Monte-Carlo generator CompHEP (4.5)

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For CompHEP Collaboration

Outline

- Motivation behind CompHEP
- CompHEP in nutshell
- Parallel calculations
- Implementation of Les Houches formats
- CompHEP-Interfaces package
- CompHEP, HepML and MCDB
- Final remarks

Motivations

Increasing collider energy and luminosity require calculations of processes with more and more particles in the final state with better and better precision (NLO, NNLO, NLL resummation)

1. SLAC/LEP I – basically 2 fermion physics;
2. LEP II – basically 4 fermion physics;
3. TEVATRON, LHC, and (I)LC – 4,5,6 and even 8 fermions + additional photons and/or gluons (jets);
   - Single top in the t-channel mode – 5 fermions;
   - Top pair production with decays – 6 fermions;
   - Strongly interacting Higgs sector in hadron collisions – 6 fermions

$$pp \to W^- W^+ + jj$$

   - Yukawa coupling – 8 fermions

$$pp \to t\,\bar{t} + H$$

Motivations

Large number of Feynman diagrams and large number of subprocesses (hadron colliders) require automation

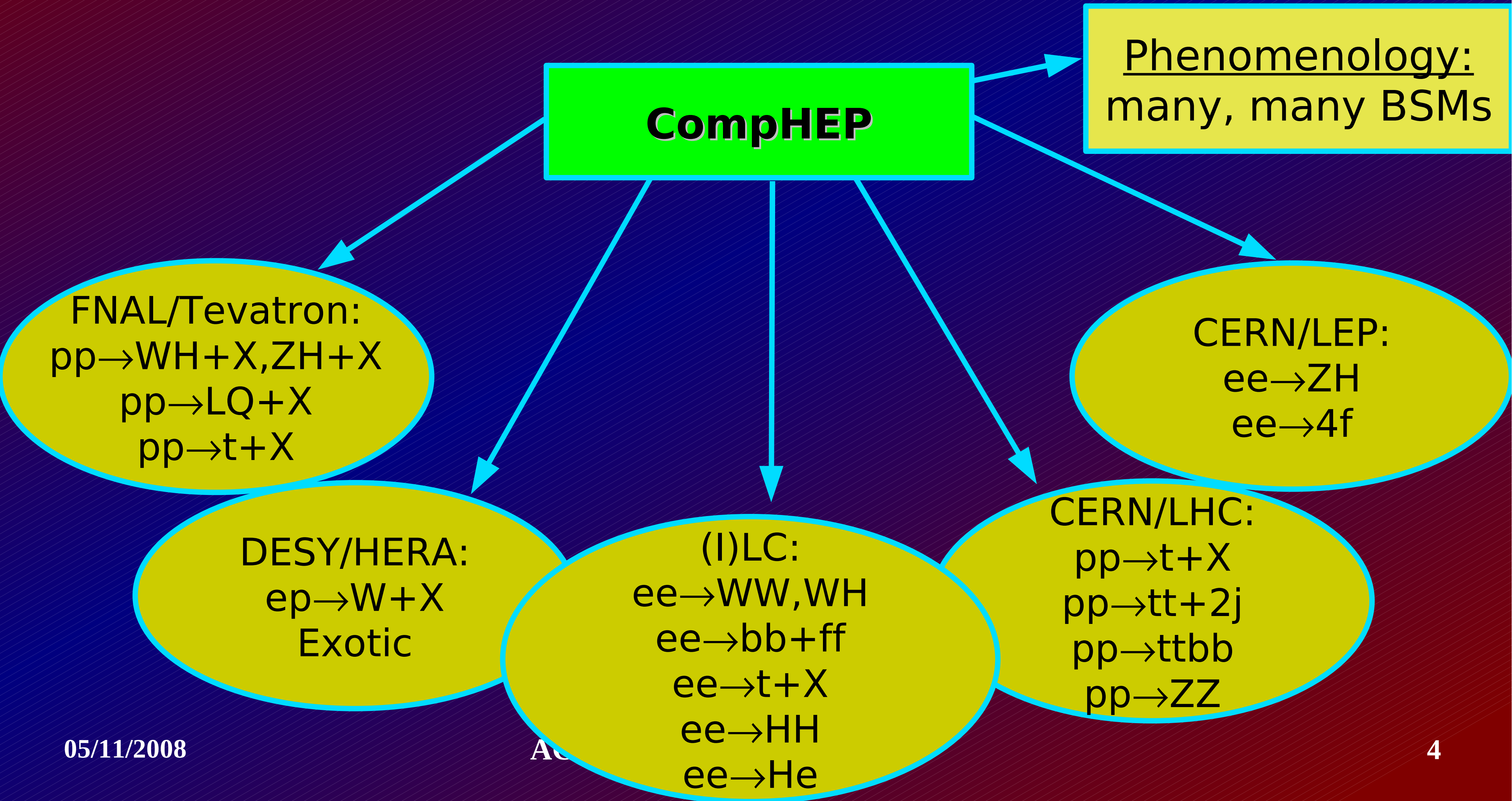
Goals:

