.-ym)*Fym);

    return result;
}
```

# Multiplication of selected squared diagrams on an external function

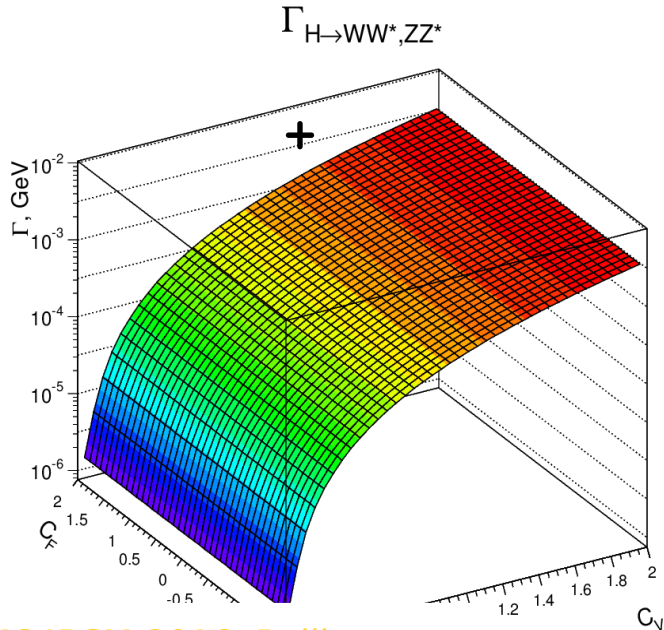
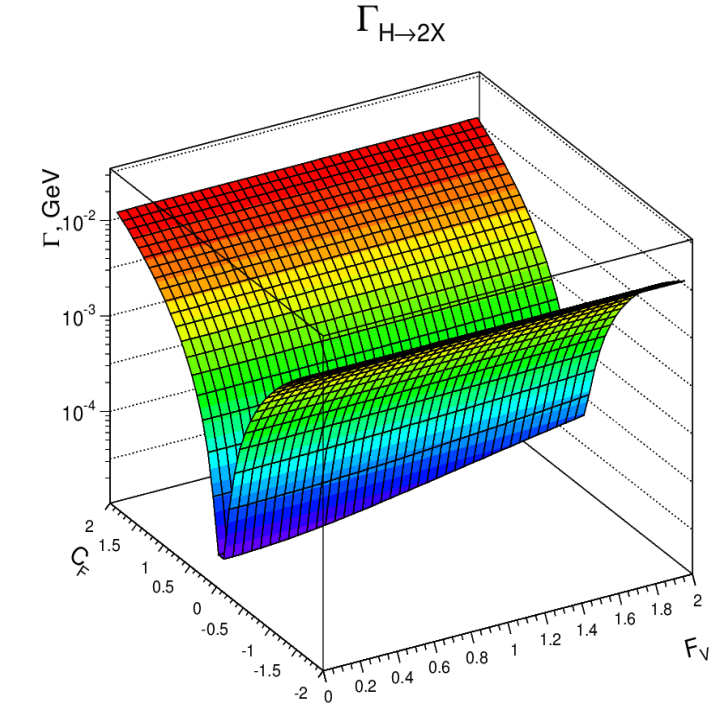
```

CompHEP version 4.6
Constraints 17
Clr Rest Del Size
Name |> Expression
coeff |coeff1(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)
ImIt |myfunc4(yt,1)
ImIW |myfunc4(yW,2)
RFF |-(b1*cos-b*sint-sint/v)
HFF |-(b1*sint+b*cos+cost/v)
Ranom |b1*cos-b*sint
Hanom |b1*sint+b*cos
RGG |7*Ranom+loopt*(-RFF)
ImRGG |ImIt*(-RFF)
HGG |7*Hanom+loopt*(-HFF)
ImHGG |ImIt*(-HFF)
RAA |-11/(3)*Ranom+(loopW+8/(3)*loopt)*(-RFF)
ImRAA |ImIW+8/(3)*ImIt)*(-RFF)
HAA |-11/(3)*Hanom+(loopW+8/(3)*loopt)*(-HFF)
ImHAA |ImIW+8/(3)*ImIt)*(-HFF)
F1 F2 Top Bottom GoTo Find Zoom ErrMes
    
```



**One can mark some squared diagrams in GUI mode, these diagrams are then multiplied by the function «coeff», where «coeff» is an external "c" -function or two-dimensional table**

# Algebraic operations with tables –cross section/width vs parameters



CompHEP version 4.6

```

: G,G -> A,A
session: 1(begin)
    
```

**Numerical Session**

\*  
 Itmx = 5  
 nCall = 98568

**Distributions**  
 Start integration  
 Clear statistic

\*  
 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

$\Gamma_{H \rightarrow 2X} + \Gamma_{H \rightarrow WW^*, ZZ^*}$

=

lp F2-Man F4-Diagrams F5-Squared Diagrams F6-Results F9-Quit

# resulting tables can be used as external functions in the Constraints Model Table

