BSM physics with SHERPA

Tanju Gleisberg

Institute for Theoretical Physics
Dresden University of Technology

CERN, Theory Division

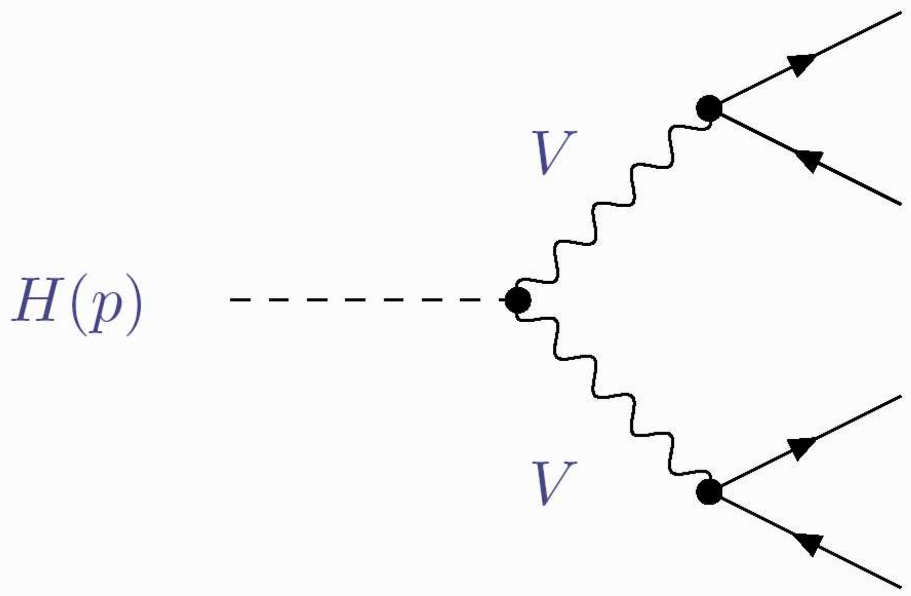
- Event generation with Sherpa
- The matrix element generator AMEGIC++
- BSM Models
  - MSSM, ADD, Anomalous gauge couplings
  - Implementation of new models

Motivation

For many BSM physics studies we need tools that

- provide matrix elements beyond $2 \to 2$ (plus decays)
- include quantum interferences and off-shell effects
- preserve all information on spins and correlations
- account for hard extra radiation
- provide interfaces to parton showers and hadronization

Example: Off-shell effects in Higgs decays



- Consider M_H below VV threshold
- $H \to VV$ and subsequent decays $V \to f\bar{f}$ not factorizable
- Best treatment: full ME for $H \to 4f$

The event generator Sherpa

SHERPA (**S**imulation of **H**igh **E**nergy **R**eactions of **PA**rticles) is a new multipurpose event generator entirely written in C++.

T. G., S. Höche, F. Krauss, A. Schälicke, S. Schumann and J. Winter, JHEP **0402** 056 (2004).

The Scope:

- Full simulation of high energy particle reactions at existing and future collider experiments, including e^+e^-, $\gamma\gamma$, $e\gamma$, $p\bar{p}$ and pp collisions
- Account for multi-jet production by using tree level matrix elements combined with the parton shower using the CKKW prescription