- Automation of tree level diagram calculations
- “Unification” of symbolical and numerical calculation (in UI) – 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

Community answer: CompHEP, GRACE, MadGraph, AlpGen, Omega/WHIZARD, Sherpa/Amegic, etc.

CompHEP
(Computation in High Energy Physics)

Incomplete list of processes simulated with CompHEP in the past (3 papers have ~1000 citations):



CompHEP conception

- CompHEP constructs tree level Feynman diagrams for a given parton process (u,U→e,E,m,M,G or p,p→e,E,m,M,j)
- Symbolical calculations of the Feynman diagrams squared
- Automated preparation of binary for numerical calculations by Monte-Carlo technique (based on C code): cross sections, distributions, events
- Model independence: Model description files are input for CompHEP. 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 parameters
- “Universal”, build-in symbolic calculator: CompHEP can calculate N^2 tree level diagrams for any process 1, 2→M. N and M are limited by computer resources only
- User-friendly interface: GUI for both symbolic and numerical parts, comprehensive build-in help (F1), batch scripts

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 vertexes
- Composite particles: proton, artificial useful particle combinations

CompHEP SM Model

Variables

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

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

Constraints

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

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-

Basic and user-defined CompHEP Models

- Simple training models: QED, Effective 4-fermion Fermi 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

