Multi-Particle SUSY Simulations at LHC & ILC — Off-Shell Effects, interferences and radiative corrections

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Hagiwara/Kilian/Krauss/Ohl/Plehn/Rainwater/JR/Schumann **PRD 73** (2006), 055005;
JR et al., hep-ph/0512012; work in progress: Alwall/Plehn/Rainwater/JR/Schumann

Karlsruhe, July 27th, 2007

SUSY Precision Measurements and Simulations

Motivation for SUSY: if needed, you're are on wrong conference

Analysis Goal:

- Mass measurements to get the spectrum
- Access spin of all new particles: angular/spin correlations
- Coupling measurements: verify SUSY by the structure of couplings

Precise predictions for SUSY processes:

- background to other (more difficult) SUSY processes
- SUSY breaking/GUT parameters $\Rightarrow$ **SPA project** `http://spa.desy.de/spa`

Corrections to the SUSY processes fall into six categories:

1) Loop corrections to SUSY production and decay processes
2) real photon [gluon] radiation Kilian/JR/Robens, EPJ C48 (2006), 389, cf. T. Robens' talk
3) nonfactorizable, max. resonant γ exchange between production/decay
4) off-shell kinematics for the signal process see also Berdine/Rainwater/Kauer, 2007
5) irreducible background from all other SUSY processes
6) reducible, experimentally indistinguishable SM background processes

Classification of approximations in (SUSY) processes

Some generic SUSY process:

$e^+e^- \to b\bar{b}e^+e^-\tilde{\chi}^0_1\tilde{\chi}^0_1$ 66478 diagrams. (It's just $e^+e^- \to \tilde{\chi}^0_2\tilde{\chi}^0_2$!)

- Entanglement of different signal diagrams ($e^+e^- \to \tilde{\chi}^0_i\tilde{\chi}^0_j, \tilde{b}_i\tilde{b}_j, \tilde{e}_i\tilde{e}_j$)
- Need for cuts to disentangle those (experimentally/simulation)
- Add SM backgrounds ($e^+e^- \to b\bar{b}e^+e^-\nu_i\bar{\nu}_i$)
- Much more complicated processes for LHC, and even also for ILC

Process $A_1A_2 \to P^{(*)} \to F_1F_2$, 3 different levels:

Narrow width	$\sigma(A_1A_2 \to P) \times \mathrm{BR}(P \to F_1F_2)$
Breit-Wigner	$\sigma(A_1A_2 \to P) \times \frac{M_P^2\Gamma_P^2}{(s-M_P^2)^2+\Gamma_P^2M_P^2} \times \mathrm{BR}(P \to F_1F_2)$
Full matrix element	$\sigma(A_1A_2 \to F_1F_2)$

last level *not* featured by ISAJET, PYTHIA, HERWIG, SUSYGEN

The generator generator O'Mega Ω / Whizard

Matrix Element Generator O'Mega: Ohl, 2000/01; M.Moretti/Ohl/JR, 2001; JR, 2002

Optimized helicity amplitudes: avoiding all redundancies

Multi-purpose Event Generator Whizard: Ohl, 1996; Kilian, 2000; Kilian/Ohl/JR, 2007

- Multi-Channel adaptive Monte-Carlo integration
- Generator generator for arbitrary multi-particle processes
- Well-suited for ILC physics (ISR, beamstrahlung); used for ILC reference event files
- **New release next month: Whizard 2.0/O'Mega 1.0**
  - Fancier support for full color flows
  - LHAPDF support
  - new BSM models: extMSSM, ext.Dim., Little Higgs, NCSM
  - new syntax for arbitrary cut functions
- Virtual (SUSY) Corrections (all $2 \to 2$ processes for ILC)
- Future features: Parton Shower/Matrix Element matching

Tests and Checks of MSSM implementation

JR et al., 2005; Hagiwara/Kilian/Krauss/Ohl/Plehn/Rainwater/JR/Schumann, 2006

– MSSM: doubled spectrum, 100 parameters, 5000 vertices

– Unitarity checks: $\sigma(2 \to 2, s), \sigma(2 \to 3, s) \sim const$ or $1/s$ ✓