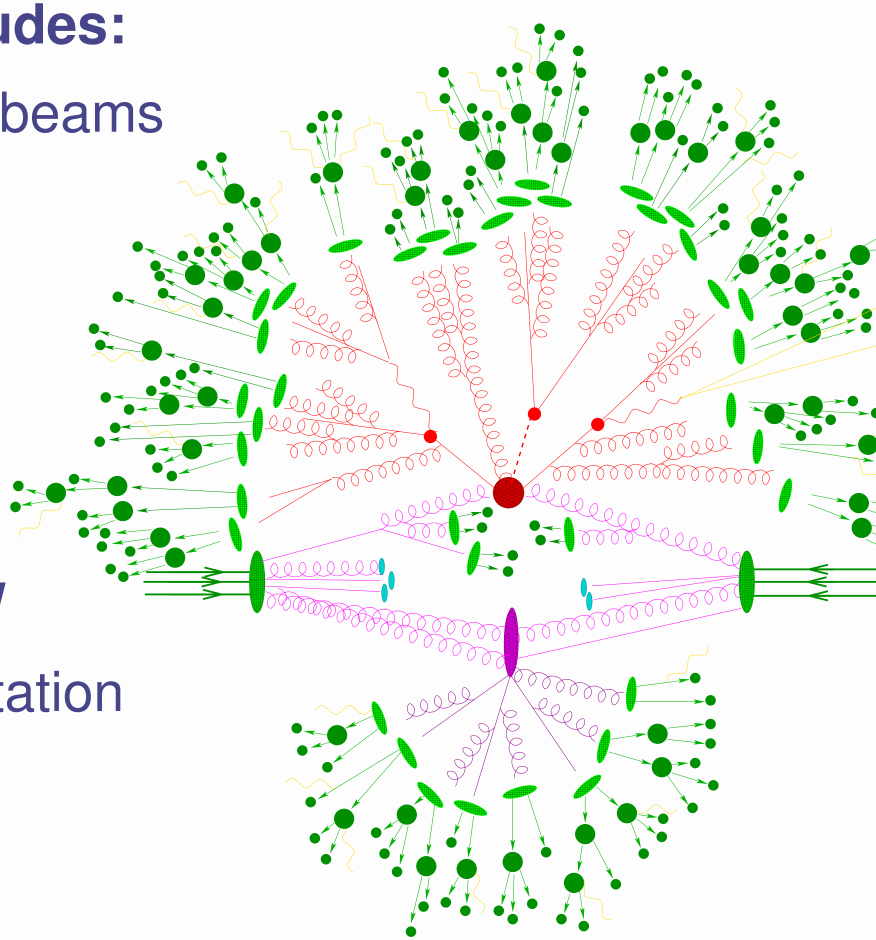
Features:

- Modular structure of independent physics modules
- Modules are interfaced through abstract handler classes
- Bottom-up approach (slim overhead that can be easily adapted)

Event generation with SHERPA

In its current version (1.0.8) SHERPA includes:

- interface to various PDF sets for hadron beams
- initial state radiation and beam spectra for $e^+/e^-/\gamma$ beams
- the ME generator AMEGIC++ (hard process and decays)
- the parton shower module APACIC++
- combination of ME's and PS's via CKKW
- an interface to the Pythia string fragmentation and hadron decays
- a simple hard underlying event model

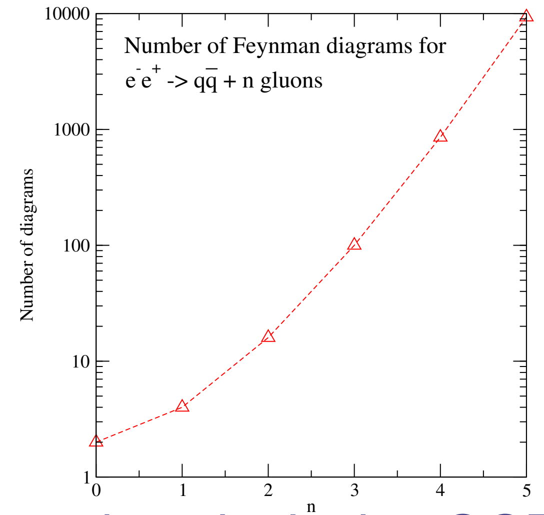


$\Rightarrow$ **Sherpa is the event generation framework.**

- **initialization of the different phases**
- **steering the event generation**

BSM physics with SHERPA

- SHERPA can be used to study new physics in the domain of hard matrix elements
- ME's are provided by the automatic parton level generator **AMEGIC++**
- Application area:



1. Precision signal processes studies
   - keep all interference terms
   - ME for the full SM interaction set (and beyond) or for subsets
2. Provide ME for the CKKW merging method to produce inclusive QCD samples

S. Catani, F. Krauss, R. Kuhn and B. Webber, JHEP **0111** 063 (2001)

F. Krauss, JHEP **0208** 015 (2002)

$\Rightarrow$ See talk by Jan Winter ...

