Introducing a New Generation of Generators:

Off-Shell Effects in SUSY Processes at the ILC

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ECFA ILC Workshop, Vienna
November 2005

in collaboration with:
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SUSY Simulations

Leading-Order Picture: SUSY Processes at colliders factorize into particle (pair) production and subsequent (cascade) decays, leading to multi-fermion final states that contain at least two LSPs

This picture is successfully implemented in various event generators. Straightforward to use for experimental analyses (e.g., TESLA TDR, Snowmass, . . .).

But:

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$O(\alpha)$: Loop corrections to the maximally resonant (i.e., signal) process

$O(\alpha)$: Nonfactorizable, but maximally resonant photon exchange between production and decay

$O(\alpha)$: Real radiation of photons

$O(\alpha)$: Off-shell kinematics for the signal process

$O(\alpha)$: Irreducible background from other SUSY processes: nonresonant continuum

$O(\alpha)$: Reducible (but in practice irreducible) background from SM processes: nonresonant continuum

This has to be available in the form of event generators that account for both SM and SUSY.

SUSY Simulations

There exist a few event generators for SM processes that account for all of these effects. Nothing for SUSY processes.

The tasks:

- Event generation including loop corrections for SUSY signals: $\rightarrow$ talk by Tania Robens
- Event generation with off-shell SUSY signals and complete continuum background: this talk
- Combine both: To Be Done.

The physical question:

How relevant is this, and how does it influence the analysis of SUSY processes at the ILC?

To get a feeling, we looked at a nontrivial physical process: Sbottom pair production

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$$e^+e^- \to b\bar{b}e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0 \qquad \text{66478 diagrams}$$

New Generation of SUSY Event Generators

For some time, programs have been available that can handle that for the SM. We just had to implement the MSSM. This project has been initiated, independently, by three groups:

O'Mega/WHIZARD by W. Kilian, T. Ohl, J. Reuter

Originally: event generator for electroweak multi-particle processes at TESLA

MadGraph/MadEvent by K. Hagiwara, F. Maltoni, T. Plehn, D. Rainwater, T. Stelzer

Originally: graph generator for tree-level QCD amplitudes

Amegic++/Sherpa by T. Gleisberg, S. Hoeche, F. Krauss, T. Laubrich, S. Schumann, C. Semmling, J. Winter

Originally: event generator that interfaces improved QCD parton showers

Present Status:

The SUSY implementation is complete. All programs now support the full MSSM, have exact color treatment, account for LHC and ILC processes, interface parton shower and hadronization, etc.

Official versions are about to be released.

[Note: SUSY-versions of CompHEP and GRACE also exist, but don't deal with 6+ fermions in the final state]

The Gory Details

Implementing the MSSM is straightforward, but tedious. There will be mistakes in

- Writing down the SUSY Lagrangian
- Rotating every field into the on-shell basis
- Deriving the Feynman rules from that
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Therefore: detailed cross-check and comparison of the three codes.

1. Self-consistency checks: High-energy unitarity, Ward and ST identities
2. Numerical comparison of cross sections for several hundred $2 \to 2$ SUSY processes, using a common SLHA input file (SPS1a) and SM parameter set.
3. Detailed error tracing for all suspicious cases

Note: From the SUSY Lagrangian conventions to the matrix element generation, helicity amplitude libraries and phase space sampling, the programs are completely independent.

Comparison Results

For instance:

$e^+e^- \to X\ (I)$							
Final state	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
$\tilde{e}_L\tilde{e}_L^*$	●	54.687(2)	78.864(6)	54.687(3)	78.866(4)	54.6890(7)	78.8670(8)
$\tilde{e}_R\tilde{e}_R^*$	●	274.69(2)	91.776(8)	274.682(1)	91.776(5)	274.695(3)	91.778(1)
$\tilde{e}_L\tilde{e}_R^*$	●	75.168(5)	7.237(1)	75.167(3)	7.2372(4)	75.1693(7)	7.23744(7)
$\tilde{\mu}_L\tilde{\mu}_L^*$	●	22.5471(7)	6.8263(2)	22.5478(9)	6.8265(3)	22.5482(2)	6.82638(7)
$\tilde{\mu}_R\tilde{\mu}_R^*$	●	51.839(2)	5.8107(2)	51.837(2)	5.8105(2)	51.8401(5)	5.81085(6)
$\tilde{\tau}_1\tilde{\tau}_1^*$	●	55.582(2)	5.7139(2)	55.580(2)	5.7141(2)	55.5835(6)	5.71399(6)
$\tilde{\tau}_2\tilde{\tau}_2^*$	●	19.0161(6)	6.5047(2)	19.0174(7)	6.5045(3)	19.0163(2)	6.50473(7)
$\tilde{\tau}_1\tilde{\tau}_2^*$	●	1.4118(4)	0.21406(1)	1.41191(5)	0.214058(8)	1.41187(1)	0.214067(2)
$\tilde{\nu}_e\tilde{\nu}_e^*$	●	493.35(2)	272.15(2)	493.38(2)	272.15(1)	493.358(5)	272.155(3)
$\tilde{\nu}_\mu\tilde{\nu}_\mu^*$	●	14.8632(4)	2.9231(1)	14.8638(6)	2.9232(1)	14.8633(1)	2.92309(3)
$\tilde{\nu}_\tau\tilde{\nu}_\tau^*$	●	15.1399(5)	2.9246(1)	15.1394(8)	2.9245(1)	15.1403(2)	2.92465(3)
$\tilde{u}_L\tilde{u}_L^*$	●	—	7.6185(2)	—	7.6188(3)	—	7.61859(8)
$\tilde{u}_R\tilde{u}_R^*$	●	—	4.6933(1)	—	4.6935(2)	—	4.69342(5)
$\tilde{c}_L\tilde{c}_L^*$	●	—	7.6185(2)	—	7.6182(3)	—	7.61859(8)
$\tilde{c}_R\tilde{c}_R^*$	●	—	4.6933(1)	—	4.6933(2)	—	4.69342(5)
$\tilde{t}_1\tilde{t}_1^*$	●	—	5.9845(4)	—	5.9847(2)	—	5.98459(6)
$\tilde{t}_2\tilde{t}_2^*$	●	—	5.3794(3)	—	5.3792(2)	—	5.37951(6)
$\tilde{t}_1\tilde{t}_2^*$	●	—	1.2427(1)	—	1.24264(5)	—	1.24270(1)
$\tilde{d}_L\tilde{d}_L^*$	●	—	5.2055(1)	—	5.2059(2)	—	5.20563(2)
$\tilde{d}_R\tilde{d}_R^*$	●	—	1.17588(2)	—	1.17595(5)	—	1.17591(1)
$\tilde{s}_L\tilde{s}_L^*$	●	—	5.2055(1)	—	5.2058(2)	—	5.20563(2)
$\tilde{s}_R\tilde{s}_R^*$	●	—	1.17588(2)	—	1.17585(5)	—	1.17591(1)
$\tilde{b}_1\tilde{b}_1^*$	●	—	4.9388(3)	—	4.9387(2)	—	4.93883(5)
$\tilde{b}_2\tilde{b}_2^*$	●	—	1.1295(1)	—	1.12946(4)	—	1.12953(1)
$\tilde{b}_1\tilde{b}_2^*$	●	—	0.51644(3)	—	0.516432(9)	—	0.516447(6)

Sbottoms at ILC

The comparison is finished, all programs agree for all processes.

Let's do physics.

Assume that sbottoms have been discovered and measured at the LHC. Assume that they are light enough to be produced at the ILC. How will an analysis look like?

We adopt a particular SUSY parameter set with light sbottoms:

- $m_{\tilde{b}_1} = 295\,\mathrm{GeV}$ and $m_{\tilde{b}_2} = 400\,\mathrm{GeV}$ (choose $\sqrt{s} = 800\,\mathrm{GeV}$)
- $\tan\beta = 20$
- light Higgs decays to $\tilde{\chi}_1^0\tilde{\chi}_1^0$ with BR=45 %
- heavy Higgses around $300\,\mathrm{GeV}$
- $\tilde{\chi}_1^0$ is [N]LSP with $m_{\tilde{\chi}_1^0} = 47\,\mathrm{GeV}$
- charginos/neutralinos all below $250\,\mathrm{GeV}$

The set satisfies all limits and low-energy constraints. Ω_{DM} is too low, so assume LSP=gravitino.

Sbottoms at ILC

The process to look at:

$$e^+e^- \to b\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0$$

Several elementary (SUSY) processes contribute to this final state:

$$e^+e^- \to Zh,\ ZH,\ Ah,\ AH,\ \tilde{\chi}_1^0\tilde{\chi}_2^0,\ \tilde{\chi}_1^0\tilde{\chi}_3^0,\ \tilde{\chi}_1^0\tilde{\chi}_4^0,\ \tilde{b}_1\tilde{b}_1,\ \tilde{b}_1\tilde{b}_2$$

Furthermore: SM background (WW fusion to Z and h)

Neutralino Background

Describe the complete process in various approximations:

- Sum of on-shell $2 \to 2$ processes multiplied by BR: $19.2\,\mathrm{fb}$
- The same, but Breit-Wigner smeared: $+15\,\%$
- Complete tree-level result with all interferences: $-11\,\%$
- Account for resummed ISR and beamstrahlung: $+15\,\%$

For instance: Neutralino production and decay. Kinematics: $\tilde{\chi}_3^0$ decays to $100\,\%$ into $Z\tilde{\chi}_1^0$.