– Gauge invariance: Ward- and Slavnov-Taylor identities ✓

– Supersymmetry: Ward-/Slavnov-Taylor identities ✓ JR, 2002; Ohl/JR, 2002

– Comparison of codes ($\mathcal{O}(600)$ processes): JR et al., 2005; K. Hagiwara/.../JR/..., 2006

Reference: http://james.physik.uni-freiburg.de/~reuter/susy_comparison.html

$\tau^+\tau^- \to X$

Process	status	Madgraph/Helas 0.5 TeV	Madgraph/Helas 2 TeV	Whizard/O'Mega 0.5 TeV	Whizard/O'Mega 2 TeV	Sherpa/A'Megic 0.5 TeV	Sherpa/A'Megic 2 TeV
$\tilde\tau_1\tilde\tau_1^*$	●	257.57(7)	79.63(4)	257.32(1)	79.636(4)	257.30(1)	79.638(4)
$\tilde\tau_2\tilde\tau_2^*$	●	46.55(1)	66.86(2)	46.368(2)	66.862(3)	46.372(2)	66.862(3)
$\tilde\tau_1\tilde\tau_2^*$	●	95.50(3)	19.00(1)	94.637(3)	19.0015(8)	94.645(5)	19.000(1)
$\tilde\nu_\tau\tilde\nu_\tau^*$	●	502.26(7)	272.01(8)	502.27(2)	272.01(1)	502.30(3)	272.01(1)
$\tilde\chi_1^0\tilde\chi_1^0$	●	249.94(2)	26.431(1)	249.954(9)	26.431(1)	249.96(1)	26.431(1)
$\tilde\chi_1^0\tilde\chi_2^0$	●	69.967(3)	9.8940(3)	69.969(2)	9.8940(4)	69.968(3)	9.8937(5)
$\tilde\chi_1^0\tilde\chi_3^0$	●	17.0387(3)	0.7913(1)	17.0394(1)	0.79136(2)	17.040(1)	0.79137(5)
$\tilde\chi_1^+\tilde\chi_1^-$	●	185.09(3)	45.15(1)	185.093(6)	45.147(2)	185.10(1)	45.151(2)
h^0h^0	●	0.3533827(3)	0.0001242(2)	0.35339(2)	0.00012422(3)	0.35340(2)	0.000124218(6)
A^0A^0	●	—	0.07975(3)	—	0.079758(6)	—	0.079744(4)
Zh^0	●	59.591(3)	3.1803(8)	59.589(3)	3.1802(1)	59.602(3)	3.1829(2)
ZA^0	●	2.9915(4)	4.682(5)	2.99162(9)	4.6821(3)	2.9917(2)	4.6817(2)

Parameter point under consideration

Following discussions do not depend on the special parameter point

SUGRA-inspired point, non-universal right-handed scalar masses

$\tan\beta = 20$

Particle	M [GeV]	Γ [GeV]	Particle	M [GeV]	Γ [GeV]
h	114.45	0.0050	$\tilde{\chi}_1^0$	46.84	—
H	300.15	2.2924	$\tilde{\chi}_2^0$	112.41	0.00005
A	300.00	2.7750	$\tilde{\chi}_3^0$	148.09	0.01162
$H^\pm$	310.96		$\tilde{\chi}_4^0$	236.77	1.0947
$\tilde{b}_1$	295.36	0.5395	$\tilde{\chi}_1^\pm$	106.60	
$\tilde{b}_2$	399.92	3.4956	$\tilde{\chi}_2^\pm$	237.25	
$\tilde{e}_L$	205.02		$\tilde{t}_1$	413.84	
$\tilde{e}_R$	205.65		$\tilde{t}_2$	978.88	