AMEGIC++ (A Matrix Element Generator in C++)

- generates tree level matrix elements for arbitrary processes in the SM and several BSM models
- direct computation of amplitudes as complex numbers using helicity amplitudes
- tested for a variety of processes with up to 6 particles in final state
- universal approach: extending AMEGIC++ by Feynman rules of another model is rather simple
- completely automatic approach: a generator generator
  - First run: initialization

    $\longrightarrow$ generation of matrix elements

    $\longrightarrow$ generation of phase space mappings for a Multi-Channel PS-integration method

    $\Rightarrow$ stored as C++ libraries
  - Compilation of the libraries
  - Second run: integration/event generation

AMEGIC++ (A Matrix Element Generator in C++)

Features:

- Specification of processes by initial and final state particles as well as by using particle containers (e.g. partons, quarks, leptons, etc.)
- Specification of decay chains possible that allows to go far beyond the usual (practical) limit of 6 final state particles (and still keep complete spin information)
  e.g. $p\bar{p} \rightarrow t\,[\rightarrow b\,W^+[\rightarrow ...]]\,\bar{t}\,[\rightarrow \bar{b}\,W^-[\rightarrow ...]]\;h[\rightarrow b\bar{b}]$
- Restriction of electroweak and QCD order possible

MSSM implementation

- MSSM spectrum taken from SLHA input files

  (→ masses etc. governed by external codes)

- General Feynman rules (unitary gauge, conserved R-party) according to J. Rosiek, Phys.Rev.D41:3436, 1990
- The violated fermion flow of Majorana fermions is cured by using appropriate Feynman rules
  - Implemented the approach of Denner *et al.* Nucl.Phys.B387, 1992
  - The relative sign of interfering Feynman graphs is determined avoiding the usage of charge-conjugated matrices
  - Instead an orientation (fermion flow) for each appearing fermion line is defined

Application area

- Calculation of total and partial widths of sparticles
- Sparticle production processes at LHC and ILC
- AMEGIC++ can provide SUSY signals and associated SM/SUSY backgrounds

MSSM: Validation

Comparison of Automated Tools for Phenomenological Investigations of SuSy

SMadGraph, **O'Mega/Whizard**, **Amegic++/Sherpa**

Hagiwara, Kilian, Krauss, Ohl, Plehn, Rainwater, Reuter, Schumann, Phys. Rev. D **73**, 055005 (2006)

- All SUSY vertices were checked testing several hundred $2 \to 2$ processes

$$e^+e^-,\ e^-\bar{\nu}_e,\ e^-e^-,\ \tau^+\tau^-,\ \tau^-\bar{\nu}_\tau,\ u\bar{u},\ d\bar{d},$$
$$uu,\ dd,\ b\bar{b},\ b\bar{t},\ W^+W^-,\ W^-Z,\ W^-\gamma,$$
$$ZZ,\ Z\gamma,\ \gamma\gamma,\ gW^-,\ gZ,\ g\gamma,\ gg,\ ug,\ dg$$