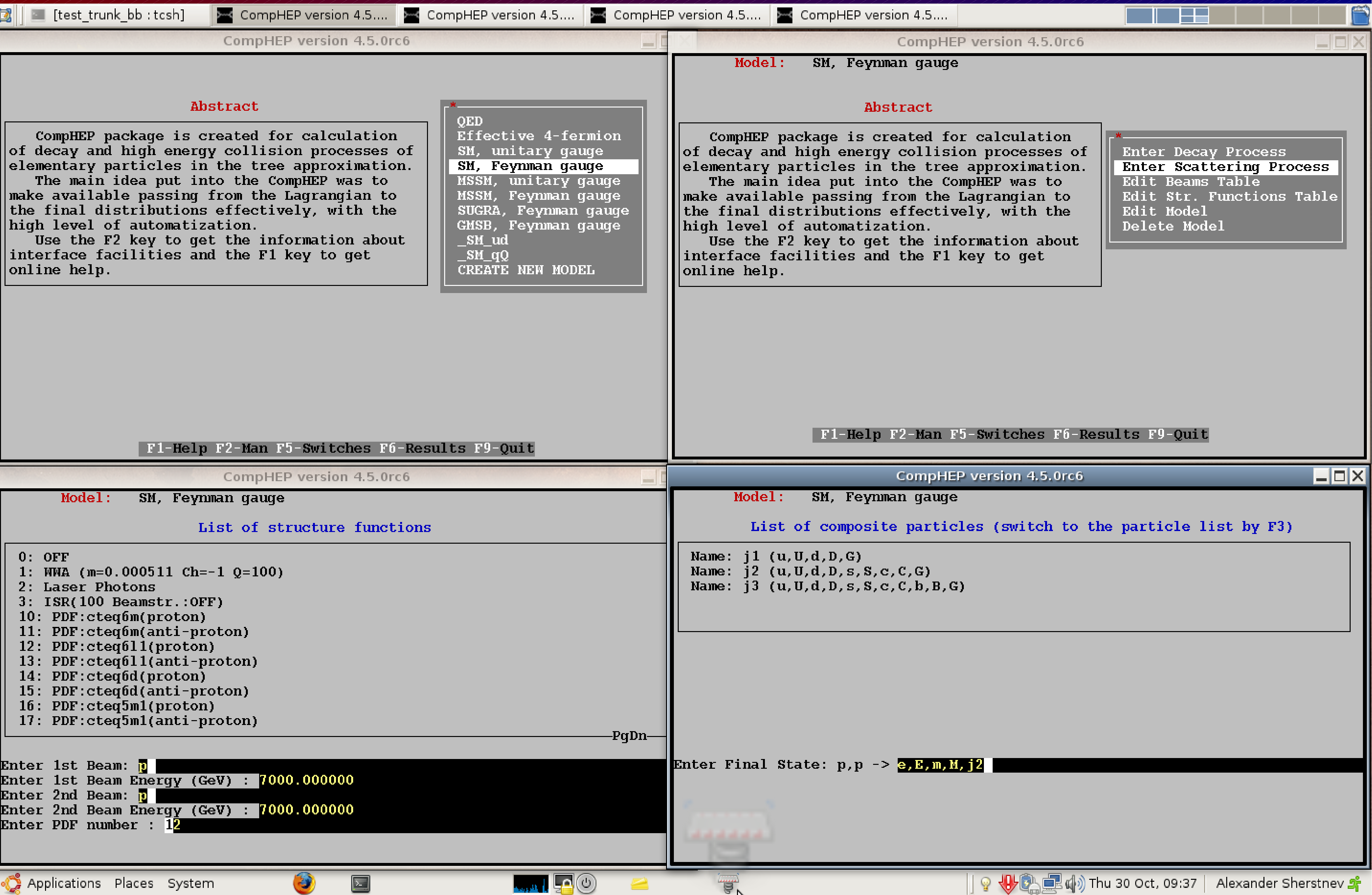
New (user-defined) Models

- 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

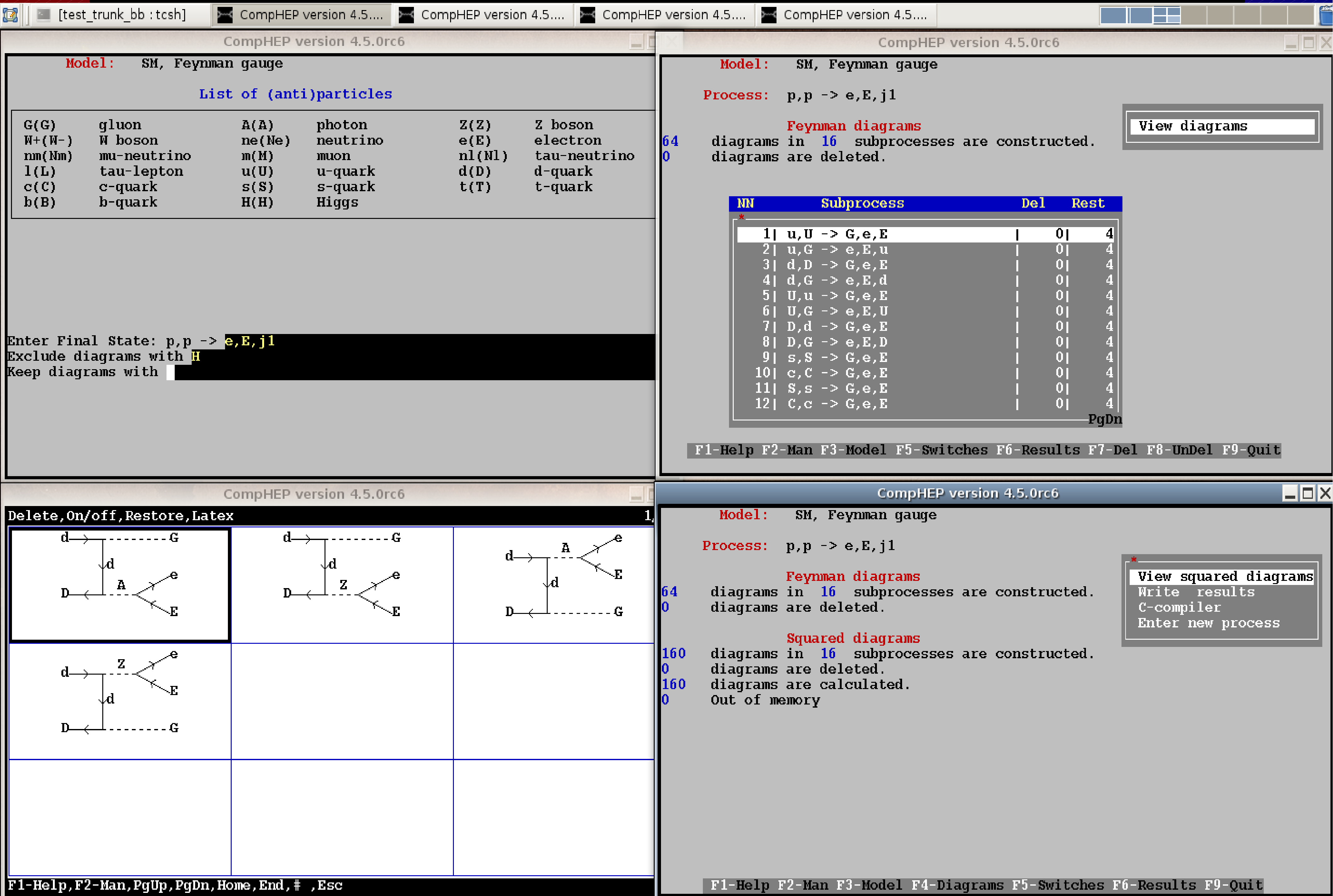
CompHEP BSM Lagrangians

- 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.

Symbolic calculations



Symbolic calculations (2)