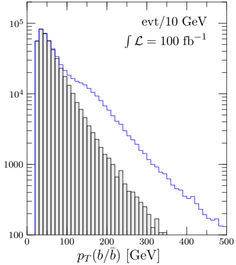
- (Very) light Higgs, directly above LEP limit
- $h \sim 47$ % invisible decays to LSP
- $m_{\tilde{q}} \sim 430$ GeV
- Light sbottoms accessible at the ILC
- Low-energy data-compatible: $b \to s\gamma$, $B_s \to \mu^+\mu^-$, $\Delta\rho$, $g_\mu - 2$, CDM

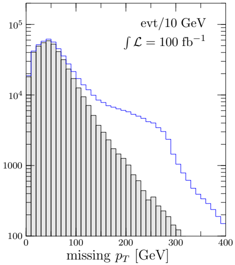
- Focus on BR$(\tilde{b}_1 \to b\tilde{\chi}_1^0) = 43.2\%$

Sbottom production at the LHC

Hagiwara/.../JR/..., 2006

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





Parton-level distributions

$pp \to b\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0$

Cuts: $p_{T,b} > 20$ GeV, $|\eta_b| < 4$, and $\Delta R_{bb} > 0.4$.

Main bkgd: $gg \to b\bar{b}\nu\bar{\nu}$

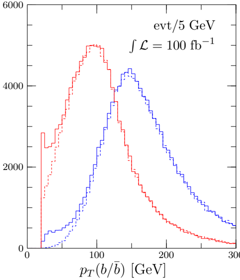
Signal jets harder

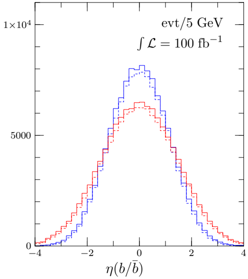
Off-Shell Effects at the LHC:

PS: harder jet more central

Off-Shell effects ($b\bar{b}Z^*$): only low-$p_{T,b}$ $\longrightarrow$ is cut out

(Un)lucky case !!





Real corrections: Bottom-jet radiation

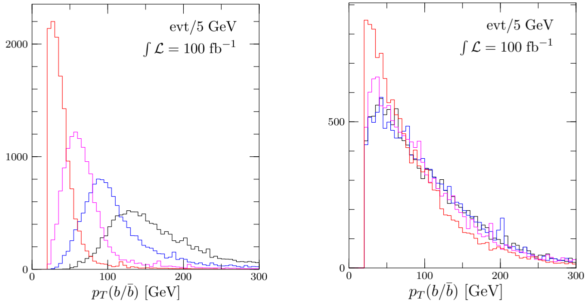
K. Hagiwara/.../JR/..., 2006

$g \to b\bar{b}$-splitting, b-ISR as combinatorial background

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

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

Forward discrimination of ISR and decay jets difficult:



Only the most forward jet considerably softer

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K. Hagiwara/…/JR/…, 2006

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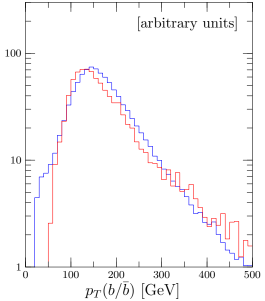
Only marginal differences in $p_{T,b}$, PDF: Maximum at lower value



shifted to lower $\not{p}_T$: light particles balance out event

Sbottom production at the ILC

Cross sections for $\sqrt{s} = 800$ GeV

- In contrast to the LHC: Electroweak production
- More channels contribute to $e^+e^- \to b\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0$:
  $e^+e^- \to Zh, ZH, Ah, HA, \tilde{\chi}_1^0\tilde{\chi}_2^0, \tilde{\chi}_1^0\tilde{\chi}_3^0, \tilde{\chi}_1^0\tilde{\chi}_4^0, \tilde{b}_1\tilde{b}_1^*, \tilde{b}_1\tilde{b}_2^*$ (412 diagrams)
- Irreducible SM background: $e^+e^- \to b\bar{b}\nu_i\bar{\nu}_i$ (WW fusion, Zh, ZZ) (47 diagrams)

