Развитие проекта CompHEP: от LEP2 до LHC

М. Дубинин

НИИЯФ МГУ

CompHEP Collaboration:

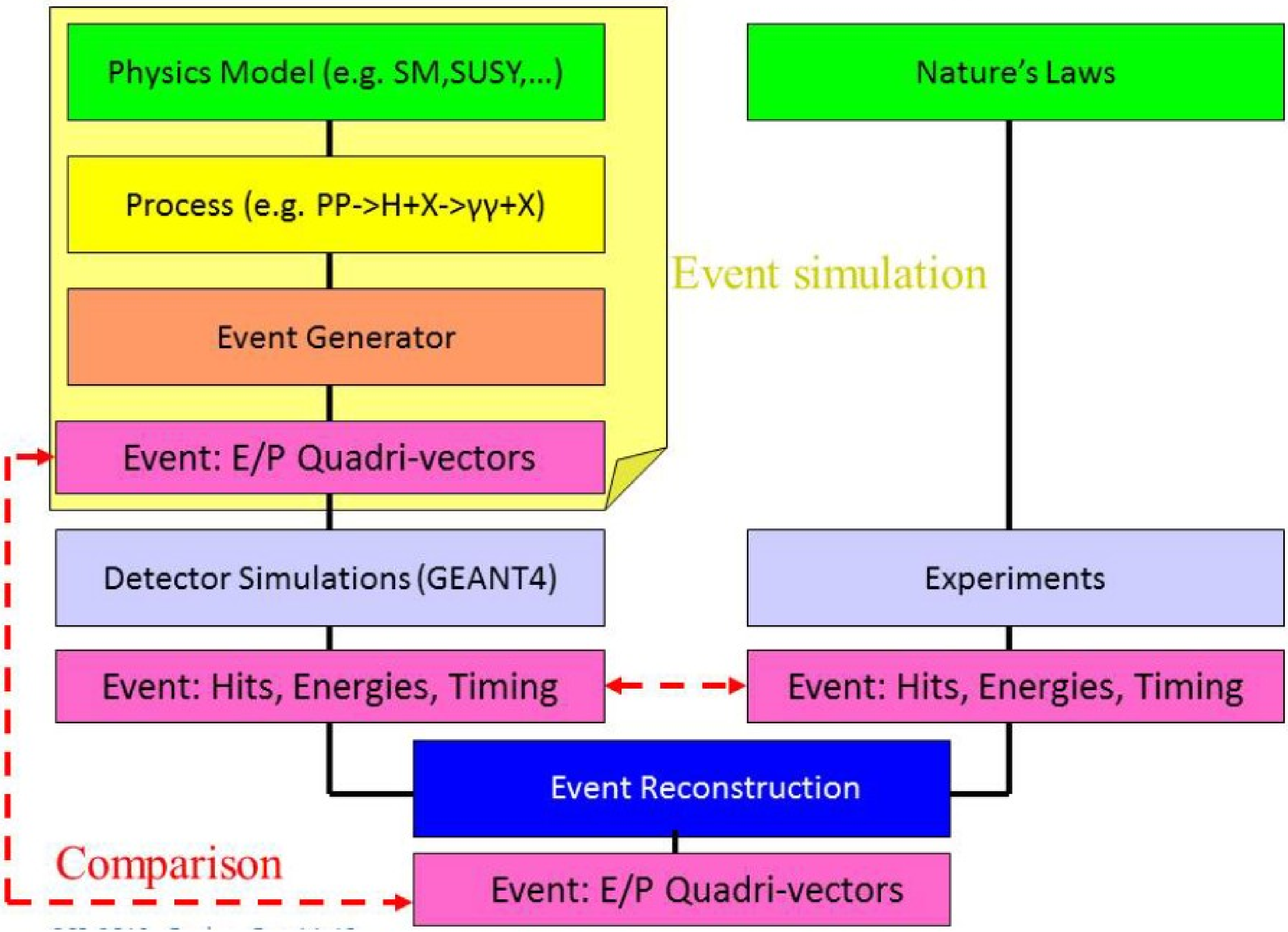
Э.Боос, М.Д., В.Буничев, Л.Дудко, А.Крюков, В.Еднерал, В.Саврин, А.Семенов

http://comphep.sinp.msu.ru

Outline

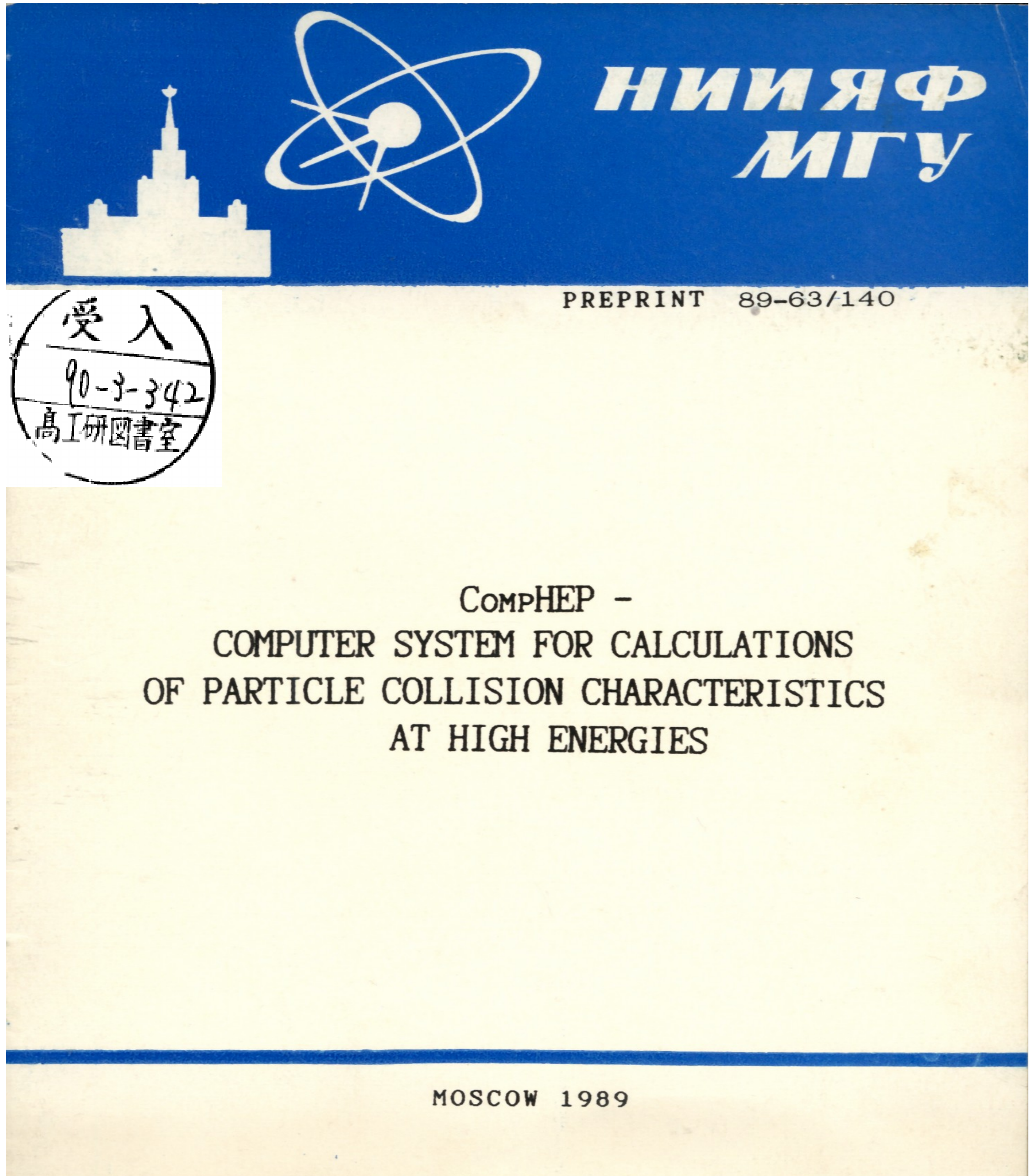
- **История. Наукометрические показатели.**
- **Стандартная модель в CompHEP**
- **Инструменты для новой физики: LanHEP, комбинированные контуры исключения, операции с таблицами**
- **Разное: batch modes, ROOT output, LHA formats, MCDB, nuclear PDF's,...**

Simulation and Data Analysis Chain



35 years of CompHEP project in 2024

Primary publication: 1989


НИИЯФ
МГУ

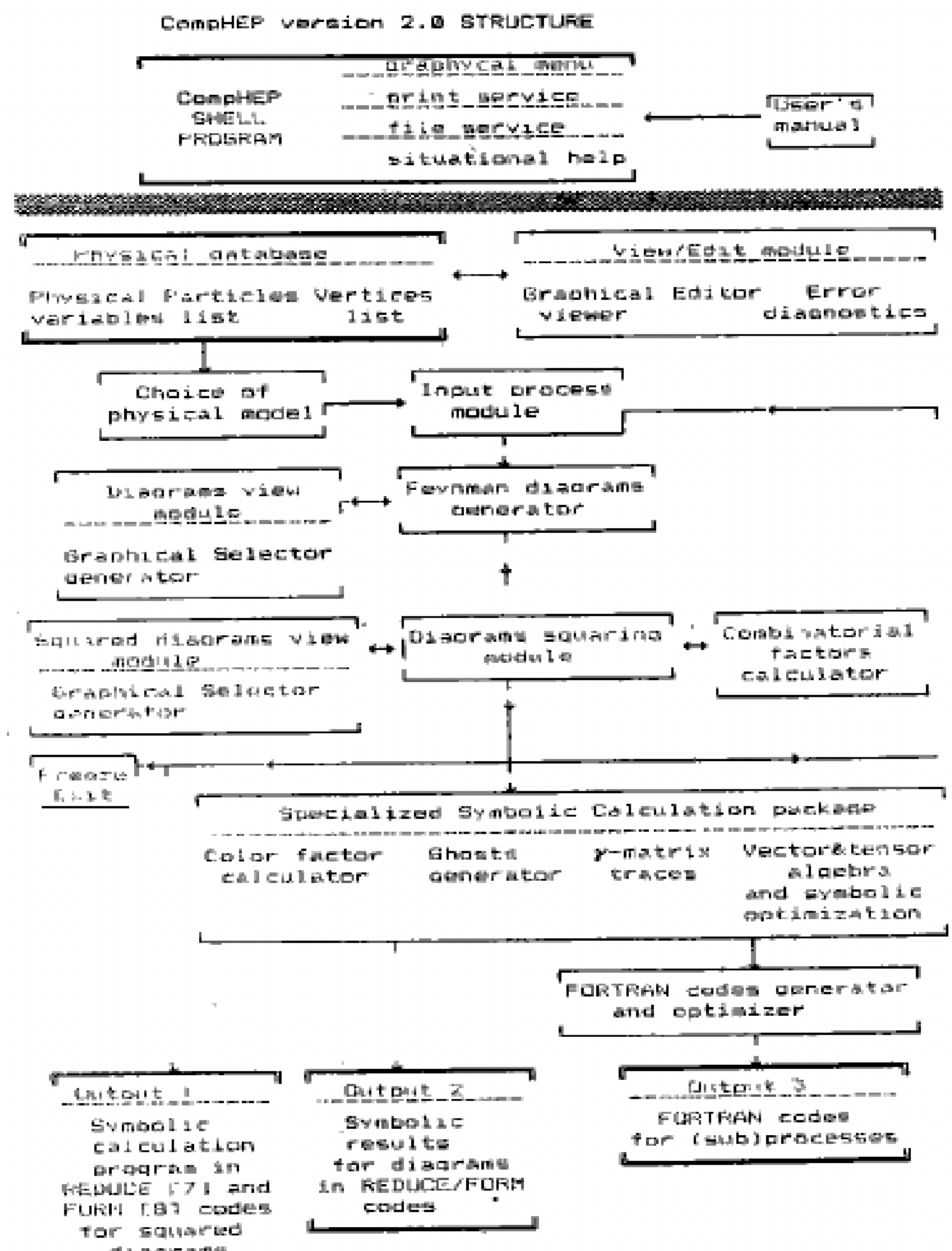
PREPRINT 89-63/140

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

MOSCOW 1989

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

- 29 -



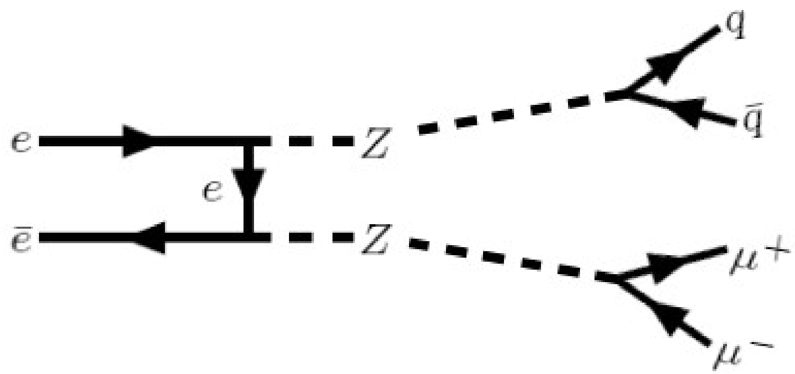
Материальное обеспечение проекта в 1989 г.

1. Три компьютера IBM AT i286, ОС MSDOS
2. Три монитора VGA
2. Один сопроцессор i287
3. Один струйный принтер HP Desk Jet
4. Три манипулятора «мышь»
5. Две коробки дискет 3`` для переноса информации

CERN Workshop «Physics at LEP2», 1995

CompHEP работает с полными калибровочно-инвариантными наборами древесных диаграмм, не используя стандартные приближения типа рождение × распад (или беск.малой ширины: PYTHIA, HERWIG, ...).