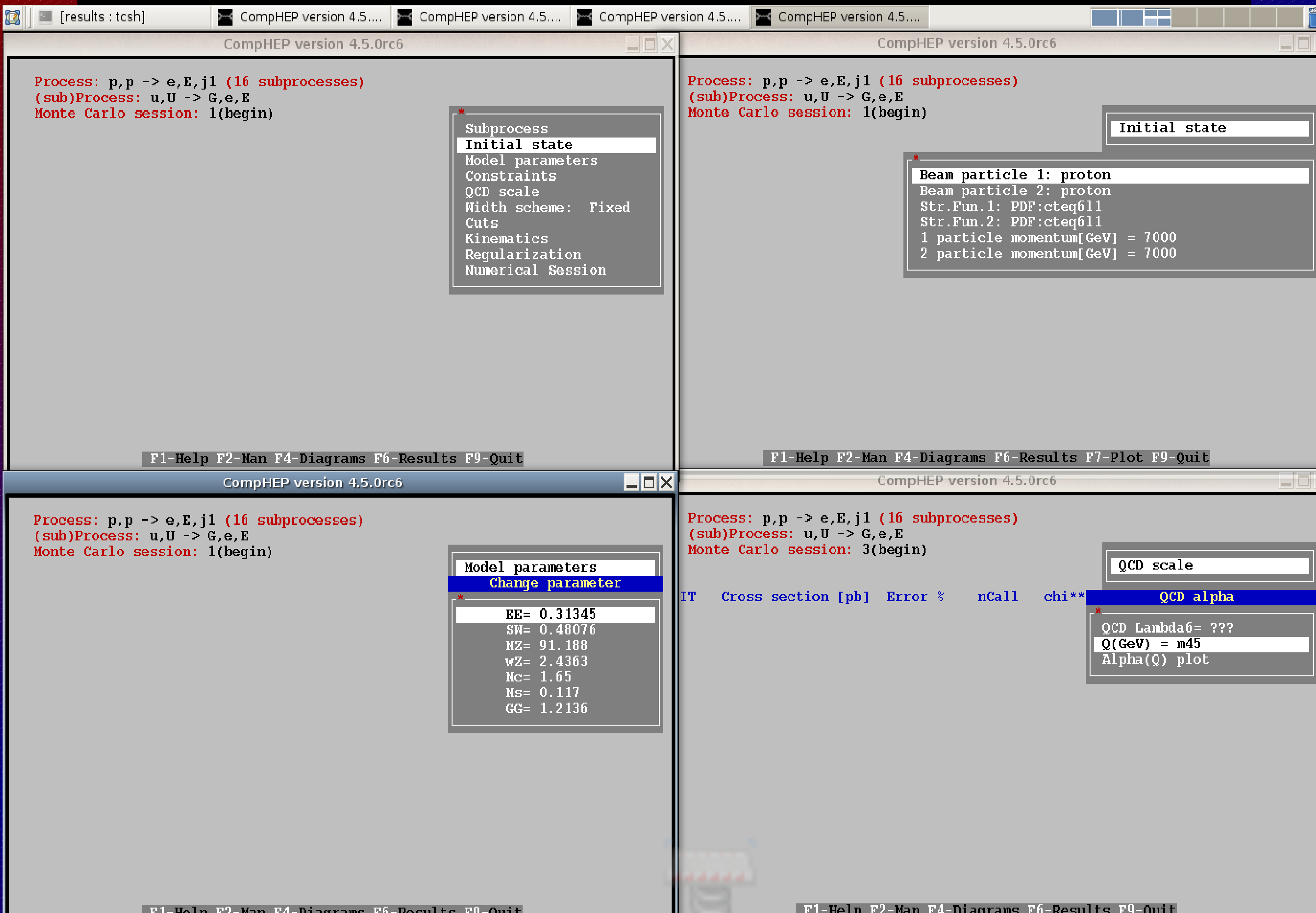


Numerical calculations

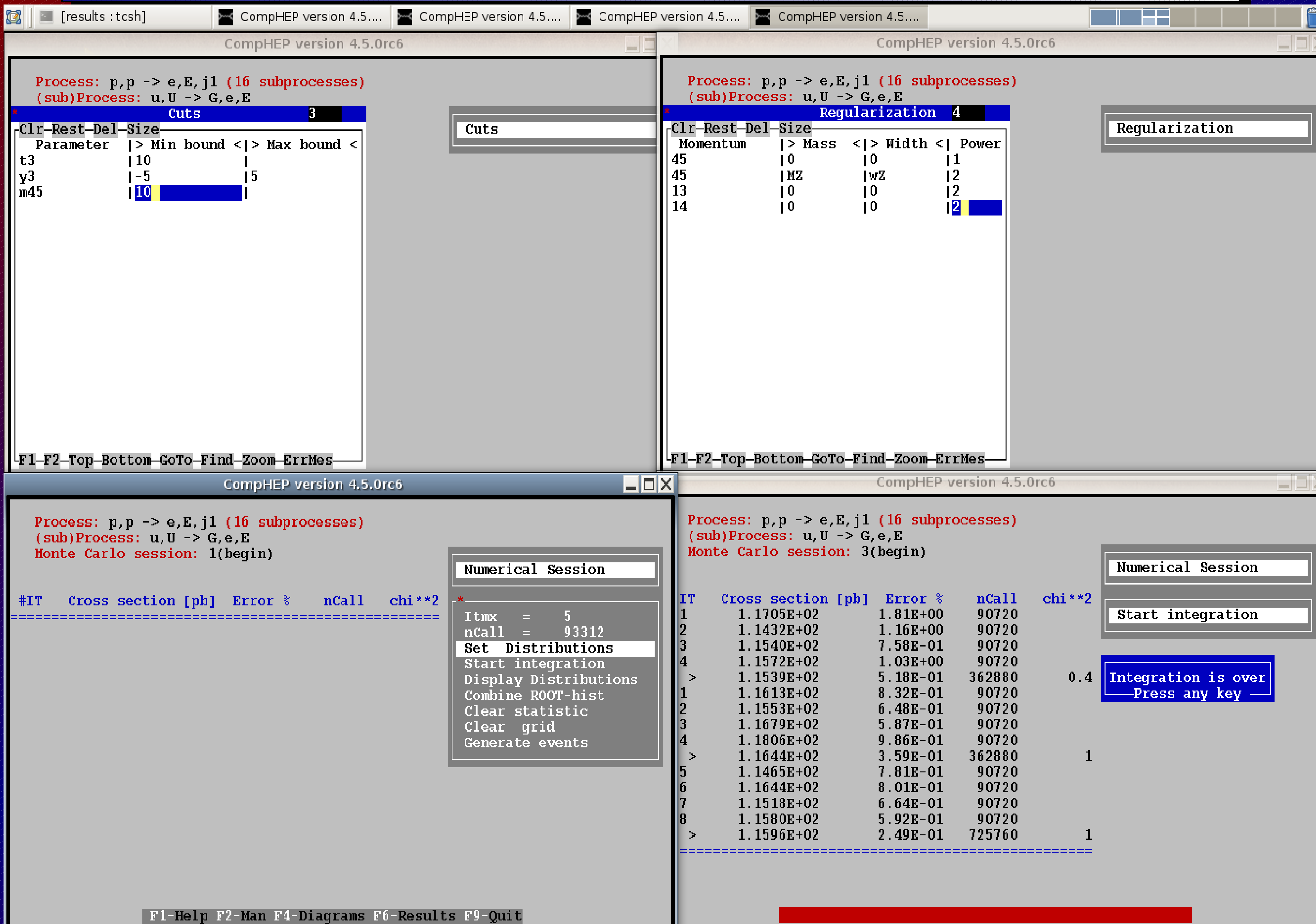
- **Customize numerical MC generator:** The most complicated part: do proper phase space sampling (regularizations + kinematics), set necessary kinematic cuts, Q^2, PDF set, etc. Main goals – to improve efficiency of MC calculation and describe physics task. User may change model parameters and set kinematic 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.