Channel	$\sigma_{2\to 2}$ [fb]	$\sigma \times$ BR [fb]	σ_{BW} [fb]
Zh	20.574	1.342	1.335
ZH	0.003	0.000	0.000
hA	0.002	0.001	0.000
HA	5.653	0.320	0.314
$\tilde{\chi}_1^0\tilde{\chi}_2^0$	69.109	13.078	13.954
$\tilde{\chi}_1^0\tilde{\chi}_3^0$	24.268	3.675	4.828
$\tilde{\chi}_1^0\tilde{\chi}_4^0$	19.337	0.061	0.938
$\tilde{b}_1\tilde{b}_1$	4.209	0.759	0.757
$\tilde{b}_1\tilde{b}_2$	0.057	0.002	0.002
Sum		19.238	22.129
Exact			19.624
w/ISR			22.552

Channel	$\sigma_{2\to 2/3}$ [fb]	$\sigma \times$ BR [fb]	σ_{BW} [fb]
ZZ	202.2	12.6	13.1
Zh	20.6	1.9	1.9
ZH	0.0	0.0	0.0
$Z\bar{\nu}\nu$	626.1	109.9	111.4
$h\bar{\nu}\nu$	170.5	76.5	76.4
$H\bar{\nu}\nu$	0.0	0.0	0.0
Sum		186.5	187.7
Exact			190.1
w/ISR			174.2

- Use widths to the same order as your process

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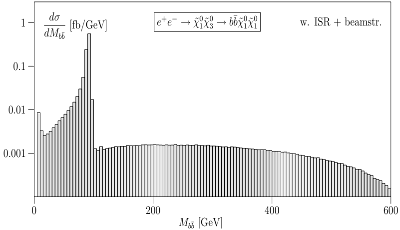
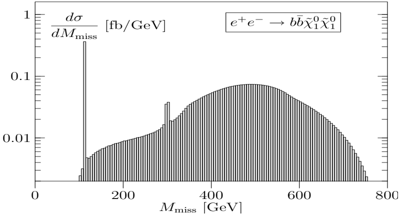
ILC Results

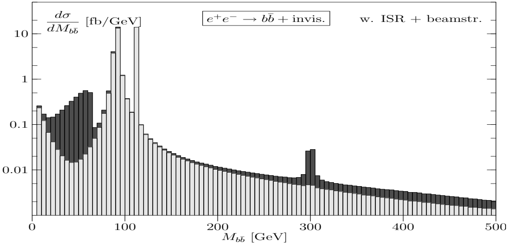
Off-shell decay $\tilde{\chi}^0_3 \to (\tilde{b}_1)_{off}\bar{b} \to b\bar{b}\tilde{\chi}^0_1$ gives broad continuum





ISR/beamstrahlung: corrections of same order (effects all p_{miss} observables)

$b\bar{b}$ invariant mass with SM background:



Cut out the resonances

$M_{b\bar{b}} < 150$ GeV

250 GeV $< M_{b\bar{b}} <$ 350 GeV

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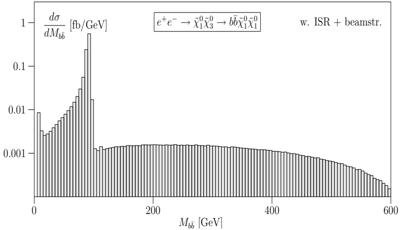

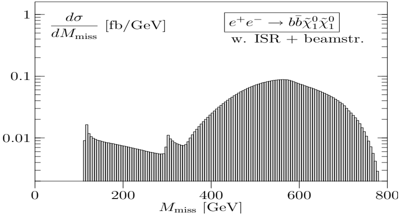

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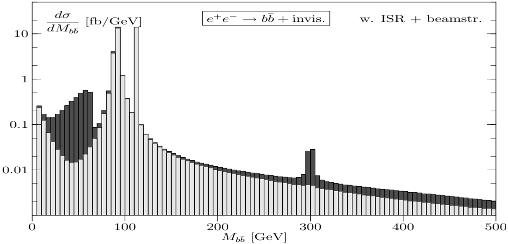

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ILC Results: Isolation of the Signal