```

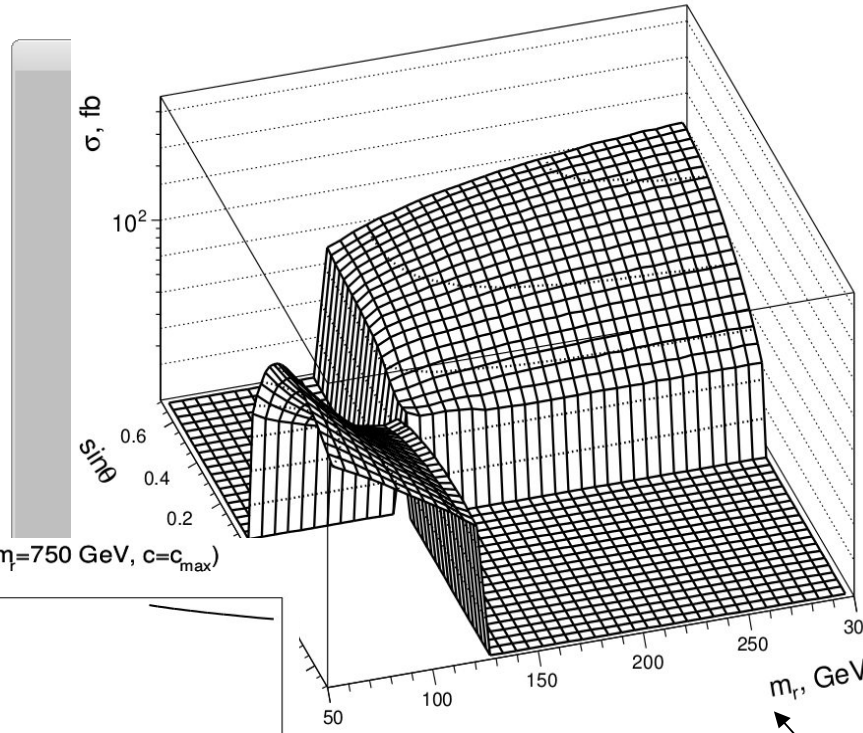
CompHEP version 4.6
Constraints 18
Clr Rest Del Size
Name |> Expression
coeff |coeff1(MR,sint)
wH |width1(MR,sint)
wR |width2(MR,sint)
c |width3(MR,sint)
b |b1*c
yt |myfunc2(Mtop)
yW |myfunc2(MW)
loopt |myfunc3(yt,1)
loopW |myfunc3(yW,2)
ImIt |myfunc4(yt,1)
ImIW |myfunc4(yW,2)
RFF |-(b1*cos+ b*sint-sint/v)
HFF |-(b1*sint+ b*cos+ cost/v)
Ranom |b1*cos+ b*sint
Hanom |b1*sint+ b*cos
RGG |7*Ranom+loopt*(-RFF)
ImRGG |ImIt*(-RFF)
HGG |7*Hanom+loopW*(-HFF)
ImHGG |ImIW*(-HFF)
RAA |-11/(3)*Ranom+(loopW+8/(3)*loopt)*(-RFF)
ImRAA |ImIW+8/(3)*ImIt*(-RFF)
HAA |-11/(3)*Hanom+(loopW+8/(3)*loopW)*(-HFF)
ImHAA |ImIW+8/(3)*ImIW*(-HFF)
F1 F2 Top Bottom GoTo Find Zoom ErrMes
  
```

width1.txt x

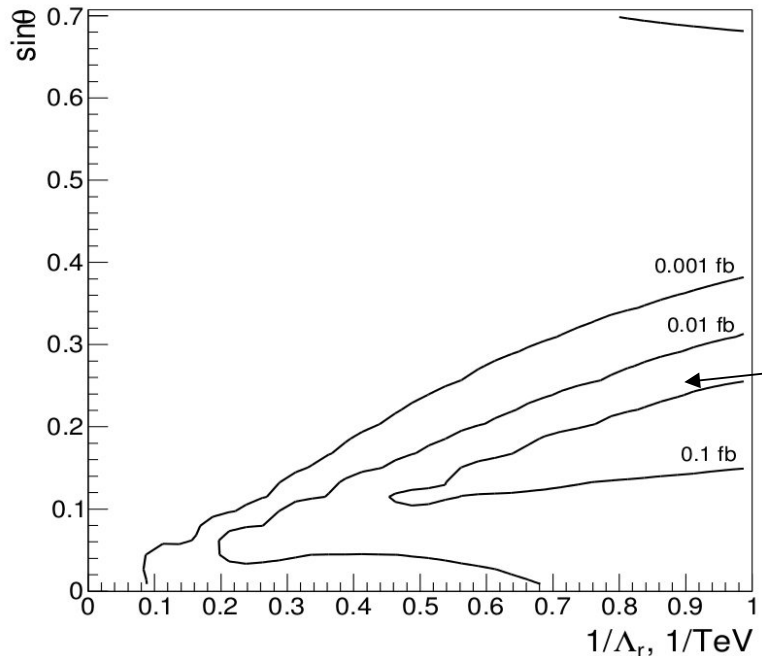
1.000000E+02	-7.071070E-01	9.265819E-04
1.000000E+02	-6.788227E-01	1.013980E-03
1.000000E+02	-6.505384E-01	1.099670E-03
1.000000E+02	-6.222542E-01	1.183458E-03
1.000000E+02	-5.939699E-01	1.265209E-03
1.000000E+02	-5.656856E-01	1.344767E-03
1.000000E+02	-5.374013E-01	1.422014E-03
1.000000E+02	-5.091170E-01	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

# ROOT code generation to draw table functions (3D surfaces or 2D contours)

$gg \rightarrow \gamma\gamma$  (LHC,  $\sqrt{s}=8$  TeV,  $m_h=125$  GeV,  $\Lambda_r=3$  TeV,  $c=c_{\max}$ )



