LHC Multi-Particle Simulation for the MSSM and beyond

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PHENO 06, 15. May 2006

Outline

New Physics at the LHC

Multi-Particle Event generators

Hard Jets and SUSY WBF

Sbottom Production at LHC

BSM Simulations beyond the MSSM

Anomalous Quartic Gauge Couplings

Summary & Outlook

Precision measurements

Hopefully: New physics signals:
$\not{E}_T$, high-p_T jets, high lepton multiplicities
but: What kind of new physics?

- Spin of all new particles (difficult at LHC!, cf. Barr/Miller/Webber et al.)
- Mass measurements to get the spectrum. Cascade decays: endpoints of energy spectra provide mass differences
- Coupling measurements: verify models by the structure of couplings
- Precise predictions for BSM processes: , these are background to other (more difficult) BSM processes
- Precise parameter values: Learn something about the UV, breaking of new symmetries, etc.
  e.g. **SPA project** EPJ C46 (2006), 43; `http://spa.desy.de/spa`

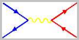
Approximations vs. Accuracy

- Radiative corrections have to be included (not only K-factors, cf. later) BUT also
- **Non-factorization of processes** into $2 \to 2$ production processes and decays *is not* sufficient. $\Rightarrow$ Include *off-shell intermediate states* and *full gauge-invariant diagram classes*
- SM *and* SUSY backgrounds (for LHC, *but also* for ILC; in general: no factorization for signal/background!
- **Large number of complicated models with complicated pheno:** Need for arbitrary, not only hard-coded processes
- Spin correlations: information about the spin of particles in cascades (0 vs. $1/2$, $3/2$?, ...)

Traditional MC generators (e.g. PYTHIA, HERWIG, SUSYGEN) limited

Overview over the Tools

New generator generation which includes *all issues* above and can handle the complexity mentioned:

-  **Helas/(S)Madgraph/MadEvent**
  K. Hagiwara, F. Maltoni, T. Plehn, D. Rainwater, T. Stelzer
  `http://www.ph.ed.ac.uk/~plehn/smadgraph/smadgraph.html`
- Ω **O'Mega/WHiZard**
  W. Kilian, T. Ohl, J. Reuter
  `http://theorie.physik.uni-wuerzburg.de/~ohl/omega/`
  `http://www-ttp.physik.uni-karlsruhe.de/whizard`
-  **Amegic++/Sherpa**
  T. Gleisberg, S. Höche, F. Krauss, T. Laubrich, S. Schumann, C. Semmling, J. Winter
  `http://www.sherpa-mc.de`

Description of the codes

Matrix element generation:

- 3 different algorithms for generation of helicity amplitudes for multi-particle processes
- elimination of redundancies in amplitudes

Phase space integration:

- 3 different but comparable approaches, based on multi-channel adaptive integration

Multi-Purpose Event Generators:

- Widths, Cross Sections and arbitrary distributions calculable
- Provide interfaces to parton showers and hadronization packages (PYTHIA); *Sherpa has its own parton shower*
- Event generation in formats that can be passed to detector simulations (like STDHEP, HEPEVT)

Validation of codes

TESTS:

- Unitarity ($2 \to 2$, many $2 \to 3$ processes)
- Ward- and Slavnov-Tayler identities for gauge groups and SUSY (Ohl/JR, EPJ C30, 525)
- Comparison of the different programs

Validation of codes

K. Hagiwara/W. Kilian/F. Krauss/T. Ohl/T. Plehn/D. Rainwater/JR/S. Schumann, PRD 73, 055005 (2006)

Aim: Test ALL SUSY couplings of phenomenological relevance

- Initial states: 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
- Final states: All combinations of SUSY particles and Higgs bosons

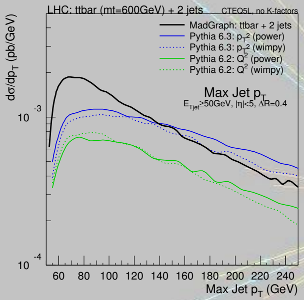
http://www-ttp.physik.uni-karlsruhe.de/~reuter/susy_comparison.html