Рождение четырех фермионов, LEP2: **e+, e- → μ+ μ- q q, e $\bar{\nu}_e$ u d**



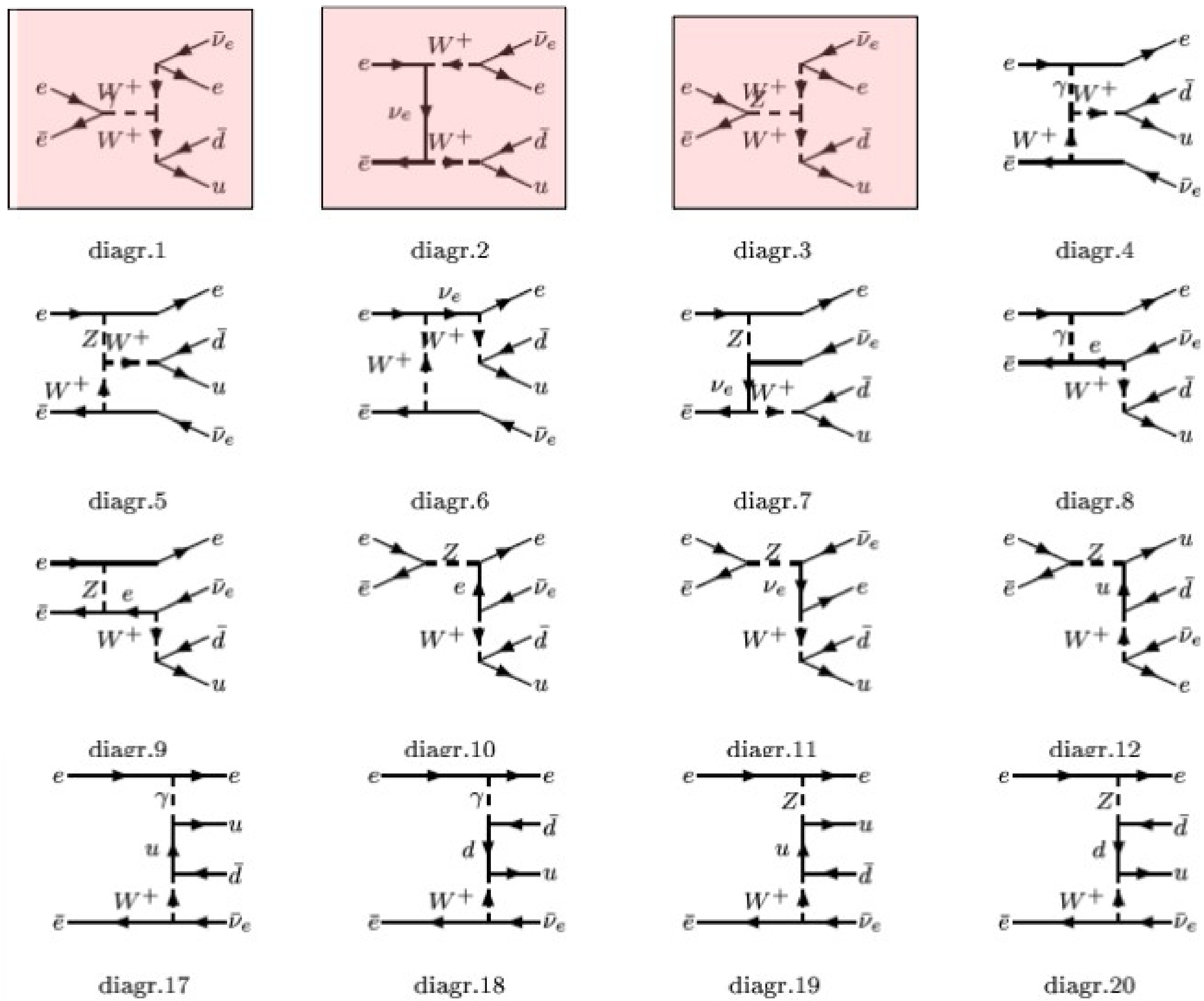
$$\frac{1}{(q^2-m^2)^2+m^2\Gamma^2} \Rightarrow \frac{\pi}{m\Gamma}\delta(q^2-m^2)$$

Удовлетворительная точность только в околорезонансной области.
Диаграммы неприводимого фона не учитываются.

Пример: одиночное рождение W -бозона, LEP2

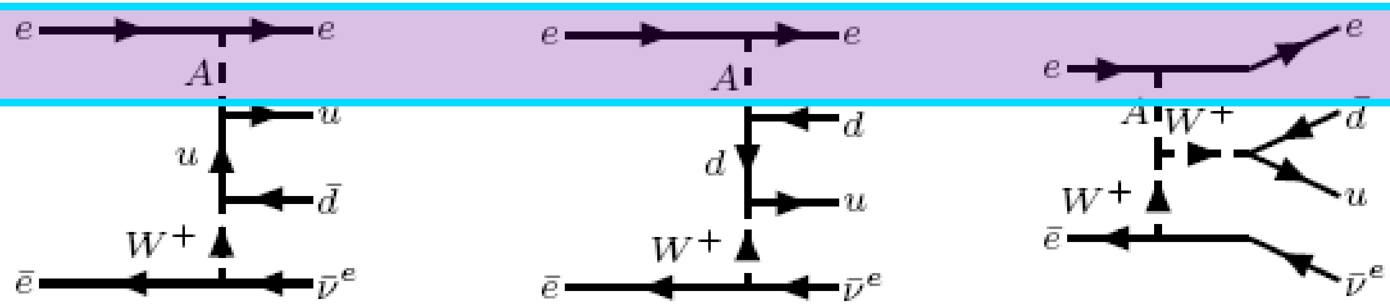
e+ e- → e- ν_e u d

розовым выделены диаграммы парного рождения W+W-, прочие диаграммы – рождение одиночного W и лестничные



Breit-Wigner propagators can violate cancellations of double poles of the matrix element in t-channel ($U(1)_{em}$ gauge cancellations), thus breaking not only gauge invariance, but also untarity

Example: diagrams with t-channel photons (A≡γ)



$$t_{max} = -m_e^2 \left(\frac{M^2}{s}\right)^2, \qquad M^2 = (p_u + p_d + p_{\nu_e})^2, \qquad m_e = 0.511\,\mathrm{MeV},\ \sqrt{s} = 200\ \mathrm{GeV}$$

$$\sigma(s) = \int_{-s}^{t_{max}} \frac{dt}{t^2} \sim s^2/M^4. \qquad \text{Nonunitary}$$

$$\sigma(s) = \int_{-s}^{t_{max}} \frac{dt}{t} \sim \log(s/M^2) \qquad \text{OK}$$

Example: QCD misidentification (fake) backgrounds for pp → γ + 3 jet [jet ⇨ γ] to Higgs boson production at the LHC in the siganture γγ+ forward jets. 50 partonic subprocesses (in the hash-model format), each of which includes 30-40 diagrams. In total about 2000 QCD diagrams

	subprocess	σ, [pb]	$\frac{\sigma}{\sigma_{max}}$
1	$u\#, u\# \to A, G, u\#, u\#$	514.1	0.36
2	$u\#, U\# \to A, G, u\#, U\#$	123.2	0.09
3	$u\#, U\# \to A, G, d\#, D\#$	0.3	0
4	$u\#, U\# \to A, G, G, G$	2.4	0
5	$u\#, d\# \to A, G, u\#, d\#$	208.1	0.15
6	$u\#, D\# \to A, G, u\#, D\#$	101.4	0.07
7	$u\#, G \to A, u\#, u\#, U\#$	52.5	0.04
8	$U\#, G \to A, u\#, d\#, D\#$	30.3	0.02
9	$u\#, G \to A, G, G, u\#$	1397.7	1
10	$U\#, u\# \to A, G, u\#, U\#$	125.7	0.09
11	$U\#, u\# \to A, G, d\#, D\#$	0.3	0
12	$U\#, u\# \to A, G, G, G$	2.4	0
13	$U\#, U\# \to A, G, U\#, U\#$	19.1	0.01
14	$U\#, d\# \to A, G, U\#, d\#$	41.9	0.03
15	$U\#, D\# \to A, G, U\#, D\#$	17.2	0.01
16	$U\#, G \to A, u\#, U\#, U\#$	8.5	0.01
17	$U\#, G \to A, U\#, d\#, D\#$	4.5	0
18	$U\#, G \to A, G, G, U\#$	196.5	0.14
19	$d\#, u\# \to A, G, u\#, d\#$	206.9	0.15
20	$d\#, U\# \to A, G, U\#, d\#$	41.9	0.03
21	$d\#, d\# \to A, G, d\,d\#$	49.7	0.03
22	$d\#, D\# \to A, G, u\#, U\#$	0.1	0
23	$d\#, D\# \to A, G, d\#, D\#$	23.3	0.02
24	$d\#, D\# \to A, G, G, G$	0.4	0
25	$d\#, G \to A, u\#, U\#, d\#$	23.9	0.02

$d\#, G \to A, d\#, d\#, D\#$	8.0	0
$d\#, G \to A, G, G, d\#$	195.2	0.14
$D\#, u\# \to A, G, u\#, D\#$	98.7	0.07
$D\#, U\# \to A, G, U\#, D\#$	17.6	0.01
$D\#, d\# \to A, G, u\#, U\#$	0.1	0
$D\#, d\# \to A, G, d\#, D\#$	23.2	0.02
$D\#, d\# \to A, G, G, G$	0.4	0
$D\#, D\# \to A, G, D\#, D\#$	9.0	0
$D\#, G \to A, u\#, U\#, D\#$	9.6	0
$D\#, G \to A, d\#, D\#, D\#$	2.8	0
$D\#, G \to A, G, G, D\#$	69.1	0.05
$G, u\# \to A, u\#, u\#, U\#$	53.3	0.04
$G, u\# \to A, u\#, d\#, D\#$	29.7	0.02
$G, u\# \to A, G, G, u\#$	1400.0	1
$G, U\# \to A, u\#, U\#, U\#$	9.5	0
$G, U\# \to A, U\#, d\#, D\#$	4.5	0
$G, U\# \to A, G, G, U\#$	198.6	0.14
$G, d\# \to A, u\#, U\#, d\#$	23.8	0.02
$G, d\# \to A, d\#, d\#, D\#$	7.7	0
$G, d\# \to A, G, G, d\#$	190.9	0.13
$G, D\# \to A, u\#, U\#, D\#$	9.9	0
$G, D\# \to A, G, G, D\#$	2.9	0
$G, D\# \to A, G, G, D\#$	68.8	0.05
$G, G \to A, G, u\#, U\#$	277.9	0.20
$G, G \to A, G, d\#, D\#$	69.5	0.05
$pp \to A, j, j, j$	5970.4	

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

Основные задачи

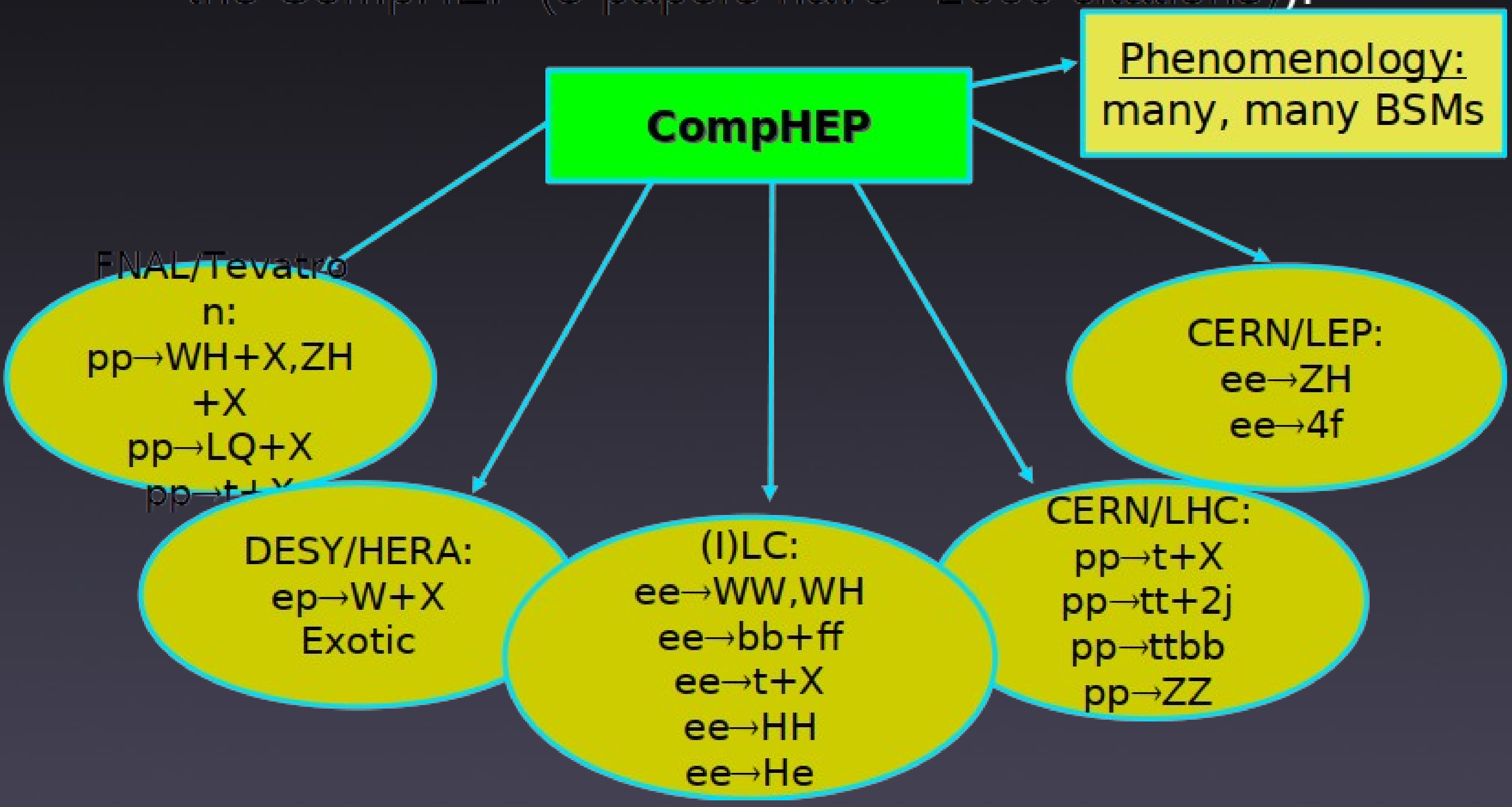
- **Автоматизация вычислений для полных наборов диаграмм**
- **“Unification” символьных и численных вычислений, генерация событий для моделирования в детекторе – полная последовательность программ моделирования**
- **Интерфейсы с другими генераторами (partonic showering, hadronization, masses and mixings)**
- **Интерфейсы с NLO codes поправок высших порядков: 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)**