$r \rightarrow \gamma\gamma$  tag (LHC,  $\sqrt{s}=13$  TeV,  $m_t=175$  GeV,  $c=c_{\max}$ )



**Numerical Session**

\* Itmx = 5  
nCall = 98568

**Distributions**

\* 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

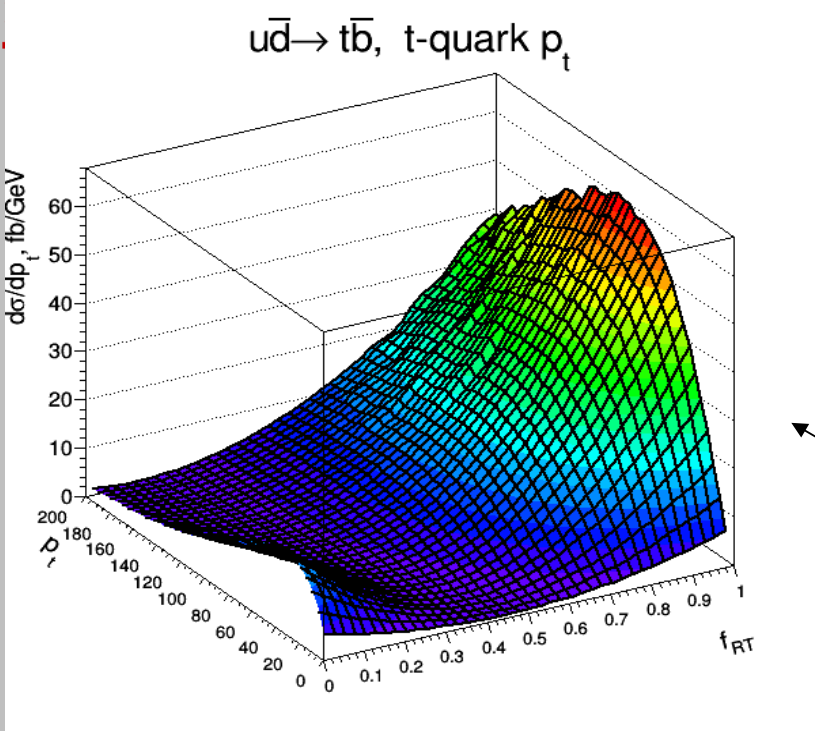
2-Man F4-Diagrams F5-Squared Diagrams F6-Results F9-Quit

# ROOT code generation for 3D phase space distributions dependent on a BSM model parameter

CompHEP version 4.6

(sub  
Monte

$u\bar{d} \rightarrow t\bar{b}$ , t-quark  $p_t$



$d\sigma/dp_t$ , fb/GeV

$p_t$

$f_{RT}$

**Numerical Session**

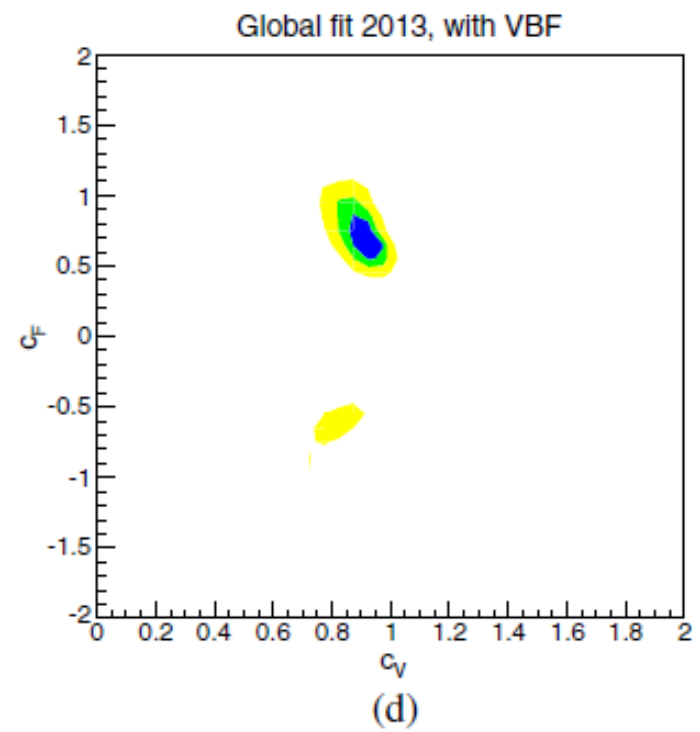
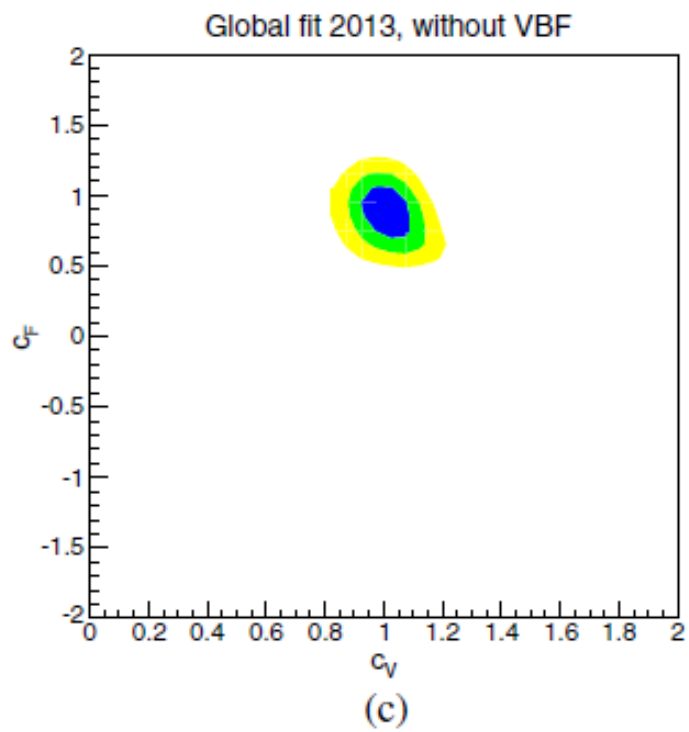
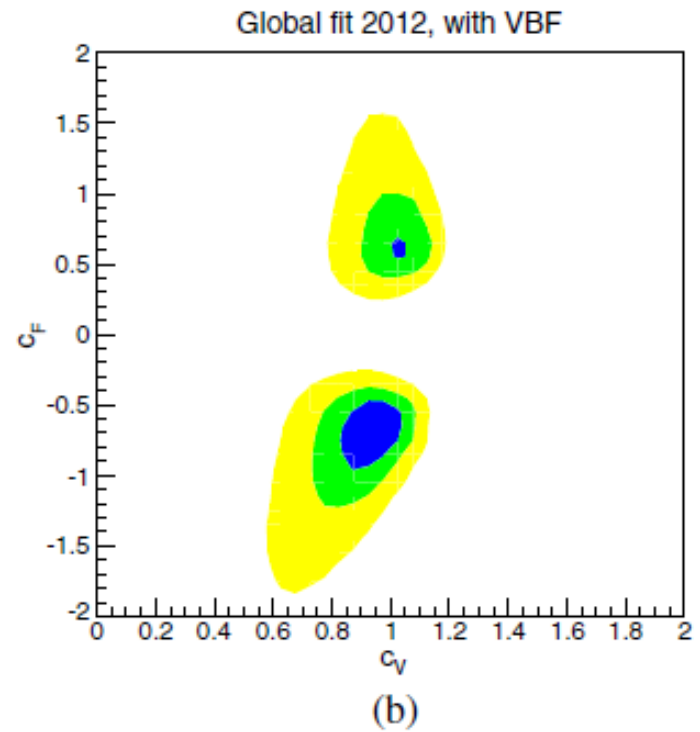
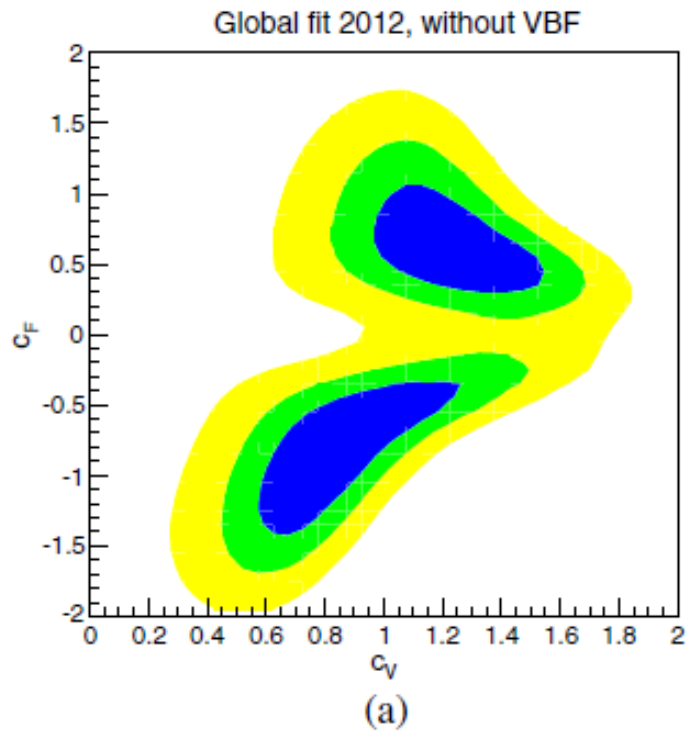
\*  
Itmx = 5  
nCall = 98568

**Distributions**

\*  
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  $h_i^2$   
Sum  $h_i^2$  tables  
Plot  $\Delta h_i^2$  contour  
Erase data

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

**LHC  
2014  
ATLAS  
+CMS  
combined**



## **Technical problems of evaluations with higher dim operators of BSM**

- **several anomalous couplings (AC) from different effective operators contribute to  $|M|^2$**
- **different AC contribute to the decay widths of unstable particles**