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

$ff \to X$								
Process	stat.	Madgraph/Helas		Whizard/O'Mega		Sherpa/A'Megic		
		0.5 TeV	2 TeV	0.5 TeV	2 TeV	0.5 TeV	2 TeV	
$e^-e^- \to \tilde{e}_L\tilde{e}_L$	●	520.30(4)	36.83(3)	520.31(3)	36.836(2)	520.32(3)	36.832(2)	
$e^-e^- \to \tilde{e}_R\tilde{e}_R$	●	459.6(1)	28.65(3)	459.59(1)	28.650(3)	459.63(3)	28.651(2)	
$e^-e^- \to \tilde{e}_L\tilde{e}_R$	●	160.04(1)	56.55(2)	159.96(2)	56.522(8)	160.04(2)	56.545(3)	
$uu \to \tilde{u}_L\tilde{u}_L$	●	—	716.9(1)	—	716.973(4)	—	716.99(4)	
$uu \to \tilde{u}_R\tilde{u}_R$	●	—	679.6(1)	—	679.627(4)	—	679.54(4)	
$uu \to \tilde{u}_L\tilde{u}_R$	●	—	1212.52(6)	—	1212.52(5)	—	1212.60(6)	
$dd \to \tilde{d}_L\tilde{d}_L$	●	—	712.6(1)	—	712.668(4)	—	712.68(4)	
$dd \to \tilde{d}_R\tilde{d}_R$	●	—	667.4(1)	—	667.448(4)	—	667.38(3)	
$dd \to \tilde{d}_L\tilde{d}_R$	●	—	1206.22(6)	—	1206.22(5)	—	1206.30(7)	

Adapt PYTHIA showers to exact results on jet radiation

Plehn/Rainwater/Skands, hep-ph/0510144



- large number of hard jets in SUSY QCD production
- correct description of spectra for $p_T > 100\,\text{GeV}$ needs hard matrix elements

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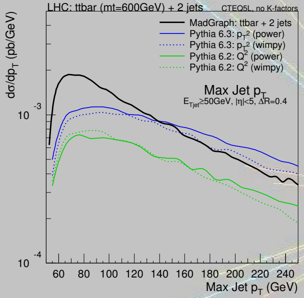

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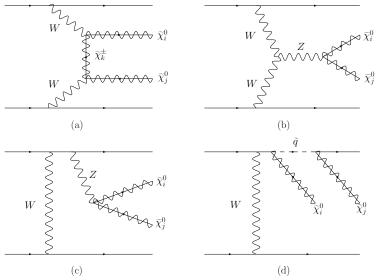
EW SUSY pairs in Weak Boson Fusion at LHC:

Cho *et al.*, Phys.Rev.D73 (2006), 054002



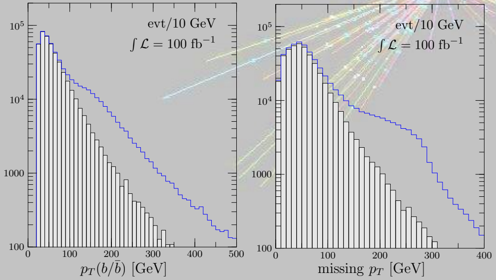
- Production of $\chi_i^0\chi_j^0$, $\chi_i^0\chi_j^\pm$, $\chi_i^\pm\chi_j^\mp$, $\chi_i^\pm\chi_j^\pm$, $\tilde\ell^+\tilde\ell^-$, $\tilde\nu_\ell\tilde\ell^+$
- For SPS points rates are very small
- Exception: $\chi_i^+\chi_j^+$

Sbottom Production at LHC

Hagiwara et al., PRD 73 (2006), 055005

$\tilde{b}_1$ production with subsequent decay $\tilde{b}_1 \to \tilde{\chi}^0_1 b$
Parameter point with

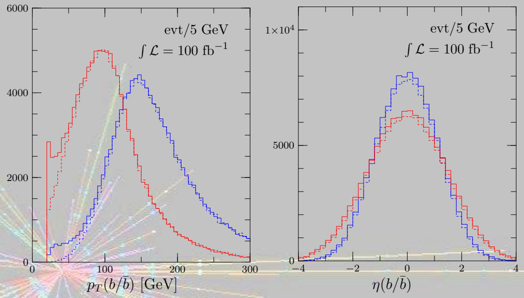
- Light LSP: $m(\tilde{\chi}^0_1) \approx 47\,\text{GeV}$
- Light Sbottom: $m(\tilde{b}_1, \tilde{b}_2) \approx 295/400\,\text{GeV}$, $m(\tilde{q}) \sim 430\,\text{GeV}$
- Large invisible Higgs decay: BR$(H \to \tilde{\chi}^0_1 \tilde{\chi}^0_1) \sim 0.45$
- Cuts: $p_{T,b} > 20\,\text{GeV}$, $|\eta_b| < 4$, and $\Delta R_{bb} > 0.4$.