$\longrightarrow$ All combinations of SUSY partners or Higgs boson

- Results are listed under

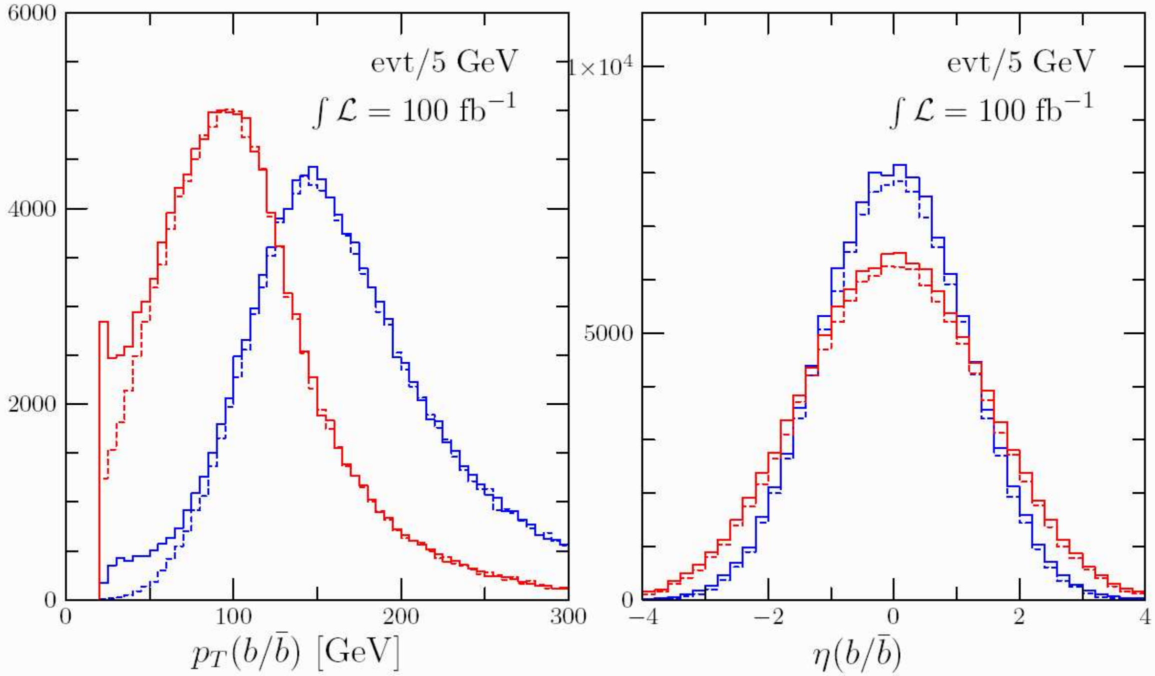
http://www.sherpa-mc.de/susy_comparison/susy_comparison.html

MSSM: Validation

Application: **Off-shell effects in sbotom production & decay at LHC**

Hagiwara et al.,Phys. Rev. D **73**, 055005 (2006)

- $\tilde{b}_1$ pair production and decay $\tilde{b}_1 \to b\tilde{\chi}_1^0$
  $(m_{\tilde{b}_1} = 295.3GeV, \Gamma_{\tilde{b}_1} = 0.53GeV, m_{\tilde{\chi}_1^0} = 46.8GeV)$
- Compare Breit-Wigner approximation $gg \to \tilde{b}_1\tilde{b}_1^* \to b\bar{b}\chi_1^0\chi_1^0$ (dashed) with full set of diagrams for $gg \to b\bar{b}\chi_1^0\chi_1^0$ (solid)

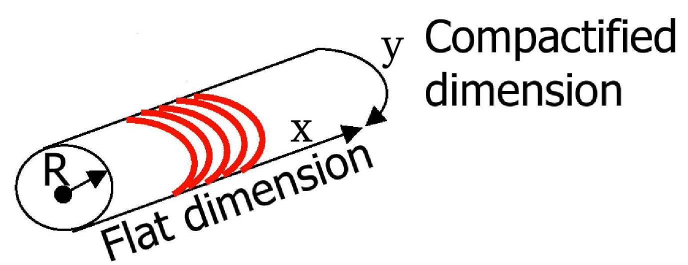


- $\Rightarrow$ Off-shell effects sizeable in the low $p_{T,b}$ region

The ADD model of Large Extra Dimensions

Large extra dimensions á la ADD

(Arkani-Hamed,Dimopoulos,Dvali, Phys. Lett. B429,263 (1998)



- n compact extra dimensions, accessible only to gravity
- Kaluza-Klein excitations lead to enhanced effective gravitational coupling

$$M_{\rm Pl}^2 \sim R^n M_{\rm D}^{n+2}$$

- Feynman rules:

  Han, Lykken, Zhang, Phys. Rev. D 59,105006 (1999)

  Giudice, Rattazzi, Wells, Phys. Lett. B 544,3 (1999)

- All 3- and 4-point interaction vertices between SM particles and Gravitons have been implemented