- **from other side, contributions of individual AC are used for event samples in experimental searches**

**Separation of congenerous contributions (e.g.  $1/\Lambda^2$  leading terms) in the event samples is of interest**



# Subsidiary bosons for BSM evaluations

## New Physics (NP) contributions to the SM vertex

$$\Gamma_\mu = \Gamma_\mu^{\text{SM}} + \Gamma_\mu^{\text{NP}_1} + \Gamma_\mu^{\text{NP}_2} + \dots$$

### Example: anomalous Wtb vertex

$$\mathcal{L}_{\text{Wtb}} = \frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (f_V^L P_L + f_V^R P_R) t W_\mu^- + \frac{g}{\sqrt{2}} \bar{b} \frac{\sigma^{\mu\nu}}{m_W} (f_T^L P_L + f_T^R P_R) t W_{\mu\nu}^- + h.c.$$

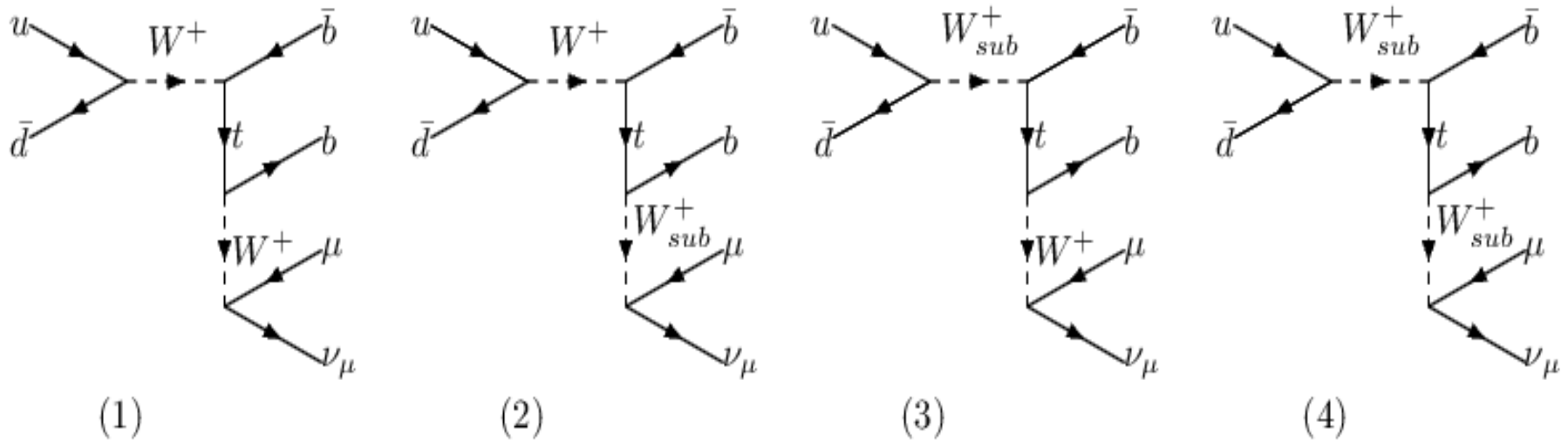
W boson SM  $\frac{g}{2\sqrt{2}} f_V^L \gamma^\mu (1 - \gamma_5)$

W boson subsidiary 1  $\frac{g}{2\sqrt{2}} f_V^R \gamma^\mu (1 + \gamma_5)$

W boson subsidiary 2  $\frac{g}{2m_W\sqrt{2}} f_T^L \sigma^{\mu\nu} q_\nu (1 + \gamma_5)$

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

**Boos, Bunichev, Dudko, Perfilov, arXiv:1512.00826, arXiv:1607.00505**



**Diagrams (2),(3),(4) with subsidiary bosons for  $qq \rightarrow bb \mu \nu_\mu$**   
**Squared amplitude with 'production'  $P_1, P_2$  and 'decay'  $D_1, D_2$**

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