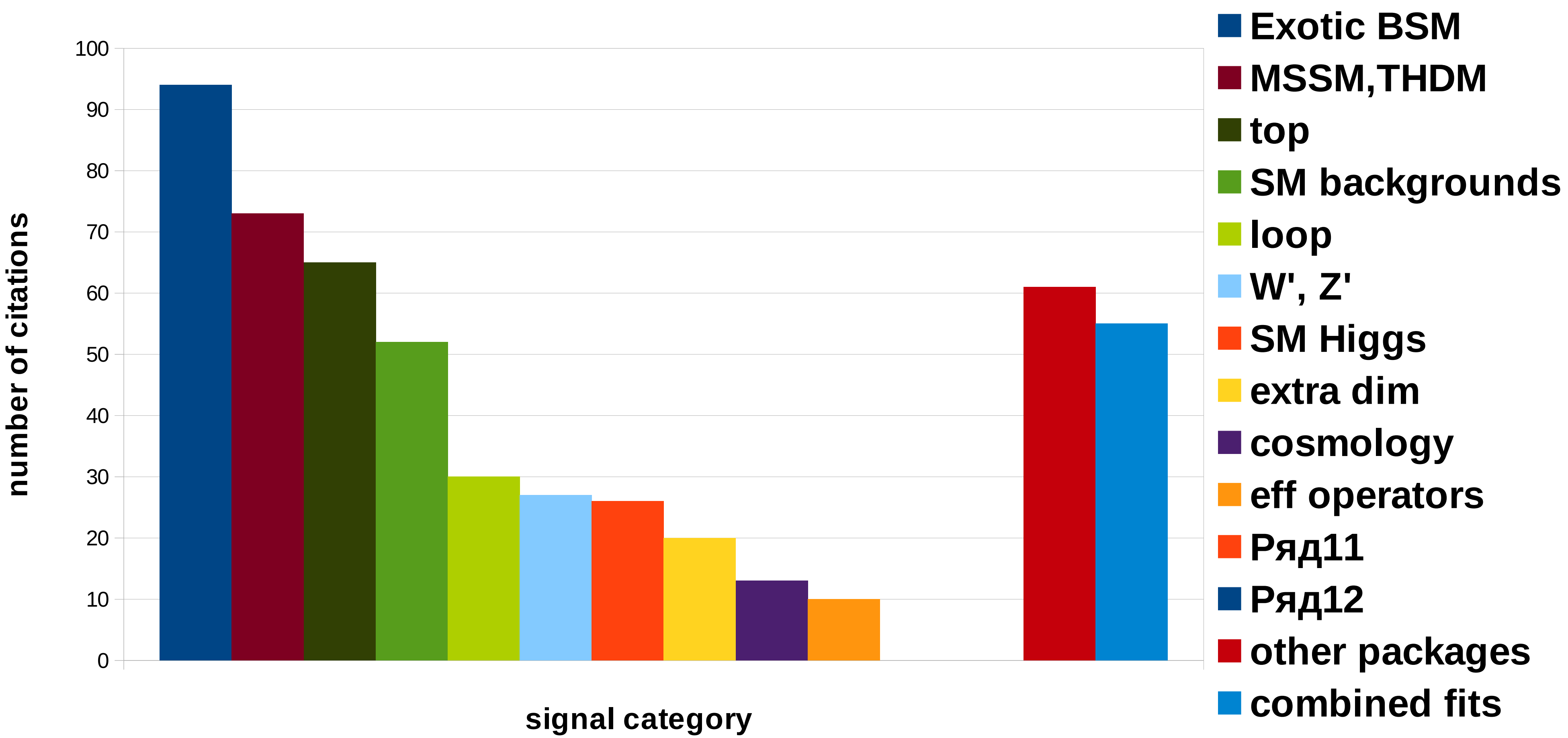
CompHEP
(Computations in High Energy Physics)

Incomplete list of processes simulated with
the CompHEP (3 papers have ~2000 citations)):



Distribution of citations: theory

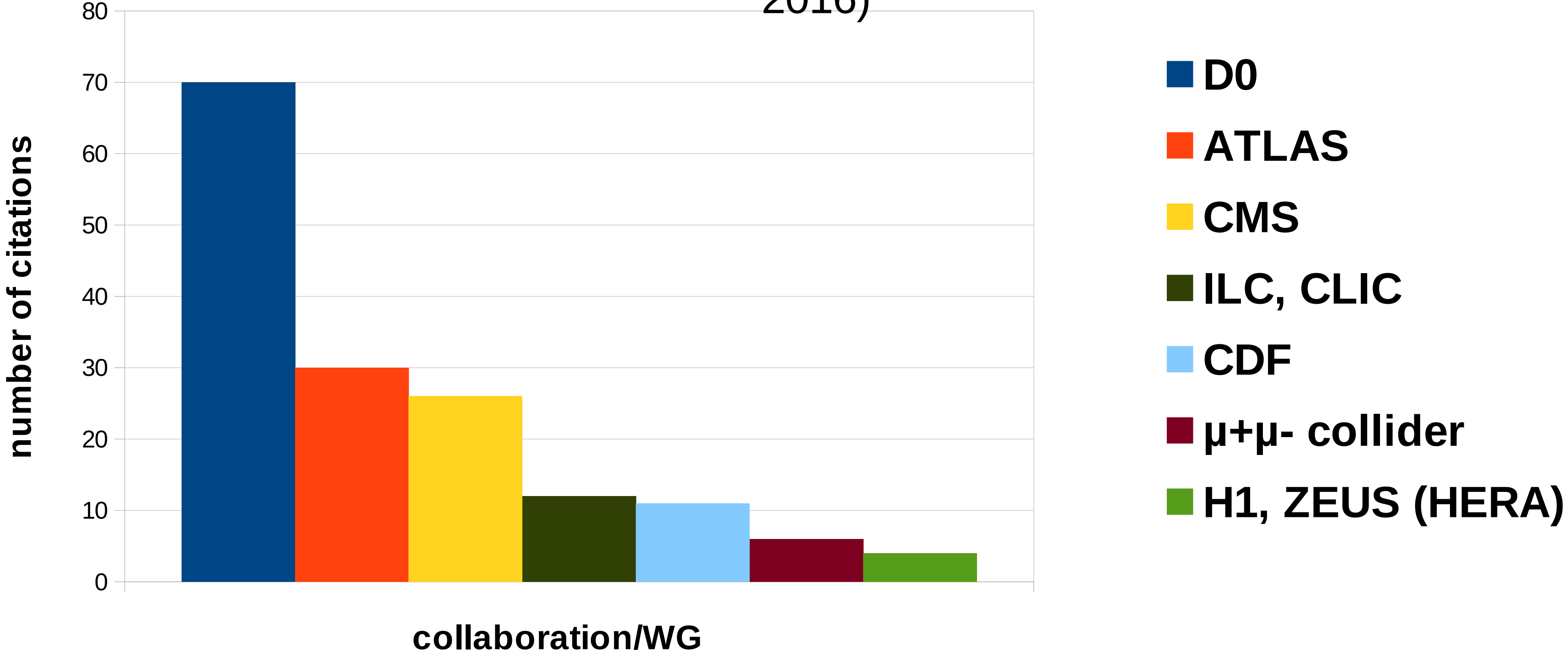
CompHEP, NIM, A534 (2004) 250, 560 citations (period 2005 - june 2016)



Exotic BSM ⇒ 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)



CompHEP: Specialized package for automatic calculations of elementary particle decays and collisions

E.Boos, M.Dubinin, V.Ilyin, A.Pukhov, V.Savrin, hep-ph/9503280 (Korean Physical Society meeting)

232

Physical results by means of CompHEP

P.Baikov, E.Boos, M.Dubinin, V.Edneral, V.Ilyin, D.Kovalenko, A.Kryukov, A.Pukhov, V.Savrin, A.Semenov, S.Shichanin, hep-ph/9503280 (QFTHEP Proceeding)

71

CompHEP: A Package for evaluation of Feynman diagrams and integration over multiparticle phase space

A.Pukhov, E.Boos, M.Dubinin, V.Edneral, V.Ilyin, D.Kovalenko, A.Kryukov, V.Savrin, S.Shichanin, A.Semenov (version 3 user`s manual), hep-ph/9908288

975

CompHEP - PYTHIA interface: integrated package for the collision events generation based on exact matrix elements

A.Belyaev, E.Boos, A.Vologdin, M.Dubinin, V.Ilyin, A.Kryukov, A.Pukhov, A.Skachkova, V.Savrin, A.Sherstnev, S.Shichanin, arXiv:hep-ph/0101232 (AIP Proceeding)

77

CompHEP 4.4: Automatic computations from Lagrangians to events

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

A. Sherstnev, Nucl.Instr.Meth A534 (2004) 250 (arXiv:hep-ph/0403113)

688

Итого CompHEP 2043

CalcHEP 2.3: MSSM, structure functions, event generation, batchs, and generation of matrix elements for other packages

A. Pukhov, hep-ph/0412191

611

CalcHEP 3.4 for collider physics within and beyond the Standard Model

A. Belyaev, N. Christensen, A.Pukhov, Comput. Phys. Commun. 184 (2013) 1729 (arXiv:1207.6082)

790

Итого CalcHEP	1401

Всего	**CompHEP + CalcHEP**	**3444**

Согласно базе данных INSPIRE, имеется 11 научных статей СССР (неколлаборационных) с индексом цитирования больше 2000

Эти статьи не относятся к вычислениям для коллайдеров:

Фаддеев, Попов,
Шифман, Вайнштейн, Захаров,
Старобинский,
Поляков,
Линде,
Белавин,
Замолодчиков,
Кузьмин, Рубаков, Шапошников;

из них четыре статьи имеют индекс цитирования более 3500.

Среди публикаций времен РФ неколлаборационных статей с индексом цитируемости (по состоянию на 2021 г.) более 2000 нет.

Аналогичные разработки после 1995 – 2000

GRACE
MadGraph
Sherpa
O`Mega/Whizard

а также библиотеки

PYTHIA
HERWIG
TAUOLA
AMEGIC++

HELAC-PHEGAS
ALPGEN
GRAPPA
HDECAY
FeynCalc

Пакеты NLO Level: MCFM, NLOJET, BlackHat, Rocket, CutTools, MadLoop, OpenLoops, GOLEM, POWHEG, aMC@NLO, GoSam

Пакеты для генерации правил Фейнмана, аналоги LanHEP: FeynRules, SARAH

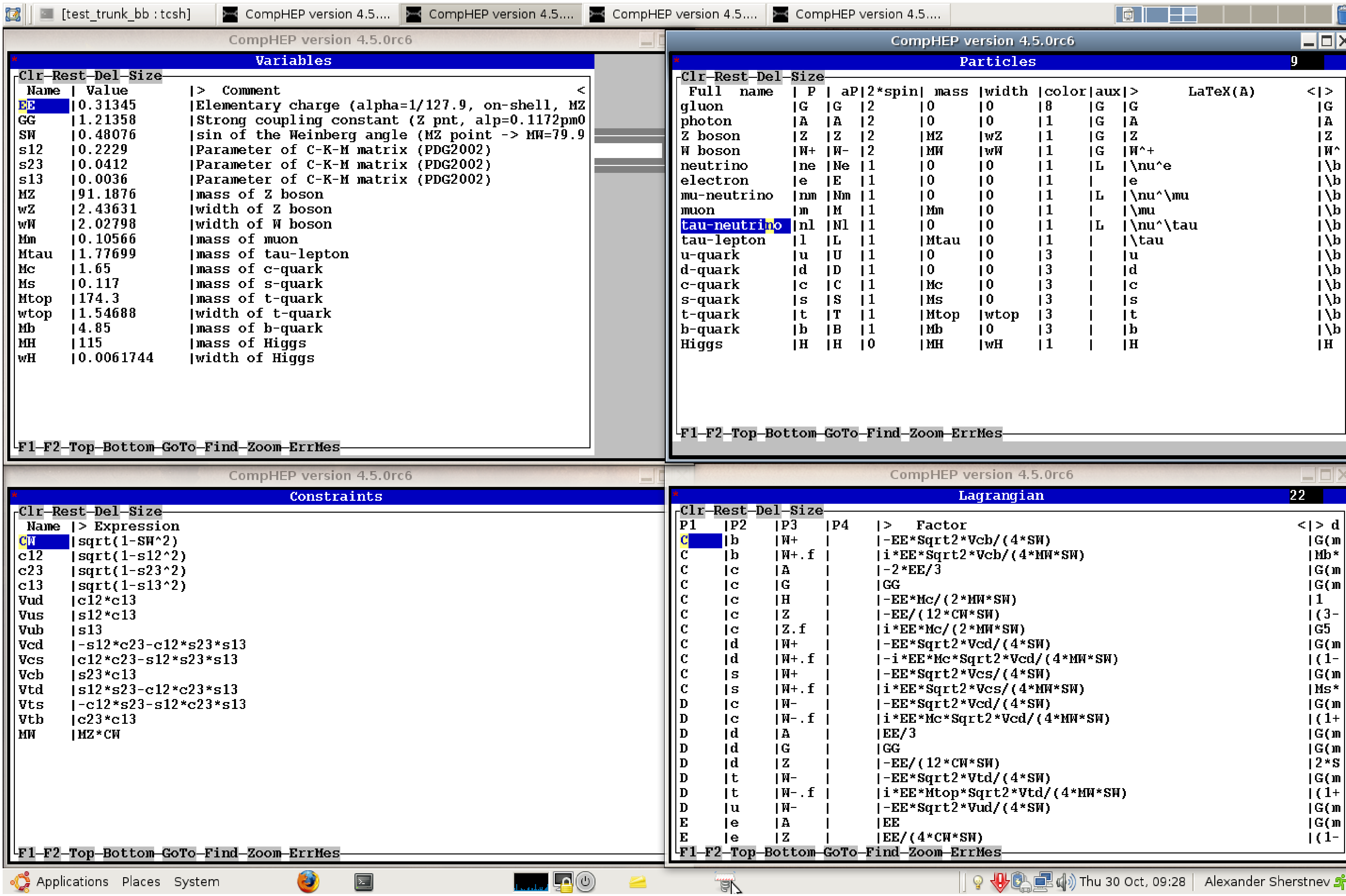
Экспертные системы для автоматической проверки моделей: GAMBIT, CHECKMATE/DELPHES

CompHEP Model

CompHEP Model defines particles and their interactions.
Technically CompHEP model is a set of 5 text files (tables)

- A set of fundamental particles: names, mass/width, spin, charges
- Numerical model parameters: mass/width values, couplings, mixing parameters, etc.
- Constrains: relations between the parameters
- Lagrangian: a set of all interaction vertices
- Composite particles: proton, artificial useful particle combinations