  Details: T. G., Krauss, Matchev, Schälicke, Schumann, Soff, JHEP 0309:001,2003

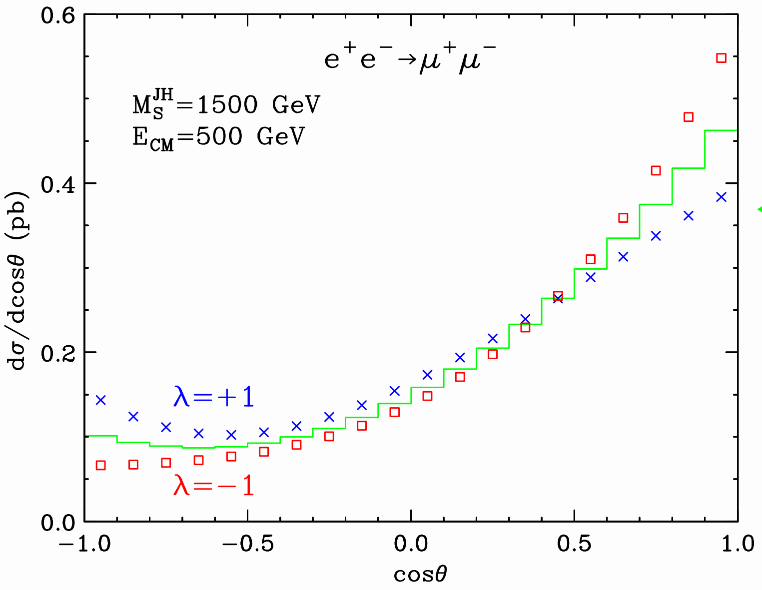
The ADD model of Large Extra Dimensions

- Special issue: summation over KK-states of the Graviton
- Virtual Gravitons:
  - Same coupling strength for all KK-states
    $\rightarrow$ summation on propagator level:

$$D(s = p^2) = \sum_{\vec{n}} \frac{i}{s - m_{\vec{n}}^2 + i\varepsilon} \approx \int_0^{Q_{\rm cut}} \mathrm{d}m_{\vec{n}}^2 \;\; \rho(m_{\vec{n}}) \frac{i}{s - m_{\vec{n}}^2 + i\varepsilon}$$

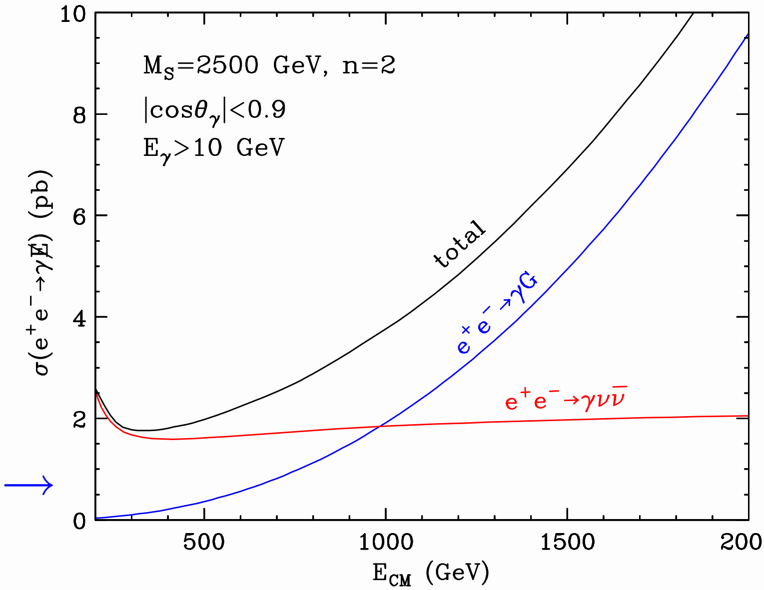
  - different conventions how to deal with the UV cut-off
    ($Q_{\rm cut}$ related to D-dimensional Planck scale)
    $\rightarrow$ most common conventions have been implemented
- Real Gravitons:
  Summation performed as a phase space integral