Numerical calculations (2)



Numerical calculations (3)



Batch system in CompHEP

Both symbolic & numerical parts have batch scripts:
Perl scripts: symb_batch.pl and num_batch.pl

Why the scripts are useful?

- Computations of many subprocesses – laborious task, can be significantly simplified especially for hadron colliders
- **Long/large-scale calculations:** GUI is not too handy
- **Support of parallel calculations**: very helpful for multi-CPU machines/computer clusters (pbs/lsf is available; grid in progress)
- **"Knowledge transfer":** theorists/phenomenoligists can prepare model/process.dat/batch.dat for further simulations by experimentalists

Symbolic parallel calculations

- Main idea:
  - symbolic calculation of one diagram is an independent task. The only unified point is the final binary data file.
  - Several calculation flows can be running at one time for several sub-sets of diagrams. The final point is to collect the binary data file
- Implemented in ./symb_batch.pl with the option -mp
- 1st step!: ./symb_batch.pl –help
- Parallel calculations on one machine: -mp N means N symbolic calculations in parallel
- Batch system version (pbs/lsf) is being implemented
- Very easy to use!

Numerical parallel calculations

- Again, 1st step: ./num_batch.pl –help (long and very detailed description). The script has lots of options (~30)!
- n_comphep.exe should be prepared! Main file is batch.dat in /results (based on session.dat). It can be edited by hand or via GUI and ./num_batch.pl –add (customized subprocess added to batch.dat)
- Then ./num_batch.pl -run vegas (cross section calculation for ALL subrocesses) and ./num_batch.pl -run max,evnt (event generation)
- Parallel calculations available. Alone machine (useful for multi-CPU desktops): -mp 3 (3 jobs are calculated simultaneously); computer clusters (with a batch system installed): -lsf and -pbs
- Many ways to present and monitor results and calculation process (see help)
- Very easy to use!

Event generation

- Events – phase space points, distributed according to $|M|^2$
- Monte-Carlo technique
- adaptive importance sampling method VEGAS
- For event generation: + stratified sampling
- Von Neumann (rejection) sampling:
  - If g(x) – importance sampling function
  - $|M|^2 = f(x)$ – matrix element squared
  - Find $f_{max}(x) = f_0$ and compare $\rho=f(x_i)/f_{max}=f_i/f_{max}$ and random number R
  - If $\rho > R$ – accept the point

Iterative Rejection sampling

- Usual efficiency in CompHEP – 0.1-1%.

What can we do with “waste”?