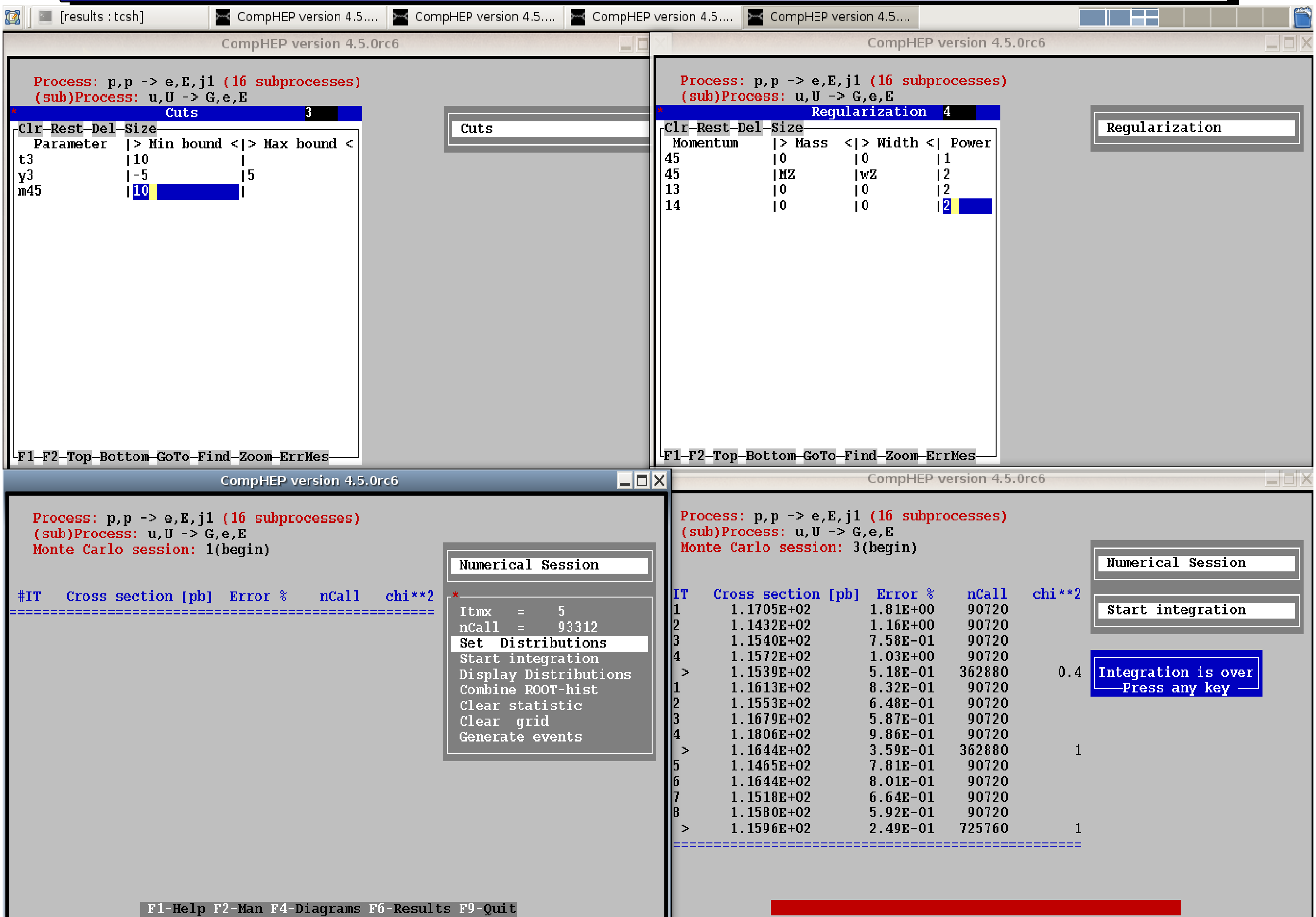
CompHEP Standard Model



Example: fermion-gauge boson sector in theCompHEP model file

```
SM, unitary gauge
 Lagrangian
P1   |P2  |P3  |P4  |>   Factor                                   <|> dLagrangian/ dA(p1) dA(p2) dA(p3)
A    |W+  |W-  |    |-EE                                            |m3.p2*m1.m2-m1.p2*m2.m3-m2.p3*m1.m3+m1.p3*m2.m3+m2.p1*m1.m3-m3.p1*m1.m
B    |b   |A   |    |EE/3                                           |G(m3)
B    |b   |G   |    |GG                                             |G(m3)
B    |b   |H   |    |-EE*Mb/(2*MW*SW)                               |1
B    |b   |Z   |    |-EE/(12*CW*SW)                                 |2*SW^2*G(m3)*(1+G5)-(3-2*SW^2)*G(m3)*(1-G5)
B    |c   |W-  |    |-EE*Sqrt2*Vcb/(4*SW)                           |G(m3)*(1-G5)
B    |t   |W-  |    |-EE*Sqrt2*Vtb/(4*SW)                           |G(m3)*(1-G5)
B    |u   |W-  |    |-EE*Sqrt2*Vub/(4*SW)                           |G(m3)*(1-G5)
C    |b   |W+  |    |-EE*Sqrt2*Vcb/(4*SW)                           |G(m3)*(1-G5)
C    |c   |A   |    |-2*EE/3                                        |G(m3)
C    |c   |G   |    |GG                                             |G(m3)
C    |c   |H   |    |-EE*Mc/(2*MW*SW)                               |1
C    |c   |Z   |    |-EE/(12*CW*SW)                                 |(3-4*SW^2)*G(m3)*(1-G5)-4*SW^2*G(m3)*(1+G5)
C    |d   |W+  |    |-EE*Sqrt2*Vcd/(4*SW)                           |G(m3)*(1-G5)
C    |s   |W+  |    |-EE*Sqrt2*Vcs/(4*SW)                           |G(m3)*(1-G5)
D    |c   |W-  |    |-EE*Sqrt2*Vcd/(4*SW)                           |G(m3)*(1-G5)
D    |d   |A   |    |EE/3                                           |G(m3)
D    |d   |G   |    |GG                                             |G(m3)
D    |d   |Z   |    |-EE/(12*CW*SW)                                 |2*SW^2*G(m3)*(1+G5)-(3-2*SW^2)*G(m3)*(1-G5)
D    |t   |W-  |    |-EE*Sqrt2*Vtd/(4*SW)                           |G(m3)*(1-G5)
D    |u   |W-  |    |-EE*Sqrt2*Vud/(4*SW)                           |G(m3)*(1-G5)
E    |e   |A   |    |EE                                             |G(m3)
E    |e   |Z   |    |EE/(4*CW*SW)                                   |(1-2*SW^2)*G(m3)*(1-G5)-2*SW^2*G(m3)*(1+G5)
E    |ne  |W-  |    |-EE*Sqrt2/(4*SW)                               |G(m3)*(1-G5)
G    |G   |G   |    |GG                                             |m2.p3*m1.m3-m1.p3*m2.m3+m3.p1*m1.m2-m2.p1*m1.m3-m3.p2*m1.m2+m1.p2*m2.m
G.C  |G.c |G   |    |GG                                             |m3.p2
H    |H   |H   |    |-3*EE*MH^2/(2*MW*SW)                           |1
H    |W+  |W-  |    |EE*MW/SW                                       |m2.m3
H    |Z   |Z   |    |EE*MW/(CW^2*SW)                                |m2.m3
```

Numerical calculations (3)



Basic and user-defined CompHEP Models

- simple training models: QED, effective 4-fermion model
- SM in two different gauges: unitary gauge and t 'Hooft-Feynman gauge. Flavour simplified SM model (#-model)
- SUSY Models: unconstrained MSSM (again in two gauges); SUGRA model; GMSB model

New (user-defined) Models

- Simple way (if your model is relatively simple): add new particles/params/vertices
- For more complicated models: LanHEP – a program for generation of Feynman rules for user-defined model (**developed by A.Semenov**)
  - Works with super-multiplets and superpotential
  - Generates all needed files for CompHEP (also FeynArts and LaTeX format)
  - Several options for self-checking (charge conservation, BRST invariance, etc.)
  - Has been used for CompHEP SUSY models and many other BSM models

CompHEP BSM Lagrangians

- Complete Leptoquark model. Includes Yukawa couplings for all types of LQ, gauge couplings and anomalous gauge couplings for vector LQ (by request)
- Top quark Lagrangian with anomalous couplings as follows from the dimension 6 effective operators (by request)
- Excited fermion Model (by request)
- Complete two-Higgs-doublet Model with conserved or broken CP invariance (by request)
- RS1 model and effective 4 particle Lagrangian for RS below KK threshold
- UED model (Matchev et al.)
- Minimal Higgsless Model (Chivukula et al.)
- Exotics: Muonic photon; para-photon; E6 isosinglet quark; Z’, W’ bosons; doubly charged Higgs, color octet pseudoscalars, Inert Douplet Model, etc.

Numerical calculations

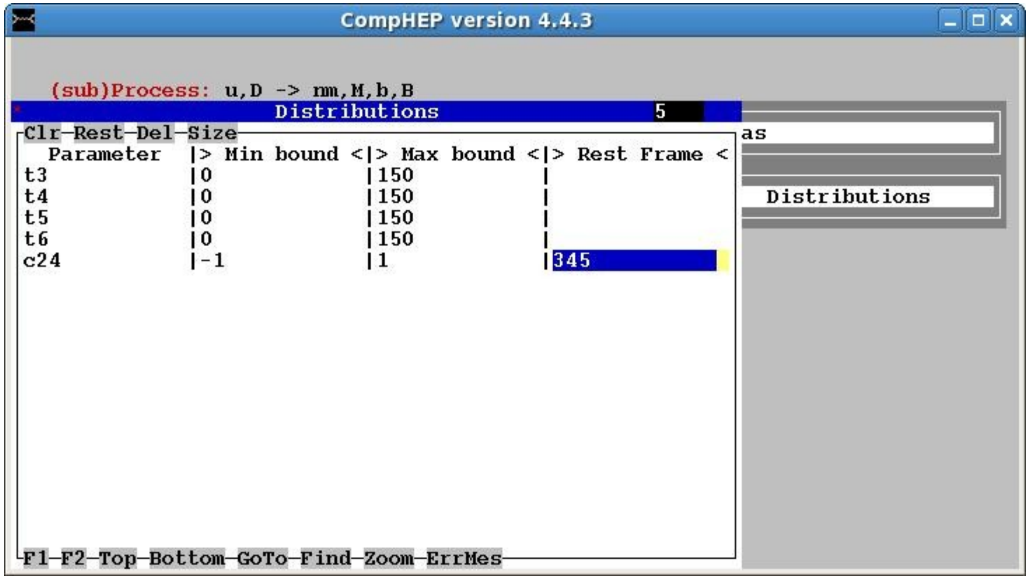
- **Customize ('tune on') numerical MC generator:** The most complicated part: do proper phase space sampling (regularizations + kinematics), set necessary kinematic cuts, Q^2, PDF set, etc. Main goals – to improve efficiency of MC calculation and describe physics task. User may change model parameters and set kinematic cuts
- **Calculate full cross section and distributions:** CompHEP uses an improved version of the adaptive VEGAS algorithm for MC calculations. User may order different variables (P_T, inv. mass, rapidity, etc.) for histogramming
- **Generate events:** As soon as CompHEP customized, events can be generated for the subprocess. User set a number of the events They are kept to text files.

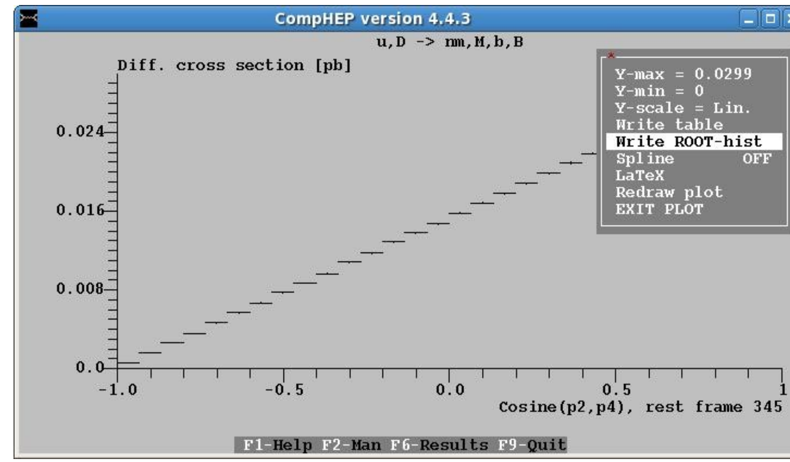
If the process consists of some subprocesses, the procedure is applied to the each subprocess.

LHEF, LHAPDF, SUSY LHA, BSM LHA

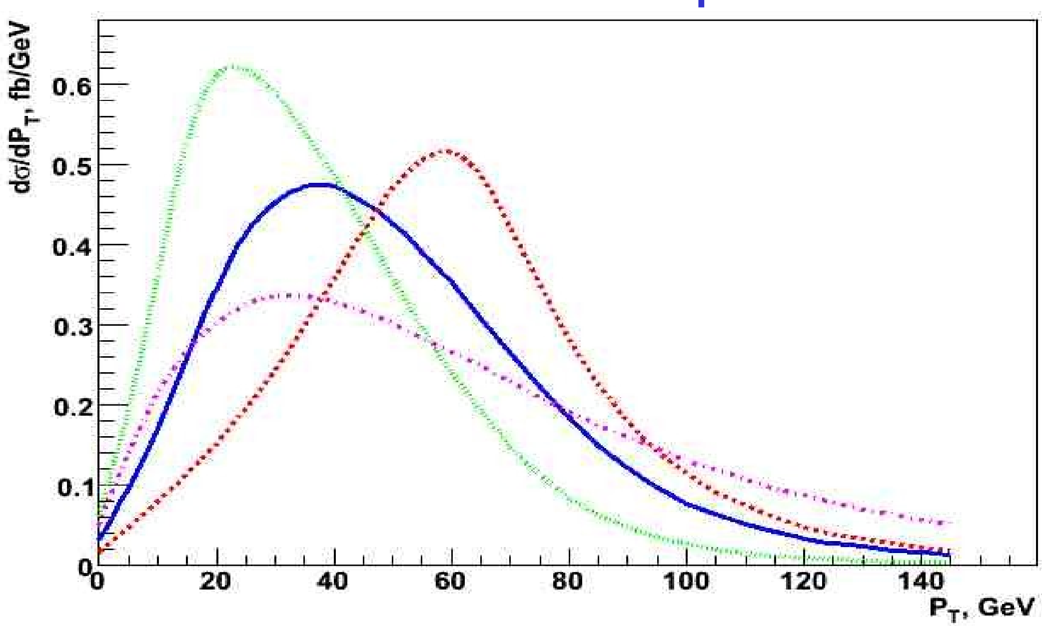
1. LHA I is implemented in CompHEP-Interfaces
2. **LHEF** - the format adopted by many developer groups (hep-ph/060917). Now CompHEP supports 3 event formats: cpyth-1, cpyth-2 (for experiments, where the formats are used), and LHEF with HepML header. There is a special option - Generator (LHEF format)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

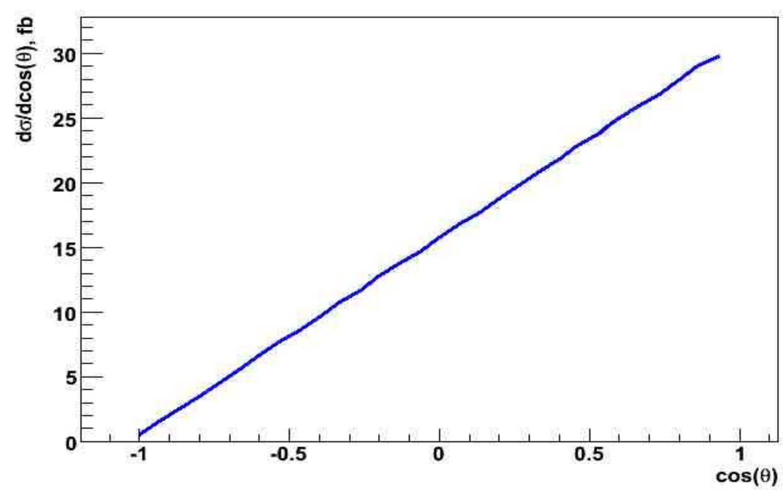
Distributions in CompHEP (ROOT interface)