- Parton level distribution
- Main SM bkgd: $gg \to b\bar{b}\nu\bar{\nu}$
- Signal jets are harder

Off-Shell Effects at the LHC:

- Both b jets are quite hard
- PS: harder jet is more central
- Off-shell effects ($b\bar{b}Z^*$): $\sigma = 1120\,\text{fb} \to 1177\,\text{fb}$, sizeable in low $p_{T,b}$ $\longrightarrow$ can be cut out here
- No guarantee in general



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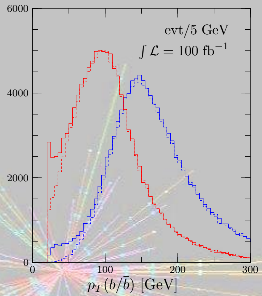
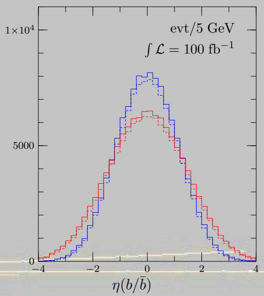




Proc.	$\sigma_{2\to2}$[fb]	$\sigma\times$ BR [fb]	σ_{BW} [fb]	$\sigma^{\text{cut}}_{\text{BW}}$ [fb]
Zh	20.574	1.342	1.335	0.009
HA	5.653	0.320	0.314	0.003
$\tilde{\chi}^0_1\tilde{\chi}^0_2$	69.106	13.078	13.954	0.458
$\tilde{\chi}^0_1\tilde{\chi}^0_3$	24.268	3.675	4.828	0.454
$\tilde{\chi}^0_1\tilde{\chi}^0_4$	19.337	0.061	0.938	0.937
$\tilde{b}_1\tilde{b}^*_1$	4.209	0.759	0.757	0.451
Sum		**19.238**	**22.129**	**2.314**
Exact			**19.624**	**0.487**

Take a look to the ILC:

- Analogous process: $e^+e^- \to b\bar{b}\tilde{\chi}^0_1\tilde{\chi}^0_1$ @ 800 GeV
- Cuts on $M_{b\bar{b}}$ to remove resonances

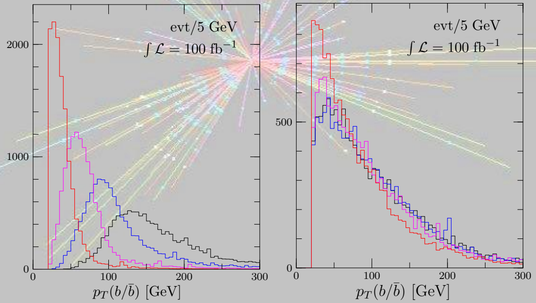
Bottom-Jet Radiation

- Study $g \to b\bar{b}$ splitting, i.e. b ISR as a combinatorial bkgd.

$pp \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 b\bar{b}b\bar{b}$: 32112 diagrams, 22 color flows, $\sim$ 4000 PS channels

- $\sigma(pp \to b\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0) = 1177\,\text{fb}$ drops to $\sigma(pp \to b\bar{b}b\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0) = 130.7\,\text{fb}$

- Forward discrimination of ISR and decay b jets difficult:



Only most forward b jet considerably softer

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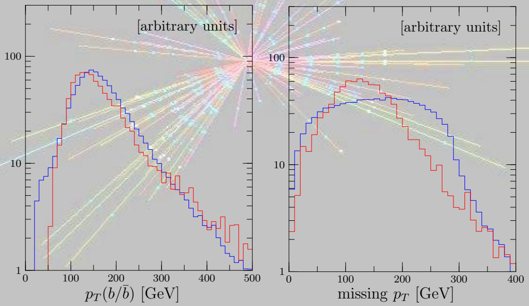
- $\sigma(pp \to b\bar{b}\tilde{\chi}^0_1\tilde{\chi}^0_1) = 1177\,\text{fb}$ drops to $\sigma(pp \to b\bar{b}b\bar{b}\tilde{\chi}^0_1\tilde{\chi}^0_1) = 130.7\,\text{fb}$
- Only minor differences for $p_{T,b}$, peaked at lower value because of PDFs