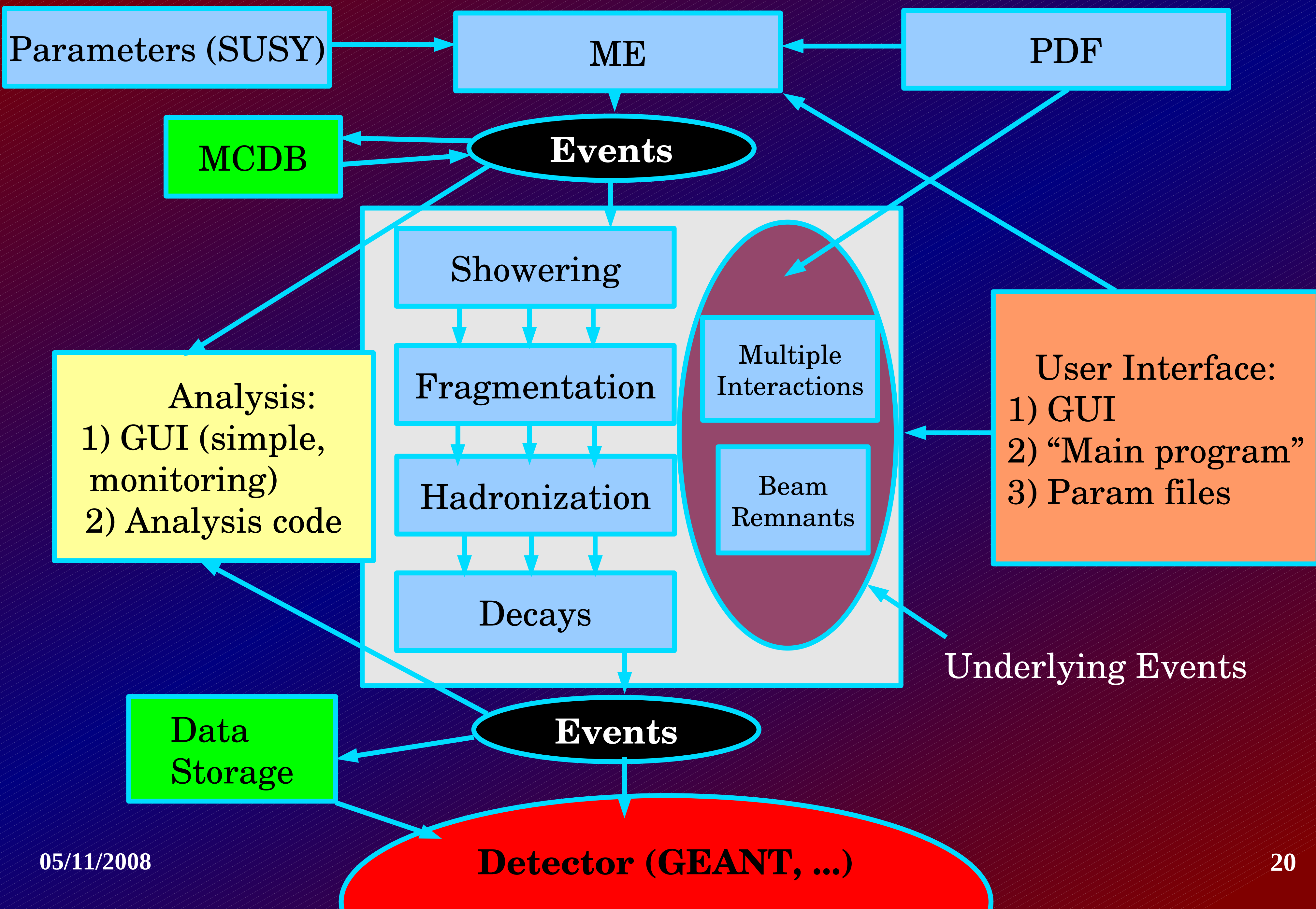
- Repeat the von Neumann procedure with the waste – rejected events!
- But importance sampling function is unknown...
- There is a way to calculate it

$$\omega_1 = \frac{N_{rej}\,\omega_0}{N_{tot} - N_{act}\,\omega_0 / I_{tot}}$$

- We can do several iterations, but should stop ar some step.
- Stopping rule: $|I_0 - I_f| \geqslant \Delta I_0 + \Delta I_f$
- Real benefit: from 20% to 1000% of extra events **without** extra calculations of $|M|^2$

more details in 0807.2823

Modern Monte-Carlo Model



MC code landscape: diversity

	General-purpose	Special
Hard Processes	PYTHIA HERWIG SHERPA ISAJET	A lot (CompHEP, MadGraph,Grace)
Parton Showers		Ariadne, NLLjet
Underlying Events		PHOJET, Jimmy
Hadronization		none
Decays		TAUOLA, EvtGen