Pt distributions for all final particles

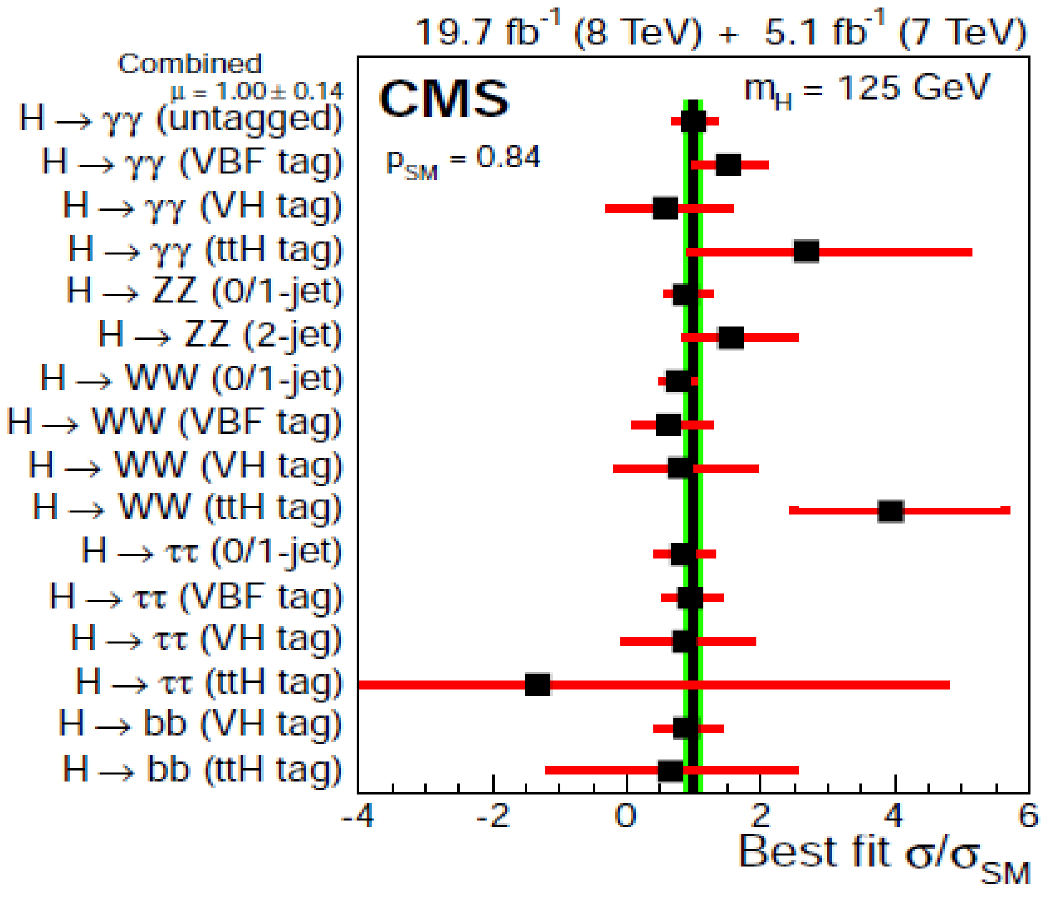




In "vegas" integration menu new submenu "combine histograms" for superimposing ROOT-histograms

Global fits

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



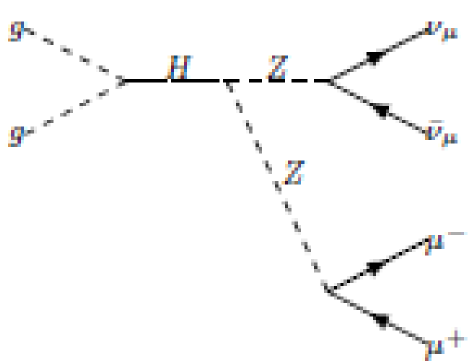
Overall signal strength – all channels

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

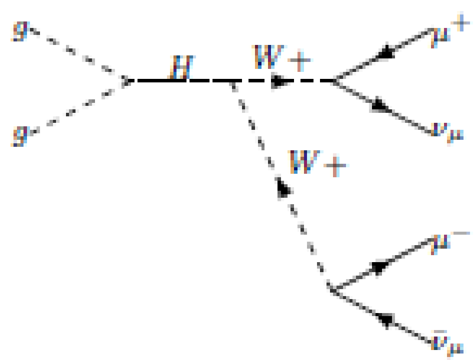
Beyond the infinitely small width approximation

In a number of channels the interference terms are not small (especially for ɣɣ, 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)

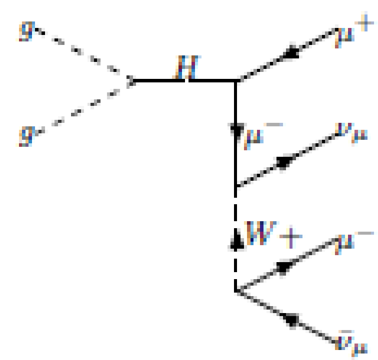
Example: $gg \rightarrow (W^*W^*, Z^*Z^*) \rightarrow \nu_\mu \nu_\mu \mu^+ \mu^-$



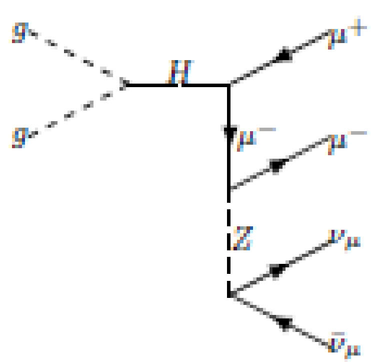
diagr.1



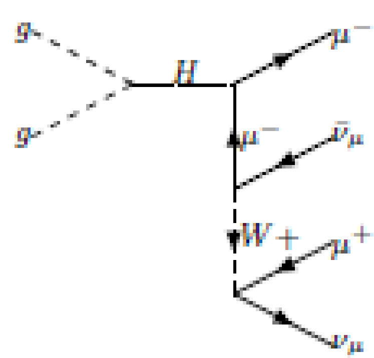
diagr.2



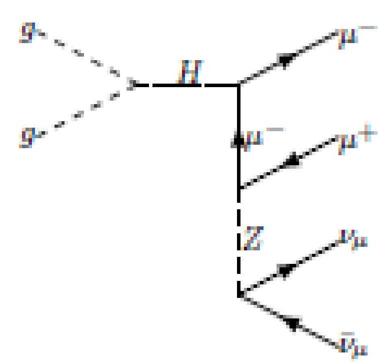
diagr.3



diagr.4



diagr.5



diagr.6

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

$$(1) \quad \mu_{\rm i} = \frac{\left[\sum_{\rm j=1}^{\rm N_{ch}} \sigma_{\rm j\to H}\,{\rm Br}({\rm H}\to {\rm i})\right]_{\rm SME}}{\left[\sum_{\rm j=1}^{\rm N_{ch}} \sigma_{\rm j\to H}\,{\rm Br}({\rm H}\to {\rm i})\right]_{\rm SM}} \qquad (2) \quad \mu_{\rm i} = \frac{\left[\sum_{\rm j=1}^{\rm N_{ch}} \sigma_{\rm j\to H(off-shell)\to i}\right]_{\rm SME}}{\left[\sum_{\rm j=1}^{\rm N_{ch}} \sigma_{\rm j\to H(off-shell)\to i}\right]_{\rm SM}}$$

(1) signal strength in the production × decay approximation
(narrow width approximation or infinitely small width approximation);
(2) signal strength for complete gauge invariant set

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

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

$$\chi^2_{\rm N_{ch}} = \sum_{\rm i=1}^{\rm N_{ch}} \frac{(\mu_{\rm i} - \hat{\mu}_{\rm i})^2}{\sigma_{\rm i}^2}$$

MC **- $\chi^2_{N\_ch}$ distribution for the number of production channels N_{CH};**

- **Up to which degree the SM Higgs boson is consistent with the available data? More than 200 production ⊗ decay combinations and rearrangements are measured**
- **Structrure 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

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*

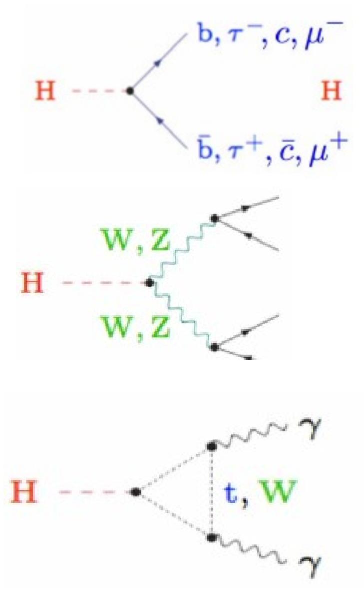
$$O_{\Phi G} = \frac{1}{2}(\Phi^\dagger\Phi - \frac{v^2}{2})G^a_{\mu\nu}G^{a\mu\nu} \qquad O_{\Phi G} = \frac{1}{2}(\Phi^\dagger\Phi - \frac{v^2}{2})G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$
$$O_{\Phi B} = \frac{1}{2}(\Phi^\dagger\Phi - \frac{v^2}{2})B_{\mu\nu}B^{\mu\nu} \qquad O_{\Phi B} = \frac{1}{2}(\Phi^\dagger\Phi - \frac{v^2}{2})B_{\mu\nu}\tilde{B}^{\mu\nu}$$
$$O_{\Phi W} = \frac{1}{2}(\Phi^\dagger\Phi - \frac{v^2}{2})W^i_{\mu\nu}W^{i\mu\nu} \qquad O_{\Phi W} = \frac{1}{2}(\Phi^\dagger\Phi - \frac{v^2}{2})W^i_{\mu\nu}\tilde{W}^{i\mu\nu}$$
$$O^{(1)}_\Phi = (\Phi^\dagger\Phi - \frac{v^2}{2})D_\mu\Phi^\dagger D^\mu\Phi$$

- *scalar-fermion sector*

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

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

(a,c) parametrization.
a rescales the VVH, c rescales the FFH



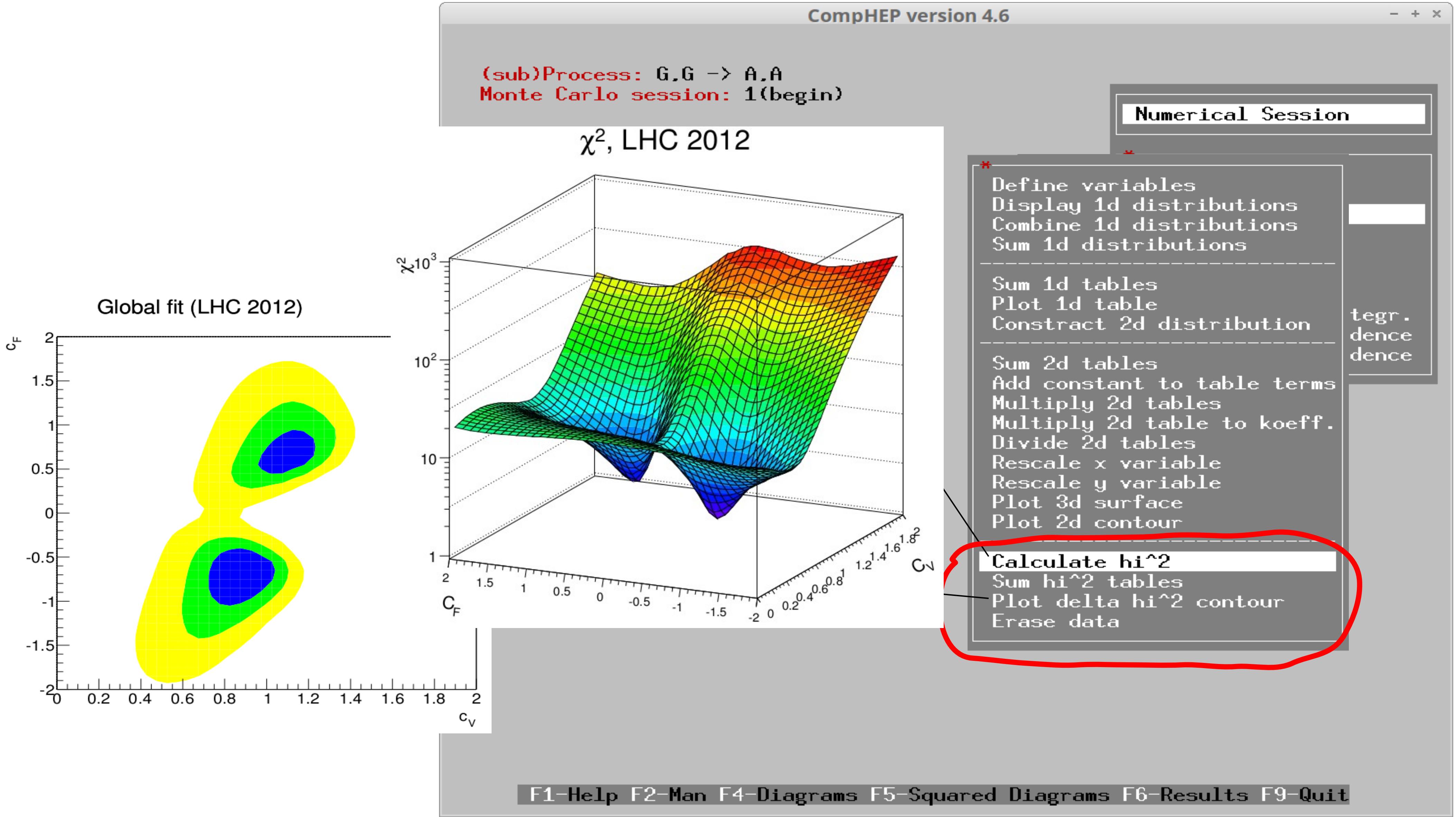
$$
\begin{aligned}
c_F &= 1 + C_{t\Phi} \cdot \frac{v^2}{\Lambda^2} \\
c_V &= 1 + \frac{v^2}{2\Lambda^2} \cdot C_{\Phi}^{(1)} \\
c_G &= c_F + \frac{6\pi}{\alpha_s} \cdot C_{\Phi G} \cdot \frac{v^2}{\Lambda^2} \\
c_\gamma &= \frac{63 c_F - 16 c_V}{47} + \frac{9\pi}{4\alpha} \cdot (c_w^2 \cdot C_{\Phi B} + s_w^2 \cdot C_{\Phi W}) \cdot \frac{v^2}{\Lambda^2} \\
c_Z &= (s_w^2 \cdot C_{\Phi B} + c_w^2 \cdot C_{\Phi W}) \cdot \frac{v^2}{\Lambda^2} \\
c_W &= C_{\Phi W} \cdot \frac{v^2}{\Lambda^2}
\end{aligned}
$$

the SM limit [a=1, $c=c_G=c_\gamma=1$, $a_W=0$, $a_Z=0$]
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: χ^2 measure in the anomalous coupling space. Global fits to μ in (cF,cV) 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 (cF,cV) space are defined by deviations from χ^2_min less than 2.1,4.6 and 9.2, respectively.