**Three sets of event samples for simulation when  $f_{LV}=f_{RV}=1, f_{LT}=f_{RT}=0$**

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

# Physics Analysis Summary CMS-PAS-TOP-14-007. Baesian Neural Network Discriminant (BNN)

CMS preliminary,  $\sqrt{s} = 7$  TeV,  $L = 5.0$  fb $^{-1}$

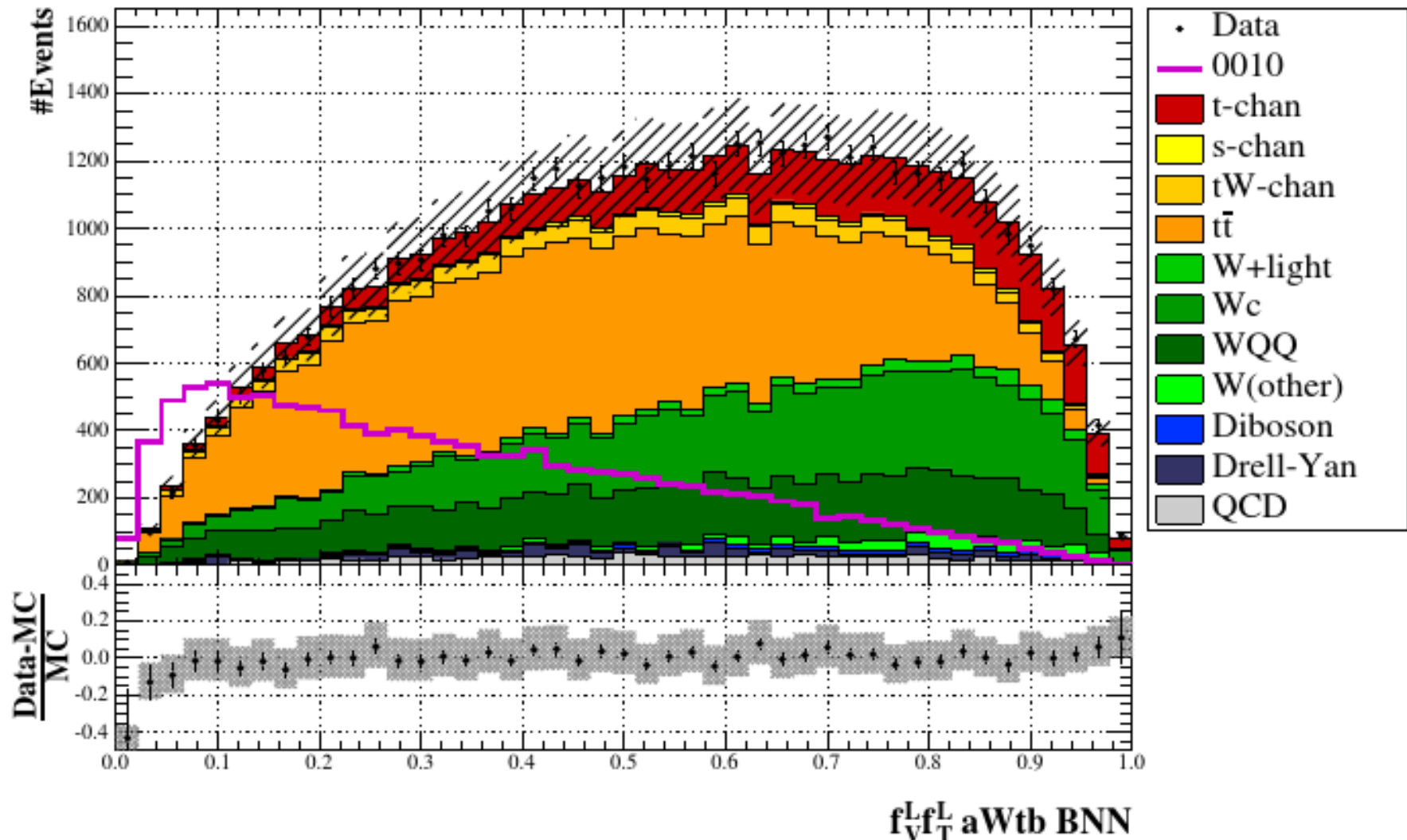
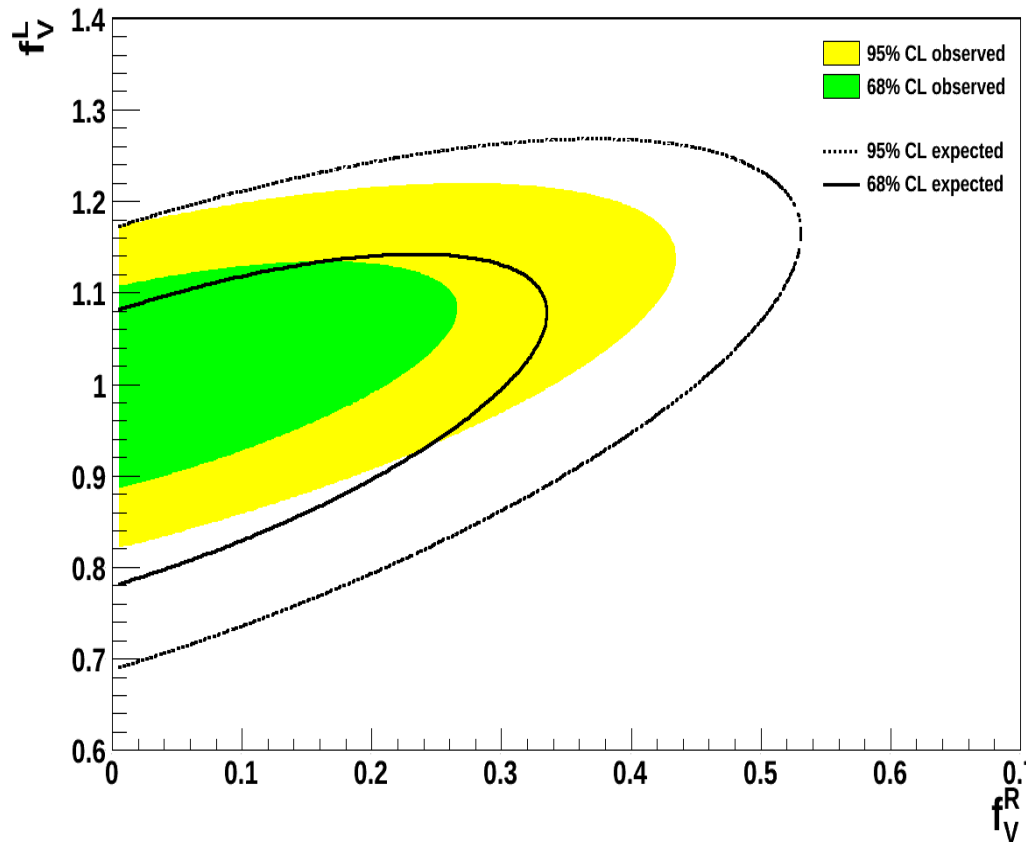


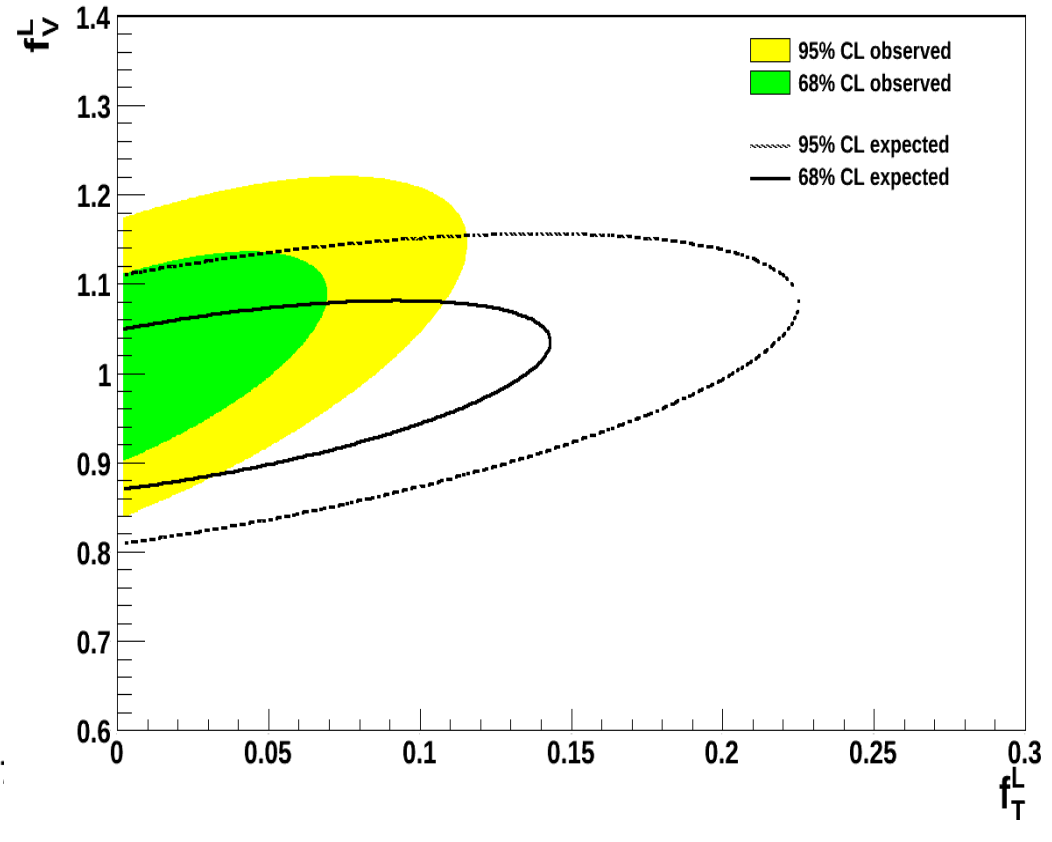
Figure 7: Data and model comparison of BNN aWtb discriminant for the  $(f_V^L, f_T^L)$  scenario. The BNN aWtb was trained to separate possible events with left tensor coupling in the Wtb interaction and SM events. The hashed band corresponds to the systematic uncertainty.

# Physics Analysis Summary CMS-PAS-TOP-14-007

CMS preliminary,  $\sqrt{s} = 7 \text{ TeV}, L = 5.0 \text{ fb}^{-1}$



CMS preliminary,  $\sqrt{s} = 7 \text{ TeV}, L = 5.0 \text{ fb}^{-1}$



## Important features improved

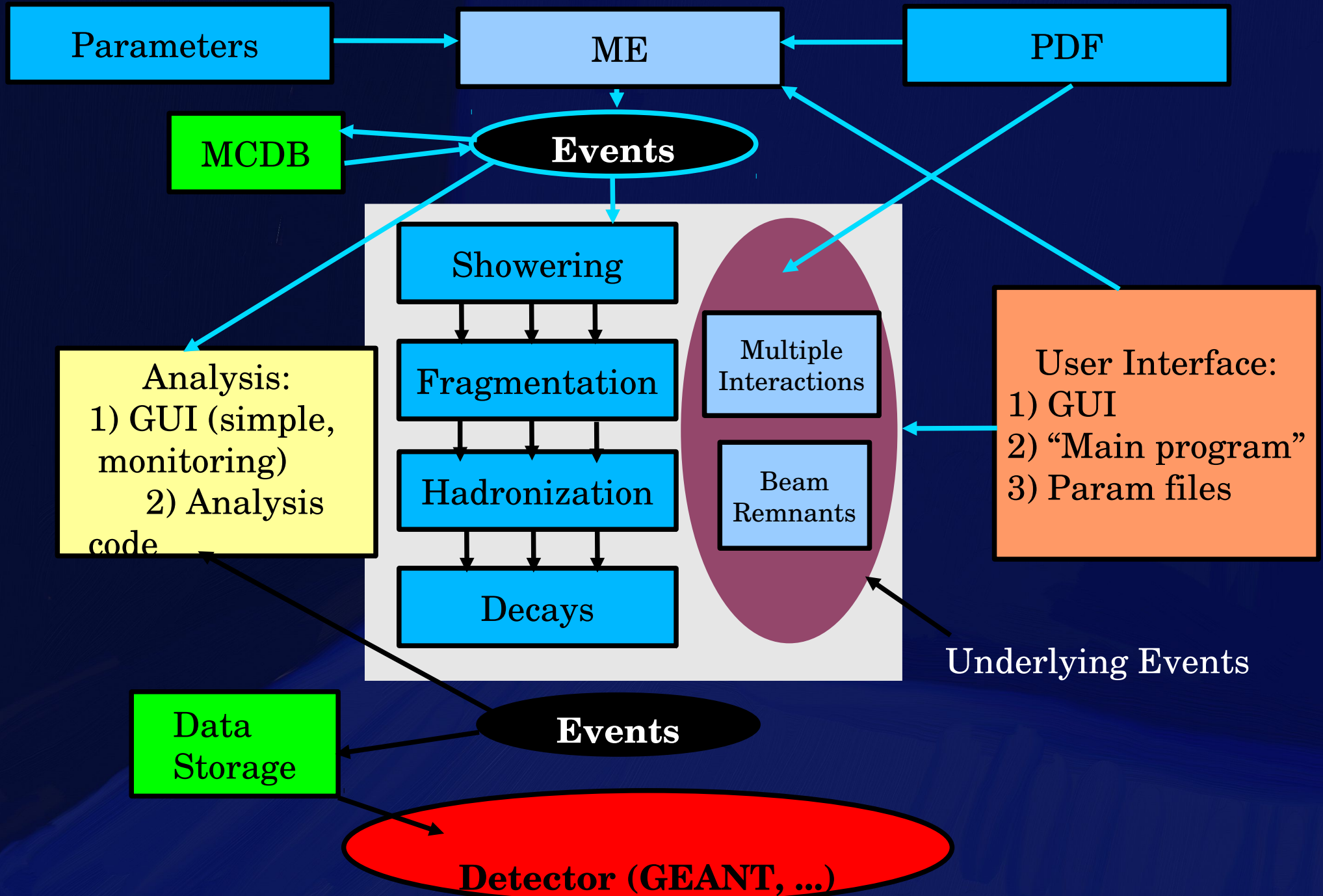
- **Batch system. Symbolical and numerical batch calculations in PBS/LSF**
- **Output event format respecting Les Houches agreements (LHEF with HepML header), convention LHAPDF, SUSY LHA format, BSM LHA format)**
- **Interfaces to PYTHIA/HERWIG and other**