- $\not{p}_T$ shifted to smaller momenta: light particles balance the event out

BSM Simulations beyond the MSSM

O'Mega/WHiZard Status Report: O'MEGA v. 000.011, WHIZARD v. 1.51

Preparation for joint new version: O'MEGA v. 1.0, WHIZARD v. 2.0 will be ready for SUSY/BSM Tools or MC4LHC 06-07 2006

implemented, upcoming in 1.0/2.0 version

- **Models:**
  - SM, MSSM, Anomalous Gauge Couplings
  - NMSSM, ESSM, SUSY exotics
  - Littlest Higgs, Simplest Little Higgs, T parity models
  - Xdim: RS, UED, (partly): Noncommutative Standard Model
- **Collider environments:**
  - LHC: CERNLIB, LHAPDF
  - ILC: ISR, beamstrahlung, beam energy spread
  - $\gamma\gamma$: photon structure functions

Example LHC projects: Anomalous QGC: Kilian/Mertens/JR/Schumacher, 2006, NCSM: Alboteanu, Ohl, Rückl, 2006 , RS-Gravitons: Boos/Kilian/JR, 2006, Little Higgs Pseudoaxions: Rainwater/JR, DESY-06-055

Anomalous Quartic Gauge Couplings

ILC: Beyer/Kilian/Krstonošić/Mönig/JR/Schröder/Schmidt, hep-ph/0604048

LHC: Kilian/Mertens/JR/Schumacher

Anomalous QGC parameterized by Chiral EW Lagrangian:

$$\mathcal{L}_4 = \alpha_4 \,\mathrm{tr}\,[V_\mu V_\nu]\,\mathrm{tr}\,[V^\mu V^\nu] \qquad \mathcal{L}_5 = \alpha_5 \,\mathrm{tr}\,[V_\mu V^\mu]^2$$

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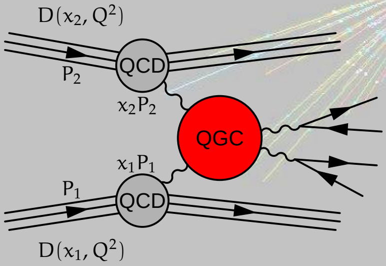
Anomalous QGC parameterized by Chiral EW Lagrangian:

$$\mathcal{L}_4 = \alpha_4 \frac{g^2}{2} \left\{ \left[(W^+ \cdot W^+)(W^- \cdot W^-) + (W^+ \cdot W^-)^2 \right] + \frac{2}{c_W^2} (W^+ \cdot Z)(W^- \cdot Z) + \frac{1}{2c_W^4} (Z \cdot Z)^2 \right\}$$

$$\mathcal{L}_5 = \alpha_5 \frac{g^2}{2} \left\{ (W^+ \cdot W^-)^2 + \frac{2}{c_W^2} (W^+ \cdot W^-)(Z \cdot Z) + \frac{1}{2c_W^4} (Z \cdot Z)^2 \right\}$$

Considered process (all leptons, including τ):



$$pp \to jj(ZZ/WW) \to jj\ell^-\ell^+\nu_\ell\bar{\nu}_\ell$$

$$\sigma \approx 40\,\text{fb}$$

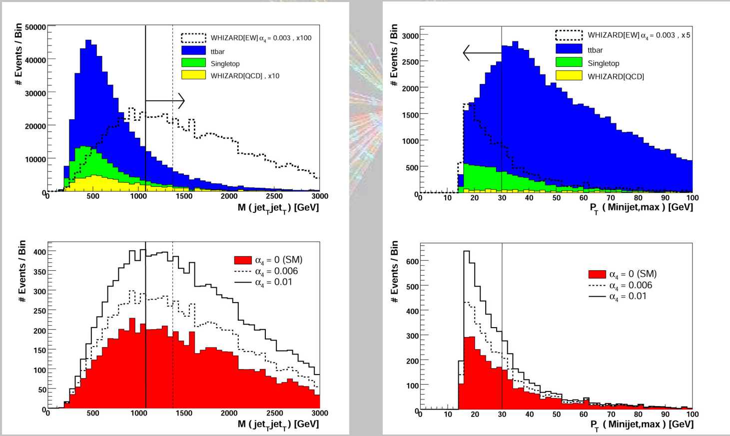
Bkgd.:

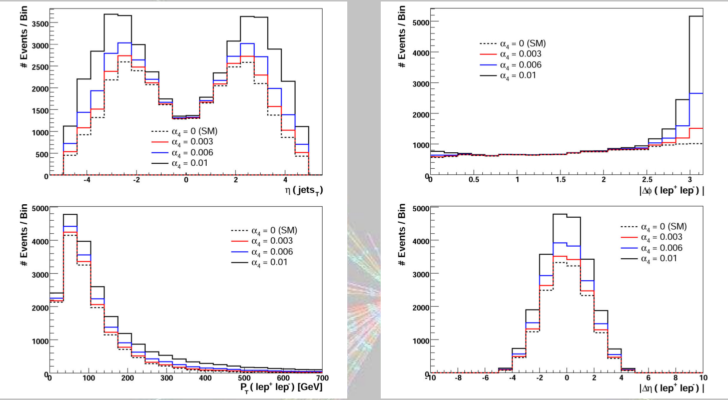
- $t\bar{t} \to WbWb$, $\sigma \approx 52$ pb
- Single t w. misrec. jet: $\sigma \approx 4.8$ pb
- QCD: $\sigma \approx 0.21$ pb

Tagging and cuts:

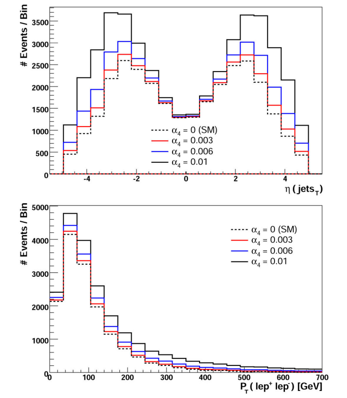
- $\ell\ell jj$ tag, $\eta_{tag}^{min} < \eta_\ell < \eta_{tag}^{max}$, veto b
- $|\Delta\eta_{jj}| > 4.4$, $M_{jj} > 1080$ GeV
- Minijet-Veto: $p_{T,j} < 30$ GeV
- $E_j > 600, 400$ GeV, $p_{T,j}^1 > 60, 24$ GeV

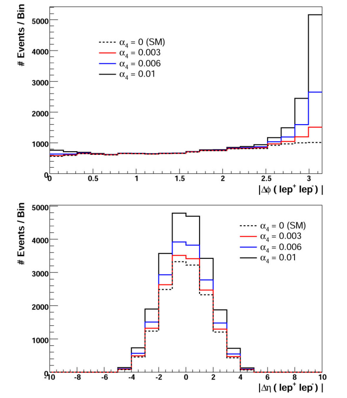
Improves $S/\sqrt{B}$ from 3.3 to 29.7.





Events / Bin
η (jets_T)
|Δφ (lep+ lep-) |
P_T (lep+ lep-) [GeV]
|Δη (lep+ lep-) |
α4 = 0 (SM)
α4 = 0.003
α4 = 0.006
α4 = 0.01

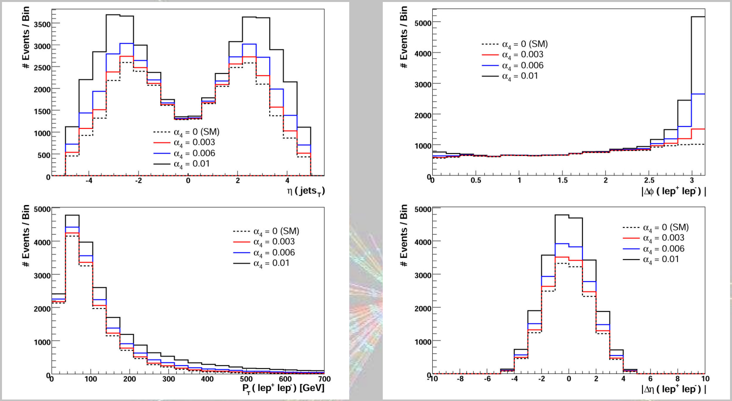




Results: (1σ sensitivity to the αs)

Coupl.	ILC (1 ab^{-1})	LHC (100 fb^{-1})
α_4	0.0088	0.00160
α_5	0.0071	0.00098

Caveat: Results for LHC preliminary...



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Bounds on Λ [TeV]:

Spin	$I = 0$	$I = 1$	$I = 2$
0	1.39	1.55	1.95
1	1.74	2.67	–
2	3.00	3.01	5.84

◇ Next generation event generators for LHC and ILC:

`MadGraph`, `O'Mega/WHiZard`, `Sherpa`, high-level validity check passed for the MSSM

- **Study of many aspects of BSM pheno possible:**
  - Signal/Background beyond $2 \longrightarrow 2$
  - Inclusion of additional hard jets, ISR, FSR
  - Systematic inclusion of: Off-shell effects, non-resonant contributions, interferences, spin correlations
- **Codes are easily extendable:**
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- Next step: Match higher-order corrections with multi-particle final states (Frixione, Webber: MC@NLO, Kilian/JR/Robens)

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