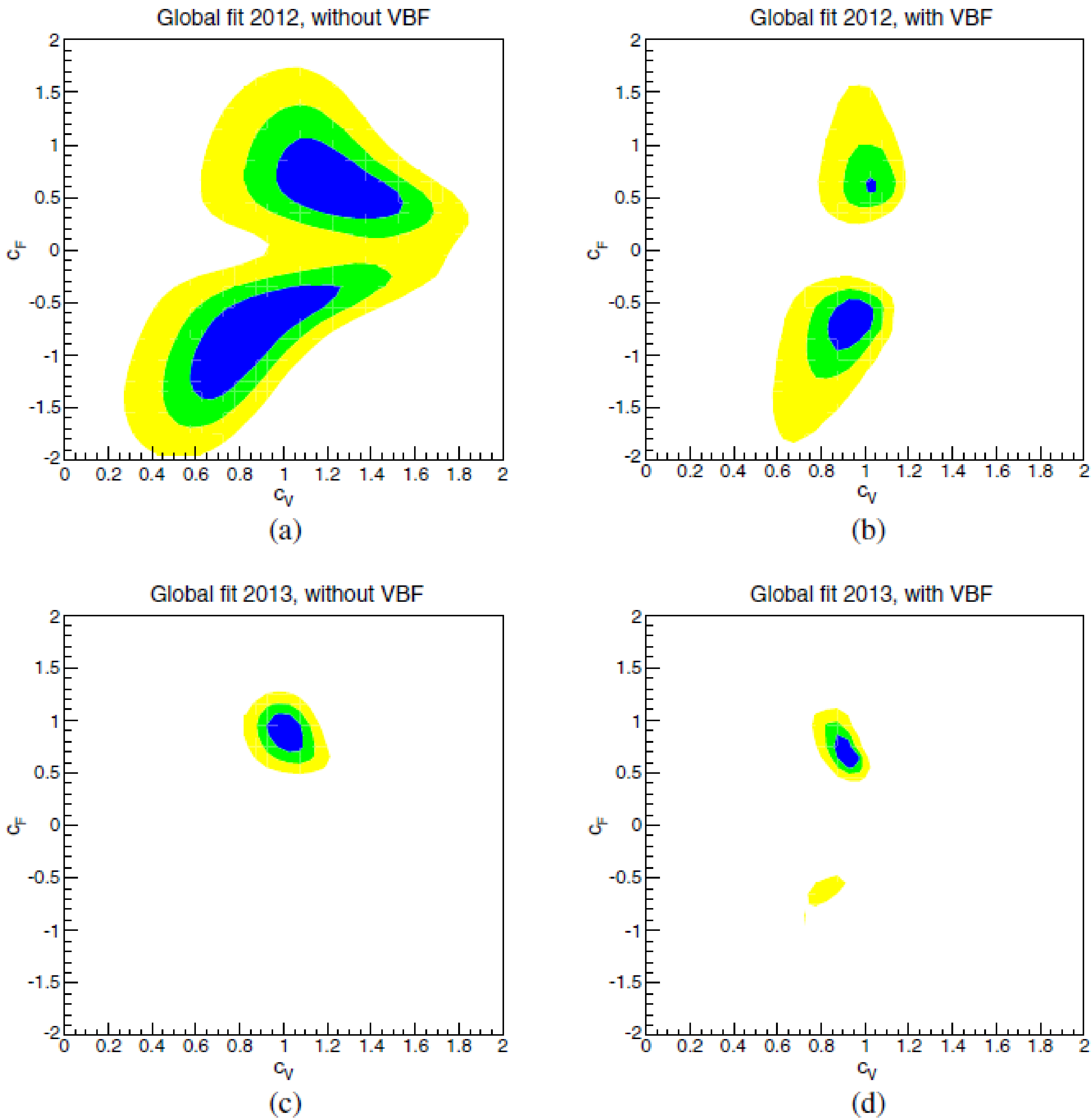
LHC

2014

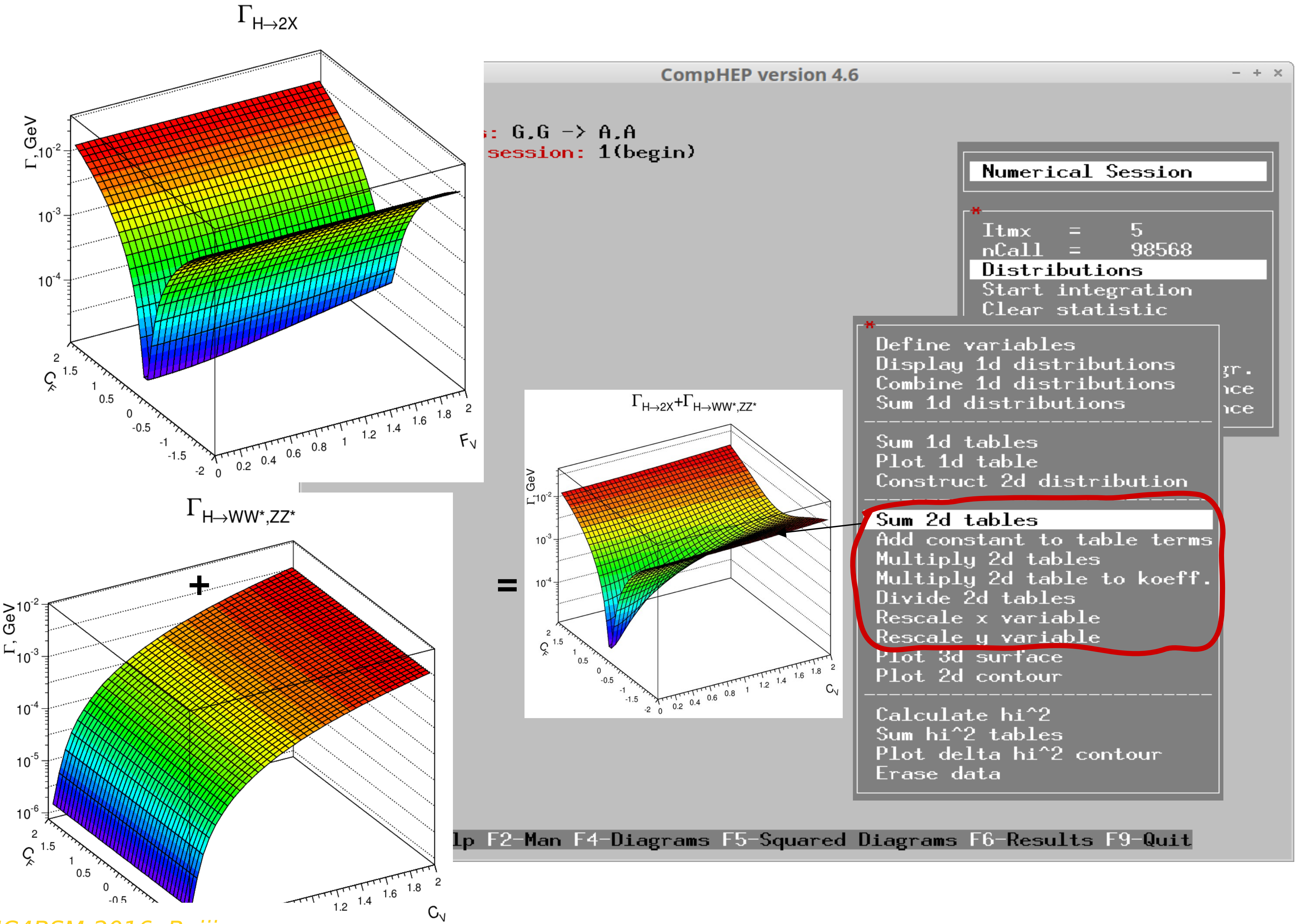
ATLAS

+CMS

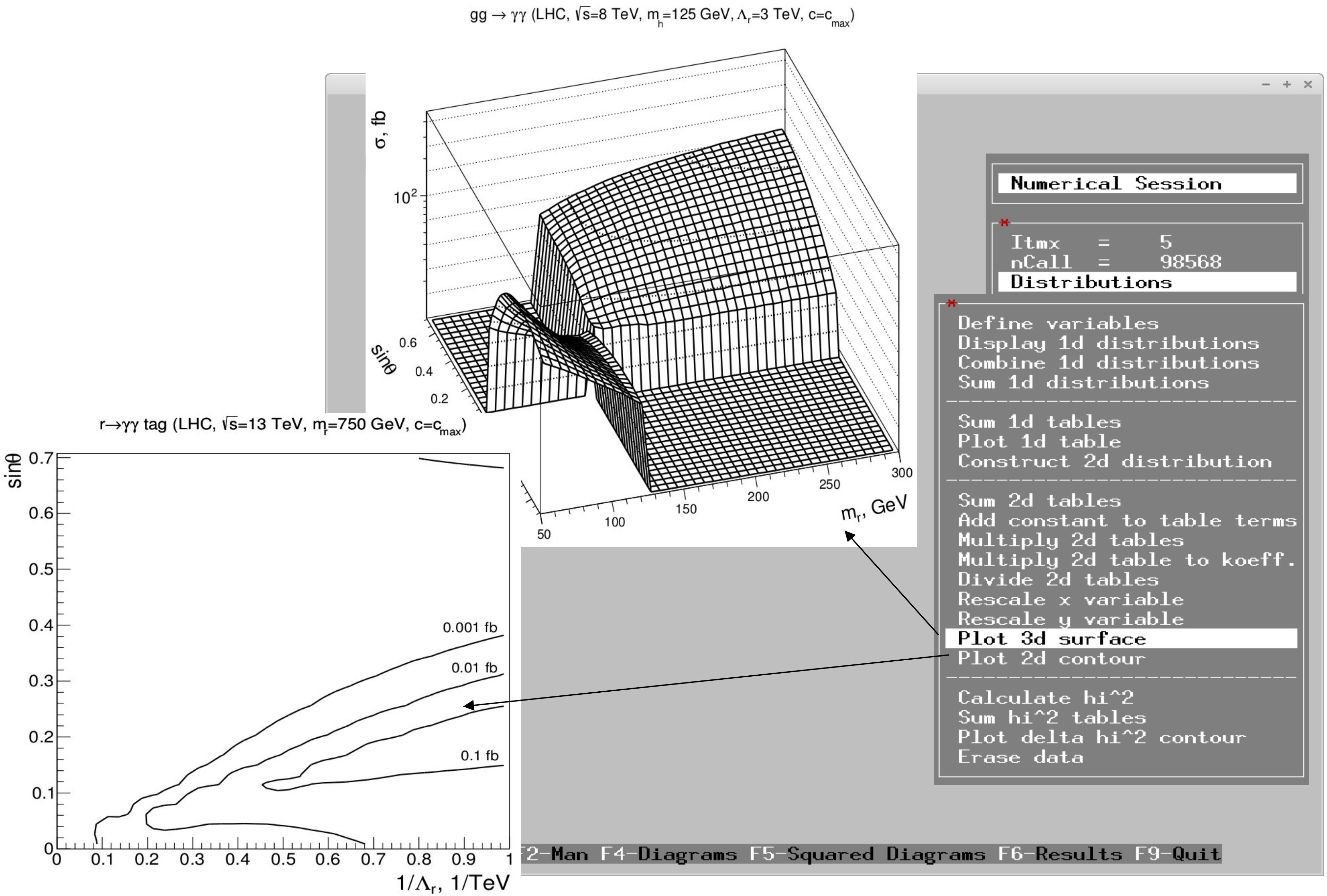
combined



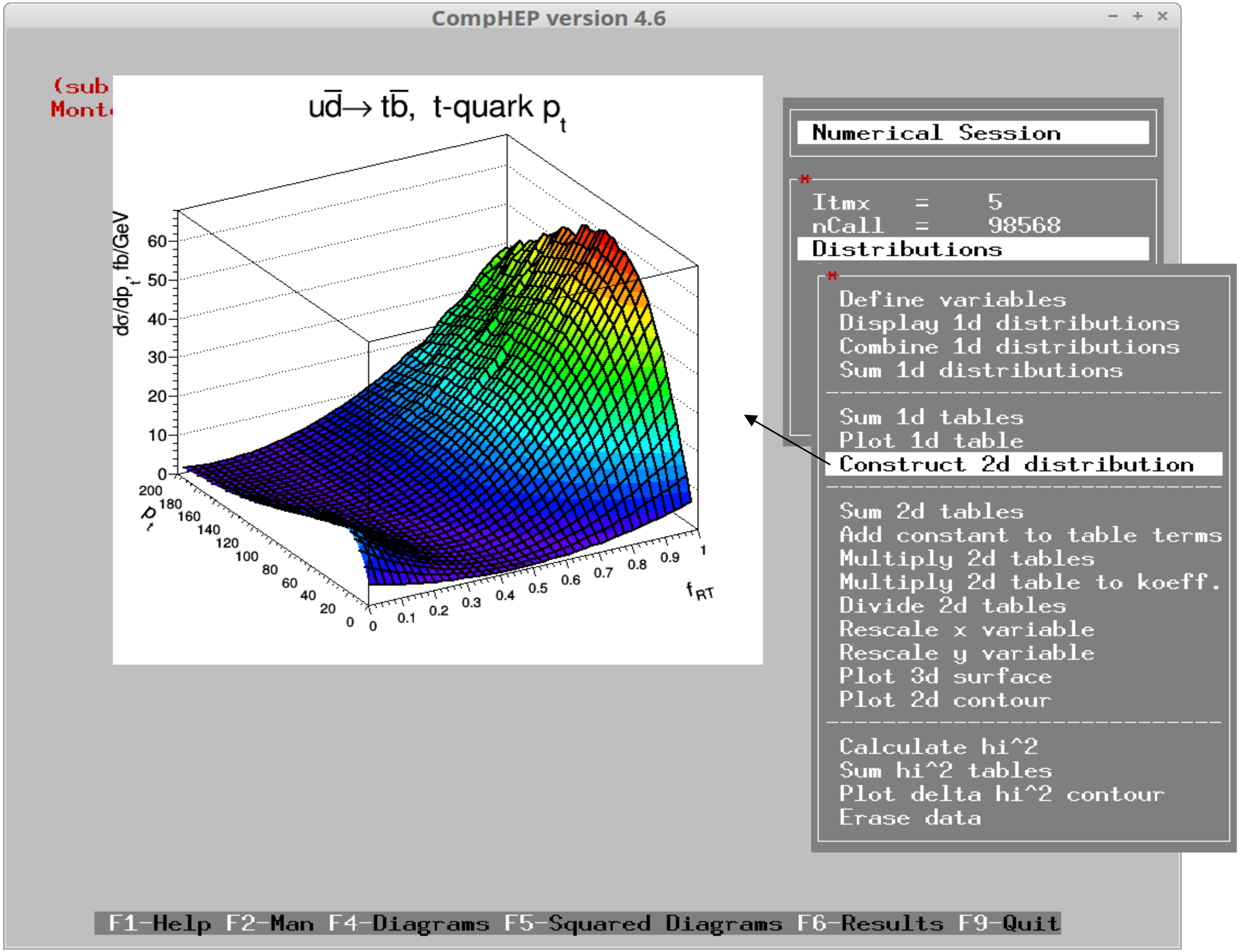
Algebraic operations with tables —cross section/width vs parameters