- **Monte Carlo events data base (MCDB, see Comput. Phys.Commun.178(2008)222, hep-ph/0703287)**
- **Nuclear PDF's (Phys.Rev.C92(2015)044901, hep-ph/0703287)**

# Summary

- **CompHEP developments in 2010-2016 have been motivated mainly by experimental analyses of CMS and D0 collaborations. Tools for identification of the Higgs boson and the top quark have been developed.**
- **External functions, operations with cross section/Br tables, generation of combined fits and implementation of subsidiary fields are introduced to work in the BSM multiparameter space.**
- **Visualization, batch modes and interfaces significantly improved.**

Backup slides

# Modern Monte-Carlo Chain





## 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

# 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, ...

# 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)

# Symbolical batch: pp->m,Nm,b,B,H+ with t->b,H+ and T->m,Nm,B MSSM, tb=0.5, MH+=150GeV (H+->t\*b->2f+bB dominates)

27

- Prepare `process.dat` following toy example: all points well documented
- `./symb_batch.pl -show diag` (to exclude several sub-leading diagrams)  
diagrams in 9 subprocesses (54 sqr. diag.) (15 G,G->m,Nm,b,B,H+ diagrams)
- `./symb_batch.pl -mp 2` calculate faster (2 times if you have 2\*CPU machine)