The ADD model of Large Extra Dimensions

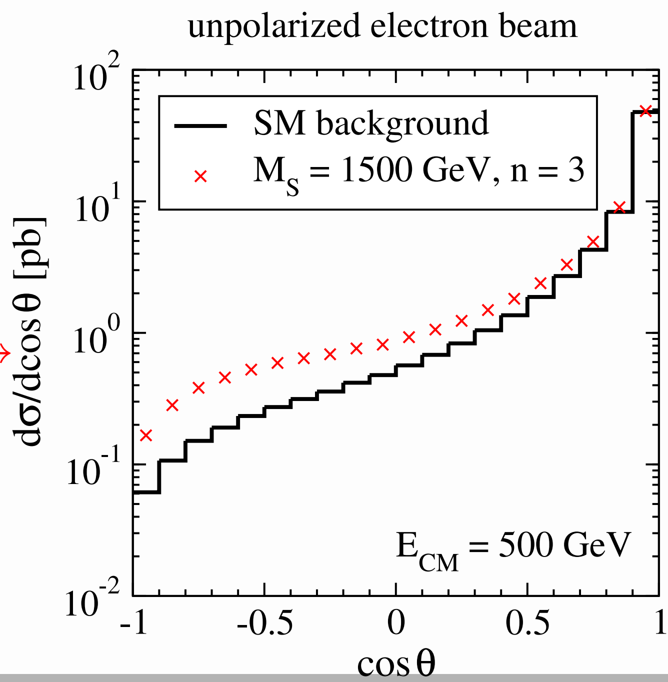


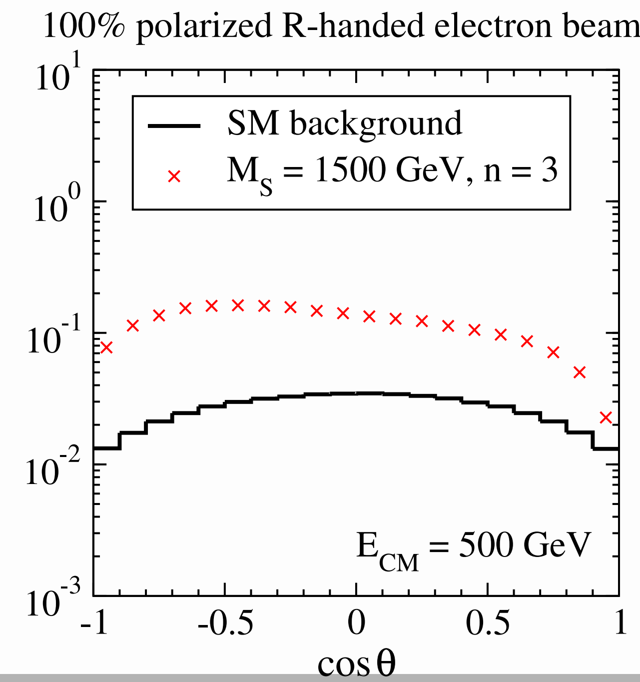
$\leftarrow e^+e^- \to \mu^+\mu^-$

$e^+e^- \to \gamma$ Graviton $\to$



$e^+e^- \to W^+W^- \to$





Anomalous electroweak gauge couplings

- Triple gauge couplings: Hagiwara et al., Nuclear Physics B282 (1987) 253-307
  Most general effective Lagrangian ($V = \gamma/Z$):

$$
\begin{aligned}
\mathcal{L}_{WWV} \quad \propto \quad & i g_1^V \left(W^\dagger_{\mu\nu} W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu} \right) + i\kappa_V W^\dagger_\mu V_\nu W^{\mu\nu} \\
& + \frac{i\lambda_V}{m_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu V^{\nu\lambda} - g_4^V W^\dagger_\mu W_\nu \left(\partial^\mu V^\nu + \partial^\nu V^\mu \right) \\
& + g_5^V \epsilon^{\mu\nu\rho\sigma} \left(W^\dagger_\mu \overleftrightarrow{\partial}_\rho W_\nu \right) V_\sigma + \frac{i\tilde{\kappa}_V}{2} \epsilon^{\mu\nu\rho\sigma} W^\dagger_\mu W_\nu V_{\rho\sigma} \\
& + \frac{i\tilde{\lambda}_V}{2m_W^2} \epsilon^{\mu\nu\rho\sigma} W^\dagger_{\mu\lambda} W^\lambda_\nu V_{\rho\sigma}
\end{aligned}
$$

  - So far implemented:
    Terms $\propto \; g_1^V, \; \kappa_V, \; \lambda_V, \; g_4^V$
    (SM @ tree level: $g_1^V = \kappa_V = 1, \; \lambda_V = g_4^V = 0$)
  - CP-violating terms ($\propto \; \epsilon^{\mu\nu\rho\sigma}$) are in preparation