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



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



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

Using external functions in the Constraints Model Table

Any model parameter and vertex form-factor my 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
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)
Imlt  |myfunc4(yt,1)
ImlW  |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 |Imlt*(-RFF)
HGG   |7*Hanom+loopt*(-HFF)
ImHGG |Imlt*(-HFF)
RAA   |-11/(3)*Ranom+(loopW+8/(3)*loopt)*(-RFF)
ImRAA |(ImlW+8/(3)*Imlt)*(-RFF)
HAA   |-11/(3)*Hanom+(loopW+8/(3)*loopt)*(-HFF)
ImHAA |(ImlW+8/(3)*Imlt)*(-HFF)
F1-F2-Top-Bottom-GoTo-Find-Zoom-ErrMes
```

myfunc.c

```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;
}
```

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:

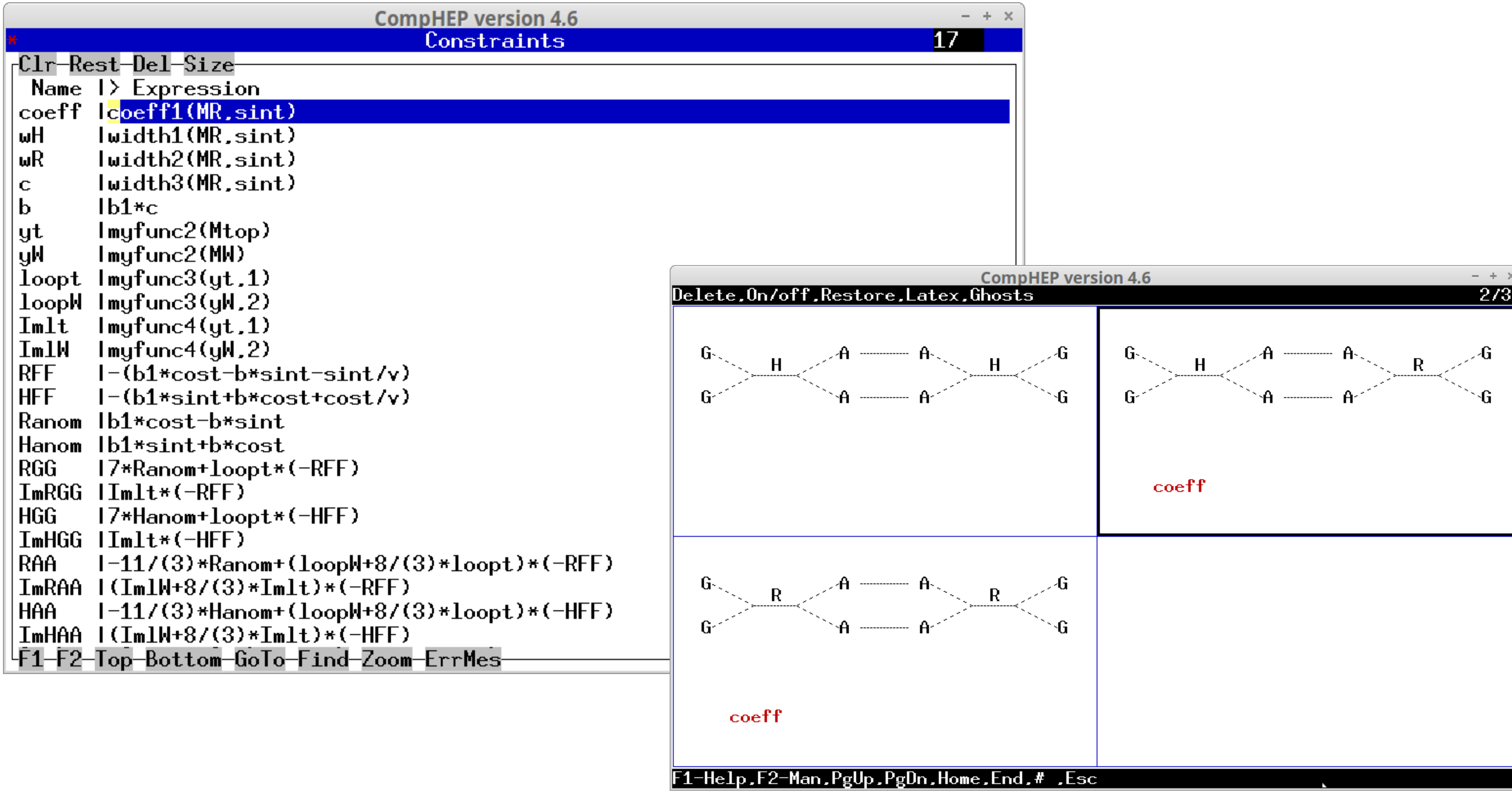
- Interfacing some MC codes (ME and SH generators): Les Houches Accord 1, Les Houches Event format
- Les Houches Accord 2: uniform interface to different PDF sets (LHAPDF package)
- Les Houches Accord 3: Interfacing SUSY codes to MC generators for parameters, spectrum, decays (SPA).
- BSM Les Houches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

Summary

- CompHEP с интерфейсами к PYTHIA/HERWIG и другим пакетам остается убедительным инструментом для моделирования процессов SM/BSM на ускорителях
- CompHEP имеет развитый графический интерфейс и возможности работы с аналитическими представлениями амплитуд перехода, что отличает его от других пакетов
- CompHEP совместим со всеми стандартами “Monte-Carlo industry” для ускорителей (напр., Les Houches Accords 1, 2, 3, LHE).
- CompHEP пригоден для параллельных вычислений на многопроцессорных комплексах
- CompHEP интегрирован в ATLAS, CMS environment для использования в Run II

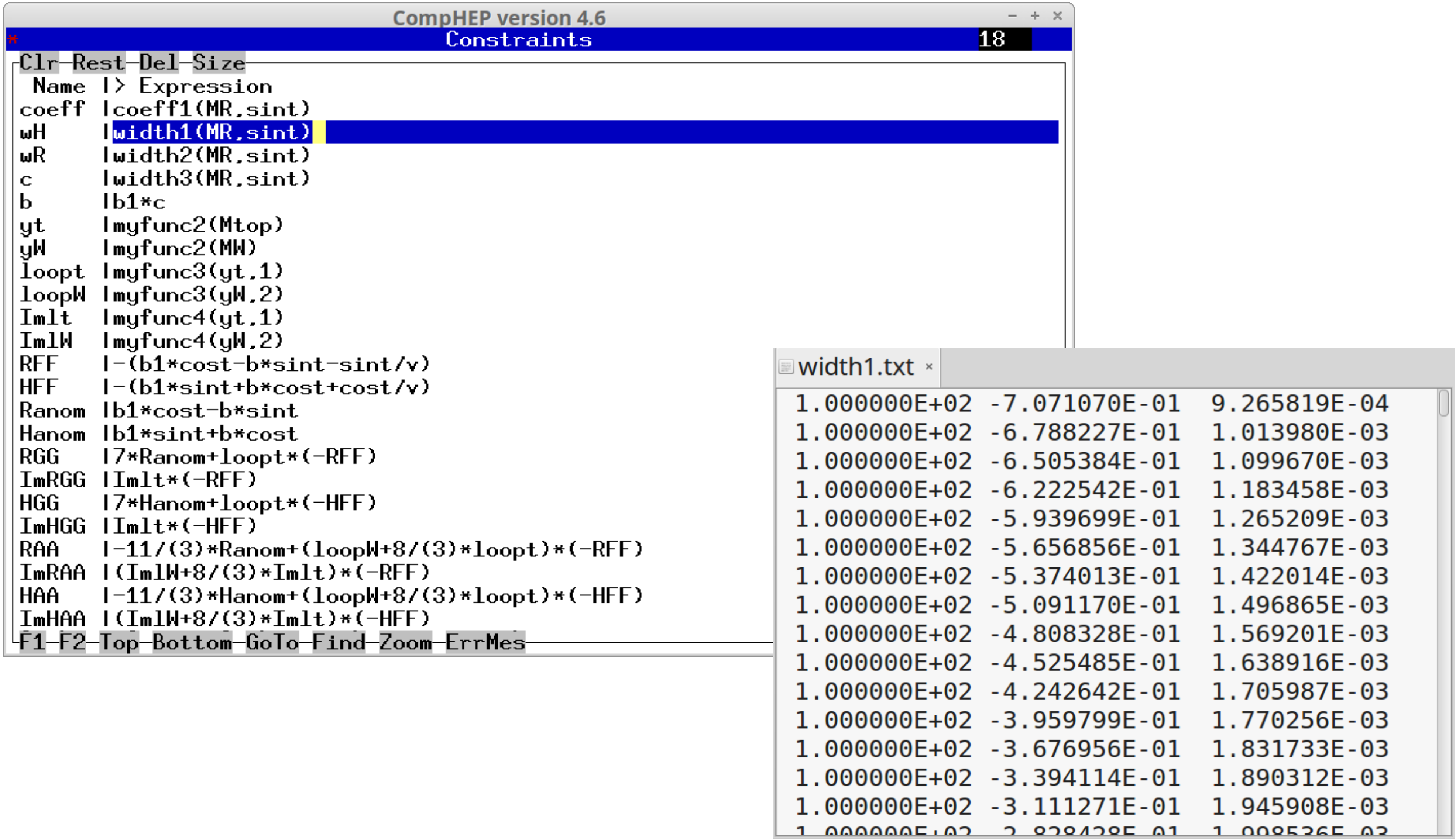
Спасибо за внимание!

Multiplication of selected squared diagrams on an external function



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

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



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

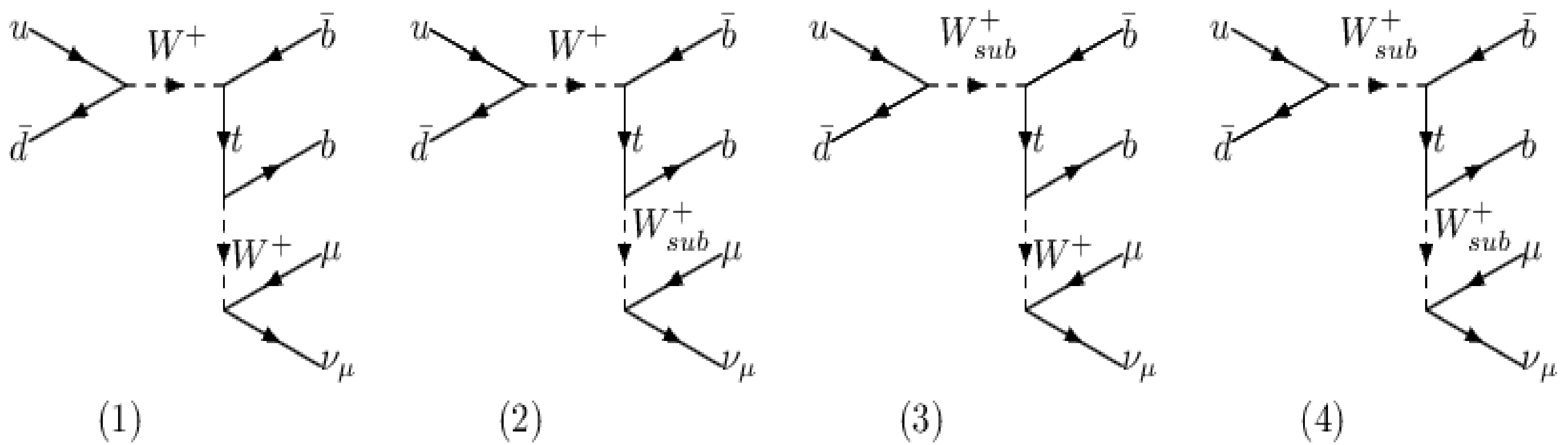
$$\Gamma_\mu = \Gamma_\mu^{SM} + \Gamma_\mu^{NP_1} + \Gamma_\mu^{NP_2} + \ldots$$

Example: anomalous Wtb vertex

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

W boson SM	$\frac{\mathbf{g}}{\mathbf{2}\sqrt{\mathbf{2}}}\mathbf{f_V^L}\gamma^\mu(\mathbf{1} - \gamma_\mathbf{5})$
W boson subsidiary 1	$\frac{\mathbf{g}}{\mathbf{2}\sqrt{\mathbf{2}}}\mathbf{f_V^R}\gamma^\mu(\mathbf{1} + \gamma_\mathbf{5})$
W boson subsidiary 2	$\frac{\mathbf{g}}{\mathbf{2m_W}\sqrt{\mathbf{2}}}\mathbf{f_T^L}\sigma^{\mu\nu}\mathbf{q}_\nu(\mathbf{1} + \gamma_\mathbf{5})$