```
#####
# Data file for symb_script.pl
# For the symb_batch script version 1.0
#####

# You have to set the model number, which you are going to
# The model number corresponds to the string number of the
# in the CompHEP model menu in the GUI mode..
model number: 6

# Beam names can be taken from a table of beams.
# (see CompHEP in the GUI regime). Energy unit is GeV
beam 1: p
beam 2: p
beam energy 1: 7000.0
beam energy 2: 7000.0

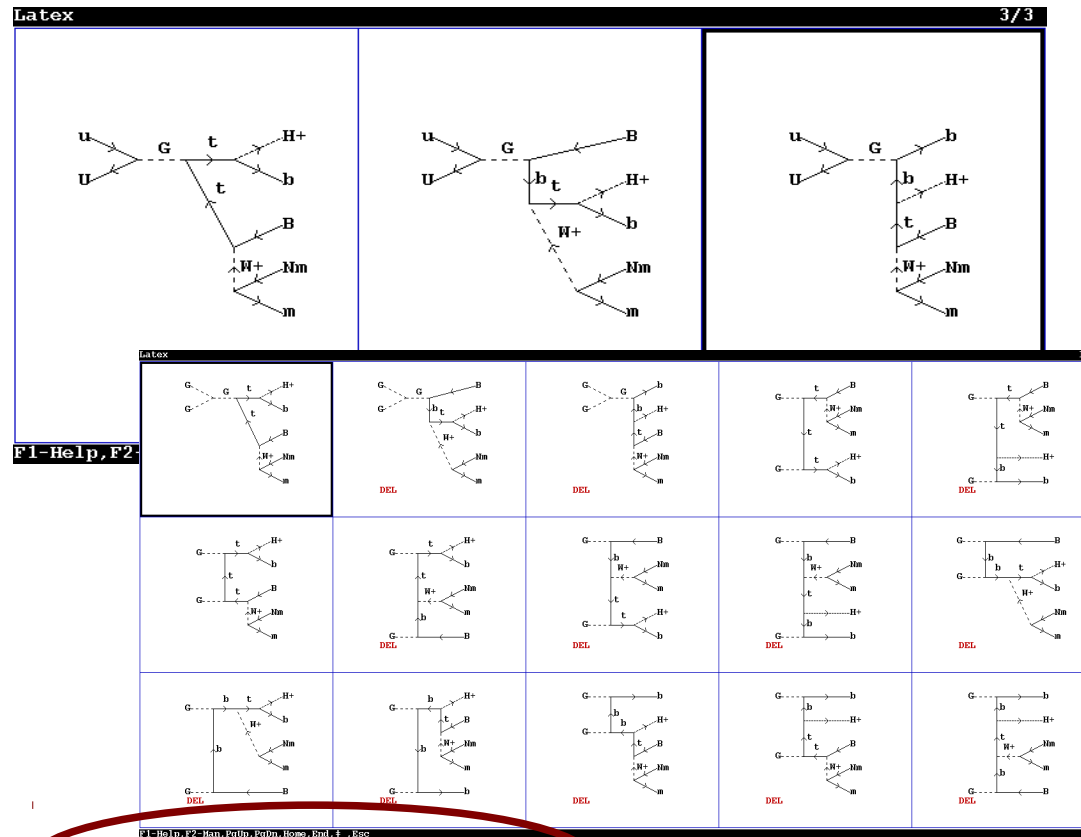
# This string defines the final state of your process. Mode
# particles and composite particles (see the corresponding
# can be used..
final state: m,Nm,b,B,H+

# If you'd like to exclude feynman diagrams with some model
# particles (in propagators!), enter the particles here]
exclude diagrams with: h,H,H3,u,d,c,s,A,Z

# If you'd like to keep feynman diagrams with some model
# particles (in propagators!), enter the particles here
# Examples:
#keep diagrams with: t,b,Z,A
keep diagrams with:

# If you enter no, s_comphep generates diagrams and does no
# do symbolic calculations.
make symbolic calculations(yes/no): yes

# If you enter no, comphep calculates all squared diagrams,.
# but n_comphep will not be created.
make n_comphep generator(yes/no): yes
```



```
[note]$ ./symb_batch.pl -show stat
Diagram statistics: total = 54, calculated = 44, deleted = 0
[note]$ Old n_comphep is deleted!
End of CompHEP symbolical session.
*** n_comphep creation details have been written to symb_batch.log
```

# Numerical batch: pp->m,Nm,b,B,H+ in MSSM

- Prepare **batch.dat**: customize first process via GUI and execute **./num\_batch.pl**
- Customize differences in other subprocesses (if needed) via GUI and execute **./num\_batch.pl - add -proc ...** for the necessary subprocesses
- Start numerical calculations with **./num\_batch.pl -run ...**

```
#Subprocess 1 (u,U -> m,Nm,b,B,H+)
#Session_number 1
#Model_number 6
#Initial_state
  SQR(T(S)) 1.400000E+04
  Rapidity(c.m.s) 0.000000E+00
  StrFun1: PDF:cteq6l1(proton)
  StrFun2: PDF:cteq6l1(proton)

#Physical_Parameters
  EE = 3.1223000000000000E-01
  SW = 4.7300000000000000E-01
  MZ = 9.1188400000000000E+01
  Mtop = 1.7500000000000000E+02
  Mb = 4.6200000000000000E+00
  wtop = 1.7524000000000000E+00
  ww = 2.0889500000000000E+00
  mu = 1.0000000000000000E+03
  MG2 = 2.0000000000000000E+02
  MG3 = 3.0000000000000000E+02
  Mq3 = 1.0000000000000000E+03
  Mu3 = 1.0000000000000000E+03
  Md3 = 1.0000000000000000E+03
  Atop = 0.0000000000000000E+00
  Ab = 0.0000000000000000E+00
  MH3 = 1.3416000000000000E+02
  tb = 5.0000000000000000E-01
  GG = 1.216002374681738E+00
```