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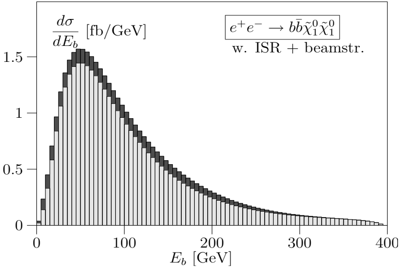
$Z\bar{\nu}\nu$	111.4	2.114
$h\bar{\nu}\nu$	76.4	0.002
$H\bar{\nu}\nu$	0.0	0.000
Sum	187.7	2.117
Exact	190.1	1.765
w/ISR	174.2	1.609

Channel	σ_{BW} [fb]	σ_{BW}^{cut} [fb]
Zh	1.335	0.009
HA	0.314	0.003
$\tilde{\chi}_1^0\tilde{\chi}_2^0$	13.954	0.458
$\tilde{\chi}_1^0\tilde{\chi}_3^0$	4.828	0.454
$\tilde{\chi}_1^0\tilde{\chi}_4^0$	0.938	0.937
$\tilde{b}_1\tilde{b}_1$	0.757	0.451
$\tilde{b}_1\tilde{b}_2$	0.002	0.001
Sum	22.129	**2.314**
Exact	19.624	**0.487**
w/ISR	22.552	**0.375**

$\tilde{b}_1 \to b\tilde{\chi}_1^0$ decay kinematics affected



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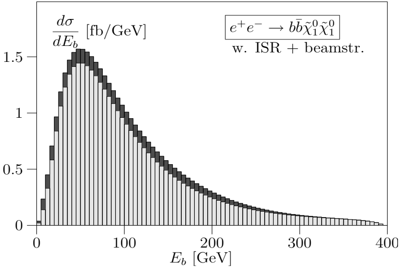
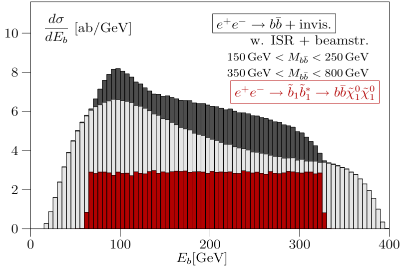




Big Off-Shell/Interference Effects at LHC

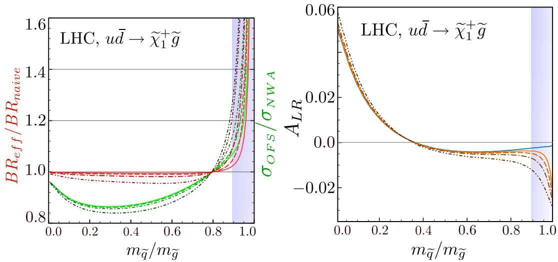
Berdine et al., 2007; Alwall/.../JR, in prep.

Off-Shell Effects in SUSY/general BSM:

- Decay chains w/ nearly-degenerate mother/daughter
- Decay matrix element: shifts q^2-dependence of propagators
- Decay thresholds: Γ/M enhanced by $1/\beta^n$
- Interference of non-resonant contributions

Large effects occur:

- Effective BRs (defined via excl. final states) deviate by up to $\mathcal{O}(100\,\%)$
- Charge asymmetries in decays: e.g. $\tilde{g}\tilde{g} \to b\tilde{b}_1^* b\tilde{b}_1^* \,/\, \bar{b}\tilde{b}_1\bar{b}\tilde{b}_1$
- Chirality asymmetries: e.g. $\tilde{g}\tilde{g} \to \tilde{q}_L\tilde{q}_L jj \,/\, \tilde{q}_R\tilde{q}_R jj$



Summary & Outlook

Precision predictions for SUSY pheno are important

- Higher orders: virtual corrections
- Higher orders: real corrections

Factorization in $2 \to 2$ production and decay insufficient/wrong

Off-shell effects and interferences affect results (especially with cuts)

Use full matrix elements

Tools are available for ILC/LHC: Whizard/O'Mega

`http://james.physik.uni-freiburg.de/~reuter`

Reconsider all edge structures [LHC]: Alwall/Plehn/Rainwater/JR/Schumann

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