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, ...

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, 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

CompHEP-interfaces package

The CompHEP-Interfaces includes two interfaces for PYTHIA and HERWIG, These interfaces allow us to use processes computed by CompHEP as external processes in PYTHIA/HERWIG

Main goal: provide ISR/FSR, hadronization (jet fragmentation), and decays as it is done in PYTHIA/HERWIG

- CompHEP generates unweighted events (event files)
- The command *mix_flows* mixes several event files in one event file
- Some governing parameters (Event file name, the number of events for generation) are kept in the file **INPARM.DAT**
- A matching code for ME events and showers in PYTHIA are being developed in the package
- Simple routines for toy analysis are provided
- Program to translate data to ROOT file (record looks like LHA I)
- TAOLA interface available (be request)

MCDB – Monte-Carlo events Data Base

Team: S.Belov, L. Dudko, A.Ribon, A.S. (CERN, MSU, JINR, Oxford)

Motivation:

- Verified MC simulation of complicated processes requires sophisticated expertise and expert knowledge
- A physics group in a collaboration requests experts and/or MC generator authors to create MC samples for the particular process
- The same physics processes are investigated by various physics groups, the same MC samples can be used in different analyses

The main motivation – to make MC event samples, prepared by experts, available for various physics groups

MCDB tasks:

- The database has to be available via the Web
- Using CASTOR/GRID technologies to keep/upload/download MC samples
- Simple and intuitive interface for events authors and end-users to find and manipulate event samples

more details in S. Belov's talk

MCDB: technical details

- Frontend: a Web site (mcdb.cern.ch)
- Backend: SQL for metadata and CASTOR for data
- Keep parton and particle level events with standard interface to the next level of simulation (PYTHIA/HERIWG, simu.software), based on LHA I
- Store detailed documentation for each set of event samples
- Provide communication between users and experts via MCDB web pages
- Direct programing interface of the collaboration software to LCG MCDB
- Divided in two zones:
  - **public area:** users can search for/browse the DB and download event files
  - **restricted area:** authors (experts) change MCDB content: upload and describe new event files, change the existed files and reply to user's comments

MCDB encourages end-users to cite event sample author's papers in case the events are used in physics analyses!

Paper: hep-ph/0703287

HepML

- Unified XML format of MC event files metadata
  - to store all possible information from MC generators in XML view
  - to store generator input parameters and setup
  - an effort to fix a unified extensible way of MC events description
  - is an allowed part of LHEF standard event file header
- 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 can generate HepML code!

more details in S. Belov's talk

Concluding Remarks

- CompHEP with the interface to PYTHIA/HERWIG is a powerful tool for a simulation of SM/BSM physics at hadron and lepton colliders
- CompHEP can calculate cross sections, build different distributions, and generate un-weighted events
- CompHEP is compatible with all modern “Monte-Carlo industry” standards (Les Houches Accords 1, 2, 3, LHE). This CompHEP-Interfaces can be easily used and included to experimental environments
- Parallel computations both in symbolic and numerical modules are implemented as part of batch scripts
- Advanced MC techniques for improving of generation efficiency applied
- In order to facilitate interfacing of different MC code and re-usage event samples CompHEP generates HepML code
- MCDB is a proper place for event sample keeping and describing

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.S. (Moscow State and Oxford University)
- CompHEP homepage: http://theory.sinp.msu.ru/comphep There are some versions of CompHEP, LanHEP, and CompHEP-interfaces available
- References:

- 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
- MCDB/HepML: Comput.Phys.Comm. 178:222 [hep-ph/0703287]