```
#Width_scheme 0

#Kinematical_scheme
12 -> 57 , 346
57 -> 5 , 7
346 -> 6 , 34
34 -> 3 , 4

#Cuts.
```

```
[note]$ ./num_batch.pl --show cs
```

```
List of available subprocesses:
```

```
Subprocess 1 (u,U -> m,Nm,b,B,H+): cross section [pb] = 6.2925e-01 +/- 1.30e-03 ( 2.06e-01 % )
Subprocess 2 (d,D -> m,Nm,b,B,H+): cross section [pb] = 3.8960e-01 +/- 8.15e-04 ( 2.09e-01 % )
Subprocess 3 (U,u -> m,Nm,b,B,H+): cross section [pb] = 6.2781e-01 +/- 1.55e-03 ( 2.47e-01 % )
Subprocess 4 (D,d -> m,Nm,b,B,H+): cross section [pb] = 3.8906e-01 +/- 9.31e-04 ( 2.39e-01 % )
Subprocess 5 (s,S -> m,Nm,b,B,H+): cross section [pb] = 6.6678e-02 +/- 1.43e-04 ( 2.14e-01 % )
Subprocess 6 (c,C -> m,Nm,b,B,H+): cross section [pb] = 3.0779e-02 +/- 6.58e-05 ( 2.14e-01 % )
Subprocess 7 (S,s -> m,Nm,b,B,H+): cross section [pb] = 6.6678e-02 +/- 1.43e-04 ( 2.14e-01 % )
Subprocess 8 (C,c -> m,Nm,b,B,H+): cross section [pb] = 3.0779e-02 +/- 6.58e-05 ( 2.14e-01 % )
Subprocess 9 (G,G -> m,Nm,b,B,H+): cross section [pb] = 1.4684e+01 +/- 3.59e-02 ( 2.44e-01 % )
```

```
Total CS [pb] = 1.6914e+01 +/- 3.60e-02 ( 2.13e-01 % )
```

```
#Regularization.
```

```
*** Table ***
```

```
Regularization
Momentum |> Mass <|> Width <| Power|
57         |Mtop  |wtop  |2.....
34         |MW    |ww    |2.....
346        |Mtop  |wtop  |2.....
```

```
#QCD Lambda6 = 1.652000E-01 Scale = 175
```

```
#Vegas_calls 41472x5
```

```
#Vegas_integral 9.16788703338995469E+13 3.46369076228:
```

```
#Distributions.
```

```
*** Table ***
```

```
Distributions
```

```
Parameter |> Min bound <|> Max bound <|> Rest Frame
```

```
#Events 500 1 0.200000 2.000000 10000
```

```
#Random FA98C8AA370E
```

```
#VEGAS Grid Vegas grid: dim=12 size=50
```

# 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*

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

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

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

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

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

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

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

- *scalar-fermion sector*

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

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

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

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

**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
$O_{t\Phi} = (\Phi^\dagger\Phi - \frac{v^2}{2})(-\lambda_t)(\bar{Q}_L\Phi^c t_R)$	$\bar{t} \quad t \quad H$	$-M_t \cdot \frac{v}{\Lambda^2} \cdot C_{t\Phi}$
$O_{b\Phi} = (\Phi^\dagger\Phi - \frac{v^2}{2})(-\lambda_b)(\bar{Q}_L\Phi b_R)$	$\bar{b} \quad b \quad H$	$-M_b \cdot \frac{v}{\Lambda^2} \cdot C_{b\Phi}$
$O_{\tau\Phi} = (\Phi^\dagger\Phi - \frac{v^2}{2})(-\lambda_\tau)(\bar{L}_L\Phi\tau_R)$	$\bar{\tau} \quad \tau \quad H$	$-M_\tau \cdot \frac{v}{\Lambda^2} \cdot C_{\tau\Phi}$
$O_{\Phi G} = \frac{1}{2}(\Phi^\dagger\Phi - \frac{v^2}{2})G_{\mu\nu}^a G^{a\mu\nu}$	$G_\mu \quad G_\nu \quad H$	$-2 \cdot \frac{v}{\Lambda^2} \cdot C_{\Phi G} \cdot (g^{\mu\nu} p_1 p_2 - p_1^\nu p_2^\mu)$
$O_{\Phi B} = \frac{1}{2}(\Phi^\dagger\Phi - \frac{v^2}{2})B_{\mu\nu} B^{\mu\nu}$	$A_\mu \quad A_\nu \quad H$ $A_\mu \quad Z_\nu \quad H$ $Z_\mu \quad Z_\nu \quad H$	$-2 \cdot c_W^2 \cdot \frac{v}{\Lambda^2} \cdot C_{\Phi B} \cdot (g^{\mu\nu} p_1 p_2 - p_1^\nu p_2^\mu)$ $+2 \cdot c_W \cdot s_W \cdot \frac{v}{\Lambda^2} \cdot C_{\Phi B} \cdot (g^{\mu\nu} p_1 p_2 - p_1^\nu p_2^\mu)$ $-2 \cdot s_W^2 \cdot \frac{v}{\Lambda^2} \cdot C_{\Phi B} \cdot (g^{\mu\nu} p_1 p_2 - p_1^\nu p_2^\mu)$
$O_{\Phi W} = \frac{1}{2}(\Phi^\dagger\Phi - \frac{v^2}{2})W_{\mu\nu}^i W^{i\mu\nu}$	$A_\mu \quad A_\nu \quad H$ $A_\mu \quad Z_\nu \quad H$ $Z_\mu \quad Z_\nu \quad H$ $W_\mu^+ \quad W_\nu^- \quad H$	$-2 \cdot s_W^2 \cdot \frac{v}{\Lambda^2} \cdot C_{\Phi W} \cdot (g^{\mu\nu} p_1 p_2 - p_1^\nu p_2^\mu)$ $-2 \cdot c_W \cdot s_W \cdot \frac{v}{\Lambda^2} \cdot C_{\Phi W} \cdot (g^{\mu\nu} p_1 p_2 - p_1^\nu p_2^\mu)$ $-2 \cdot c_W^2 \cdot \frac{v}{\Lambda^2} \cdot C_{\Phi W} \cdot (g^{\mu\nu} p_1 p_2 - p_1^\nu p_2^\mu)$ $-2 \cdot \frac{v}{\Lambda^2} \cdot C_{\Phi W} \cdot (g^{\mu\nu} p_1 p_2 - p_1^\nu p_2^\mu)$
$O_\Phi^{(1)} = (\Phi^\dagger\Phi - \frac{v^2}{2})D_\mu\Phi^\dagger D^\mu\Phi$	$W_\mu^+ \quad W_\nu^- \quad H$ $Z_\mu \quad Z_\nu \quad H$	$M_W^2 \cdot \frac{v}{\Lambda^2} \cdot C_\Phi^{(1)} \cdot g^{\mu\nu}$ $M_Z^2 \cdot \frac{v}{\Lambda^2} \cdot C_\Phi^{(1)} \cdot g^{\mu\nu}$