Anomalous electroweak gauge couplings

- Quadruple gauge couplings: Longhitano, Nucl. Phys. B188 (1981) 118; Gangemi et al. hep-ph/001065

Effective Lagrangian for HO interaction with heavy Higgs boson

$$\mathcal{L}_4 = \alpha_4 g^4 \left(\frac{1}{2} W^\dagger_\mu W^{\dagger\mu} W_\nu W^\nu + \frac{1}{2}(W^\dagger_\mu W^\mu)^2 + \frac{1}{c_W^2} W^\dagger_\mu Z^\mu W_\nu Z^\nu + \frac{1}{4c_W^4}(Z^\mu Z^\mu)^2 \right)$$

$$\mathcal{L}_5 = \alpha_5 \left((W^\dagger_\mu W^\mu)^2 + \frac{1}{c_W^2} W^\dagger_\mu Z^\mu W_\nu Z^\nu + \frac{1}{4c_W^4}(Z^\mu Z^\mu)^2 \right)$$

Further models (partly implemented/in preparation)

- UED, RS1, Z'
- Effective gg-Higgs coupling for SM and Susy Higgs
- R-parity violating SUSY
- Susy models with Gravitinos

Implementing new models in SHERPA

- Extension of the matrix element generator AMEGIC++ to further models is rather simple (although change of the code is still necessary)
- AMEGIC++ provides generic treatment of internal and external particles with spin 0, 1/2, 1 and 2;
  (treatment for external particles with spin-3/2 is in preparation)
- Huge list of Lorentz/Dirac structures for interaction vertices available:
  - interaction of scalars, fermions and vectors proportional to a SM or MSSM vertex
  - interaction with Gravitons via energy-momentum-tensor (used in the ADD model)

  $\rightarrow$ can be reused for many new models just by adjusting coupling constants
- In principle two major things have to be done:
  - Specification of new particles: quantum numbers, spin, mass, width
  - Specification of new interactions
- Easiest way is to start is to use an existing model as a template
- A brief tutorial can be found on the wiki-section of our home page (http://www.sherpa-mc.de)

Implementing new models in SHERPA

Sample definition of an interaction vertex: t $\to G'$ t in RS1 model

```
vertex[vanz].in[0]            = Flavour(kf::t);
vertex[vanz].in[1]            = Flavour(kf::GPrime);
vertex[vanz].in[2]            = Flavour(kf::t);

Kabbala kcpl = -g3*M_I;
Kabbala num5 = Kabbala(string("5"),5.);
vertex[vanz].cpl[0]           = (kcpl*num5).Value();   //right handed coupling
vertex[vanz].cpl[1]           = (kcpl).Value();        //left handed coupling
vertex[vanz].Str              = (kcpl*PR+kcpl*PL).String();

vertex[vanz].ncf              = 1;
vertex[vanz].Color            = new Color_Function(cf::T,1,2,0,'1','2','0');

vertex[vanz].nlf              = 1;
vertex[vanz].Lorentz          = new Lorentz_Function(lf::Gamma);
vertex[vanz].Lorentz->SetParticleArg(1);

vertex[vanz].on               = 1;
```

How will the SHERPA-framework deal with BSM-models?

- AMEGIC++ generates tree level ME implying new particles/interactions
- The phase space integrator automatically adopts to BSM resonances, masses, widths for efficient integration of corresponding XS
- Showering / Merging / Hadronization only applies to SM partons; external BSM particles will be treated as stable

  (but there is no limit on this given by the framework)
- Can be applied to study signal and background processes and to analyze effects of extra hard jets

Conclusion and outlook

- Sherpa is ready for BSM studies at LHC and ILC (signals and background)
- MSSM and ADD are fully implemented and tested
- Further models are almost ready (however some more test and completion necessary): Anomalous gauge couplings, RPV Susy, Models with Gravitinos (Spin 3/2), UED, RS1, ...
- User extendible as long as Lorentz-/Dirac-structures of propagators and vertices are available
(in principle there is no limit, however this part is quite involved!)

- The latest SHERPA version (1.0.8) is available from our homepage:

  http://www.sherpa-mc.de

  Coming soon: version 1.0.9