W boson subsidiary 3	$\frac{\mathbf{g}}{\mathbf{2m_W}\sqrt{\mathbf{2}}}\mathbf{f_T^R}\sigma^{\mu\nu}\mathbf{q}_\nu(\mathbf{1} - \gamma_\mathbf{5})$

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



Diagrams (2),(3),(4) with subsidiary bosons for qq→bb $\mu\nu_\mu$

Squared amplitude with 'production' P_1,P_2 and 'decay' D_1,D_2

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

$$\sim \frac{1}{\Gamma}[(\mathrm{f_V^L})^4\mathrm{P_1D_1} + (\mathrm{f_V^L})^2(\mathrm{f_V^R})^2\mathrm{P_1D_2} + (\mathrm{f_V^L})^2(\mathrm{f_V^R})^2\mathrm{P_2D_1} + (\mathrm{f_V^R})^4\mathrm{P_2D_2}]$$

Three sets of event samples for simulation when fLV=fRV=1,fLT=fRT=0

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

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

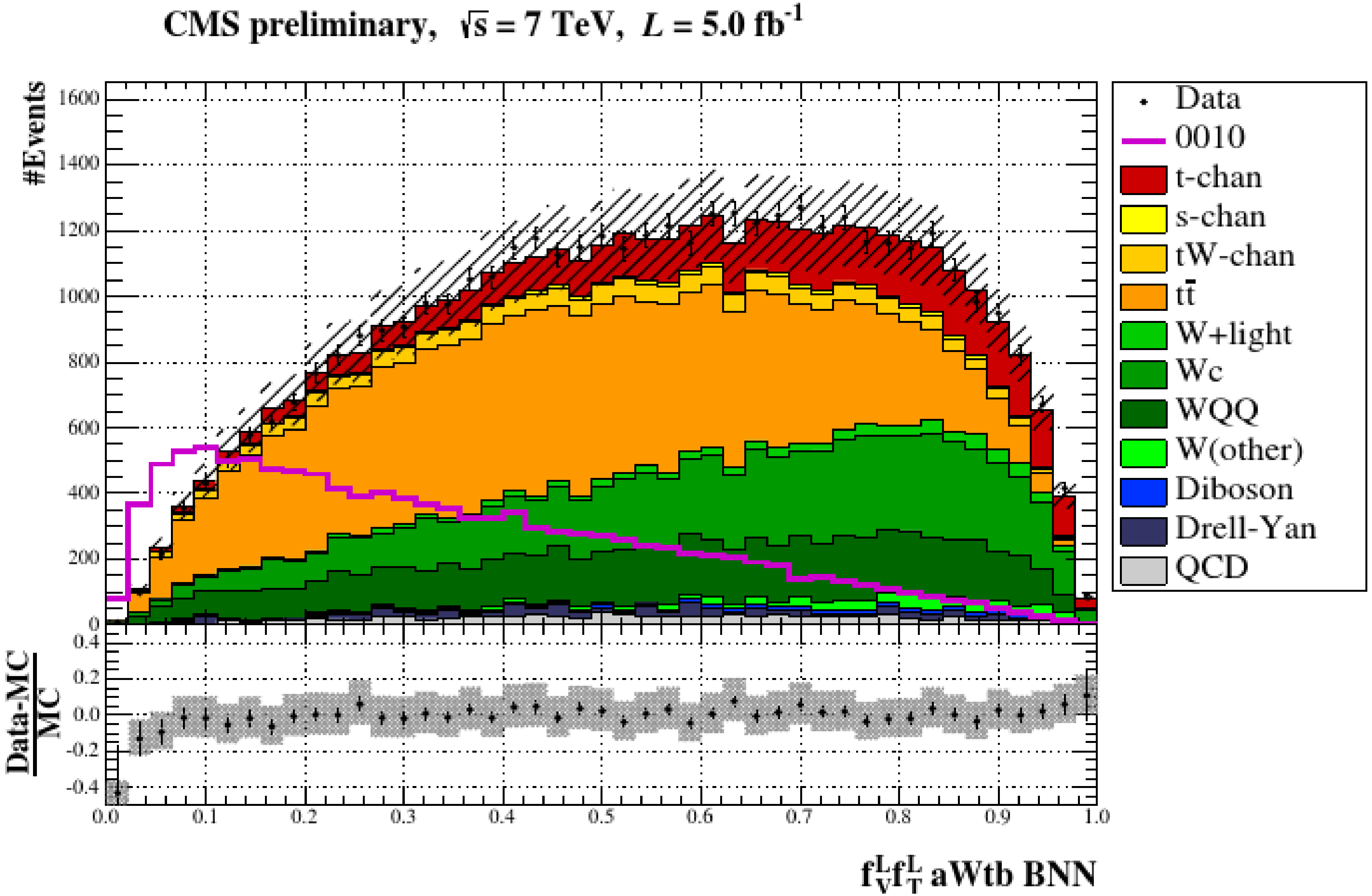
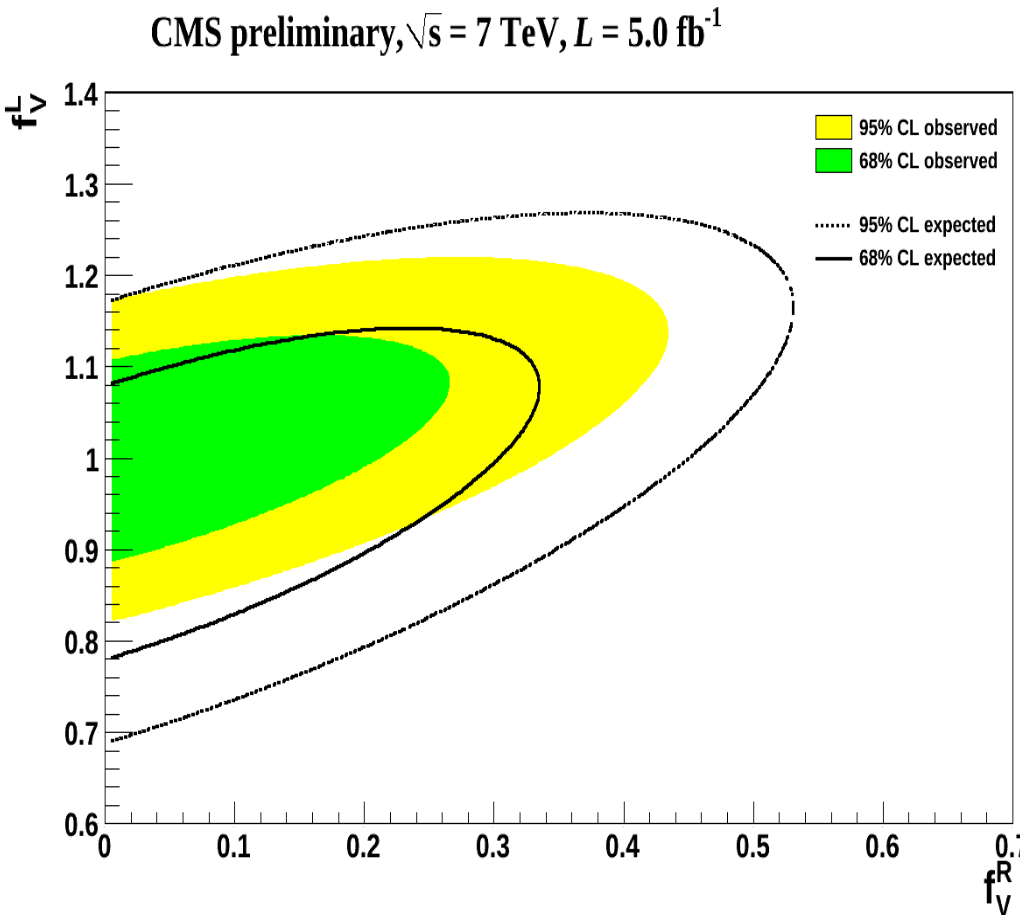
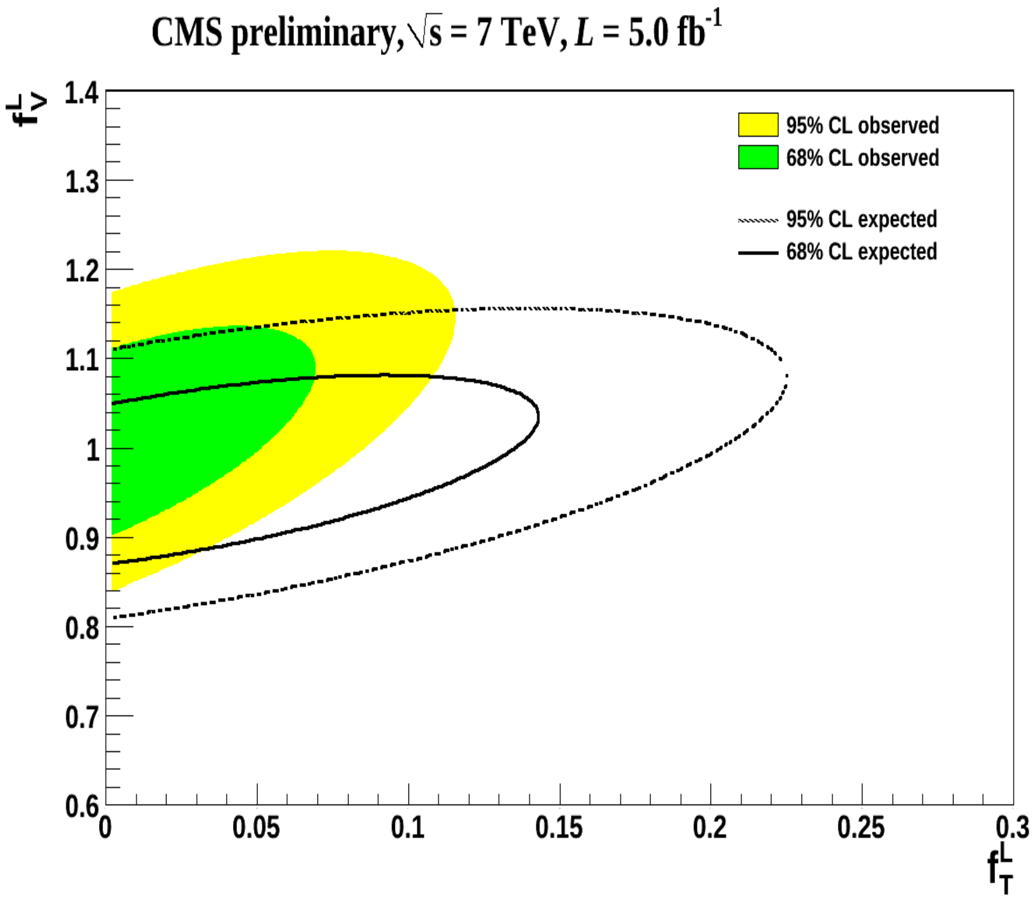


Figure 7: Data and model comparison of BNN aWtb discriminant for the (f_V^L, f_T^L) scenario. The BNN aWtb was trained to separate possible events with left tensor coupling in the Wtb interaction and SM events. The hashed band corresponds to the systematic uncertainty.

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





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)**

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)

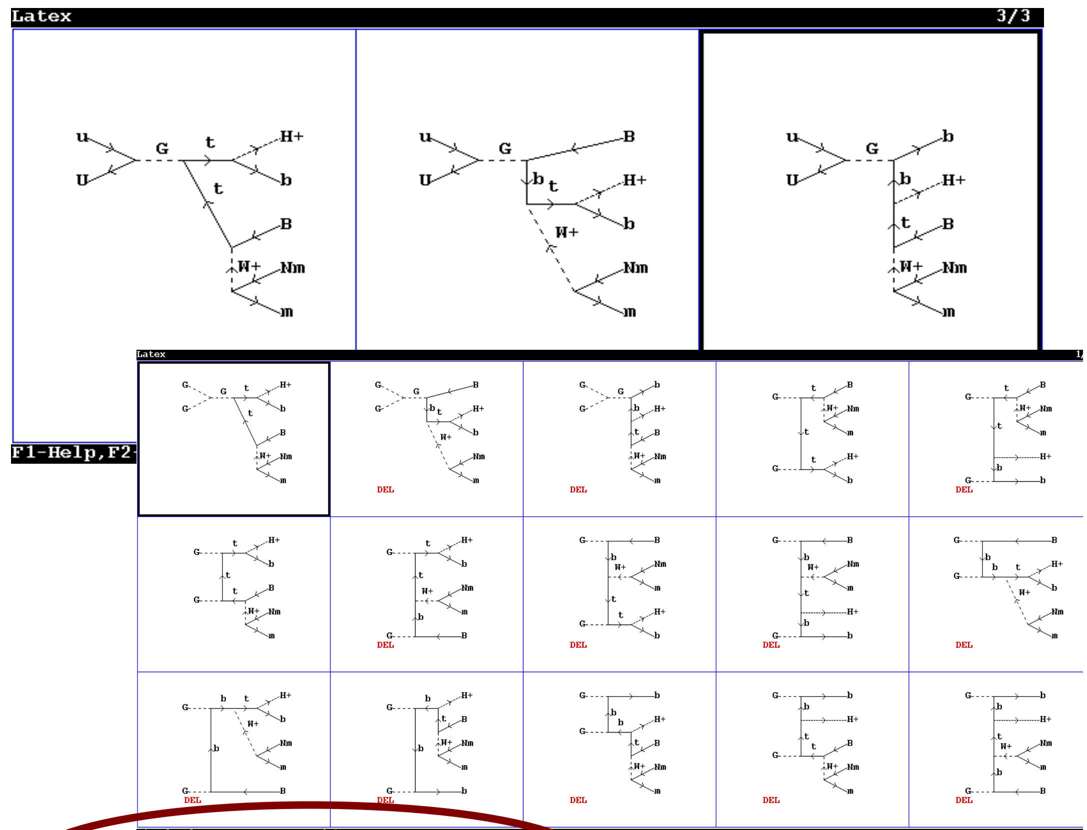
Symbolical batch: pp->m,Nm,b,B,H+ with t->b,H+ and T->m,Nm,B MSSM, tb=0.5, MH+=150GeV (H+->t*b->2f+bB dominates)

- Prepare process.dat following toy example: all points well documented

./symb_batch.pl -show diag (to exclude several sub-leading diagrams) 27 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
  SQRT(S) 1.400000E+04
  Rapidity(c.m.s) 0.000000E+00
  StrFun1: PDF:cteq6l1(proton)
  StrFun2: PDF:cteq6l1(proton)

#Physical_Parameters
        EE = 3.122300000000000E-01
        SW = 4.730000000000000E-01
        MZ = 9.118840000000000E+01
      Mtop = 1.750000000000000E+02
        Mb = 4.620000000000000E+00
      wtop = 1.752400000000000E+00
        wW = 2.088950000000000E+00
        mu = 1.000000000000000E+03
       MG2 = 2.000000000000000E+02
       MG3 = 3.000000000000000E+02
       Mq3 = 1.000000000000000E+03
       Mu3 = 1.000000000000000E+03
       Md3 = 1.000000000000000E+03
      Atop = 0.000000000000000E+00
        Ab = 0.000000000000000E+00
       MH3 = 1.341600000000000E+02
        tb = 5.000000000000000E-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
```

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	$-2 \cdot \frac{v}{\Lambda^2} \cdot C_{\Phi W} \cdot (g^{\mu\nu}p_1p_2 - p_1^\nu p_2^\mu)$
$O^{(1)}_\Phi = (\Phi^\dagger\Phi - \frac{v^2}{2})D_\mu\Phi^\dagger D^\mu\Phi$	W^+_μ W^-_ν H	$M_W^2 \cdot \frac{v}{\Lambda^2} \cdot C^{(1)}_\Phi \cdot g^{\mu\nu}$
	Z_μ Z_ν H	$M_Z^2 \cdot \frac{v}{\Lambda^2} \cdot C^{(1)}_\Phi \cdot g^{\mu\nu}$