$b\bar{b}$ invariant mass spectrum should show Breit-Wigner shape for Z.

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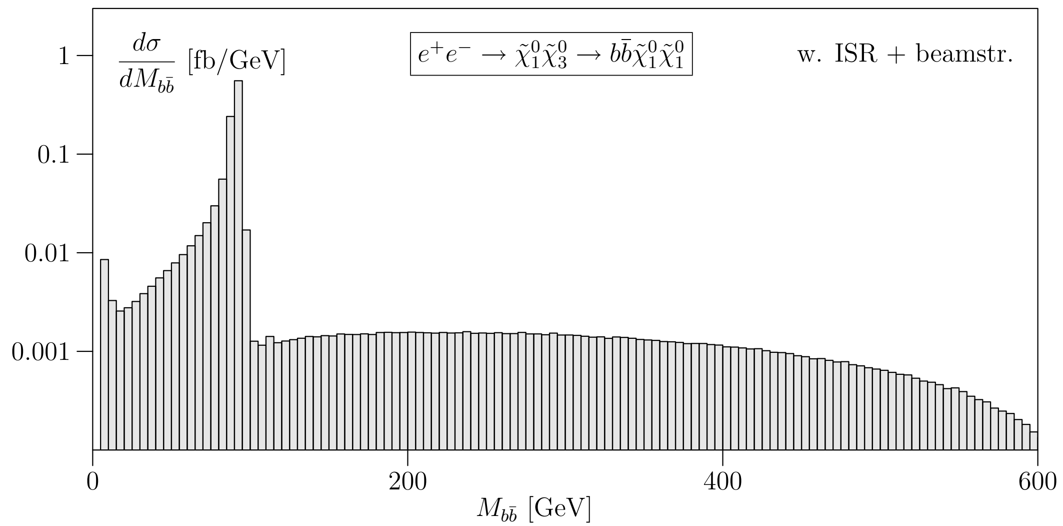
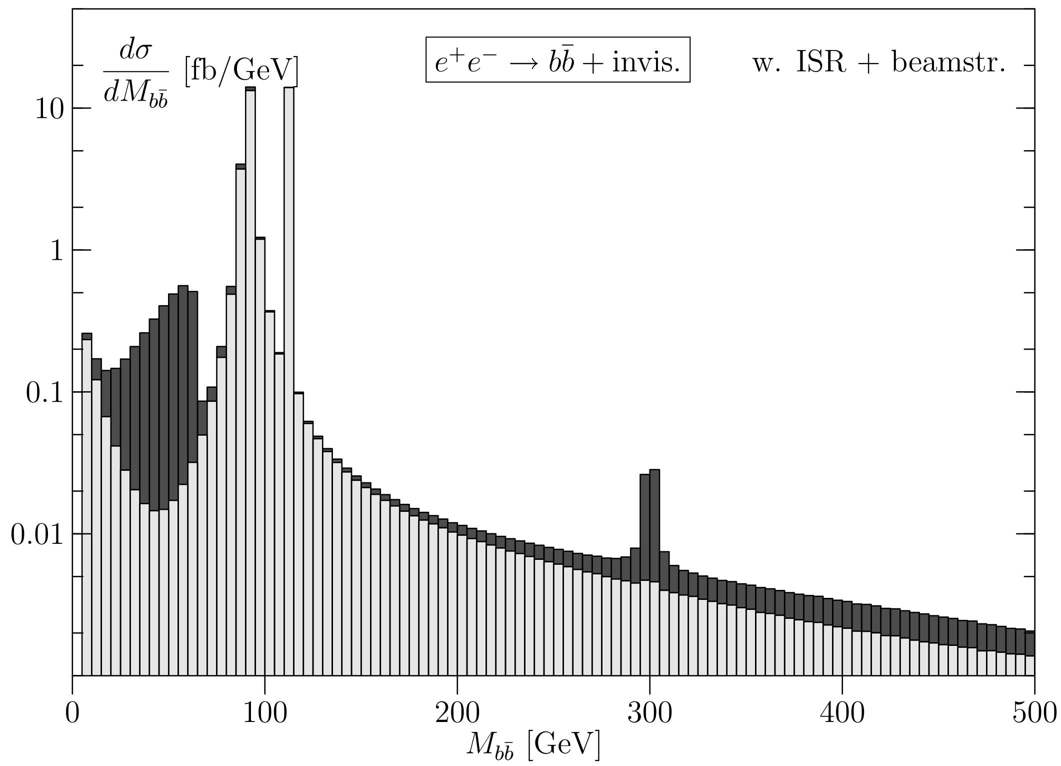


Higgs and Z background

The complete $b\bar{b}$ invariant mass spectrum looks like this:

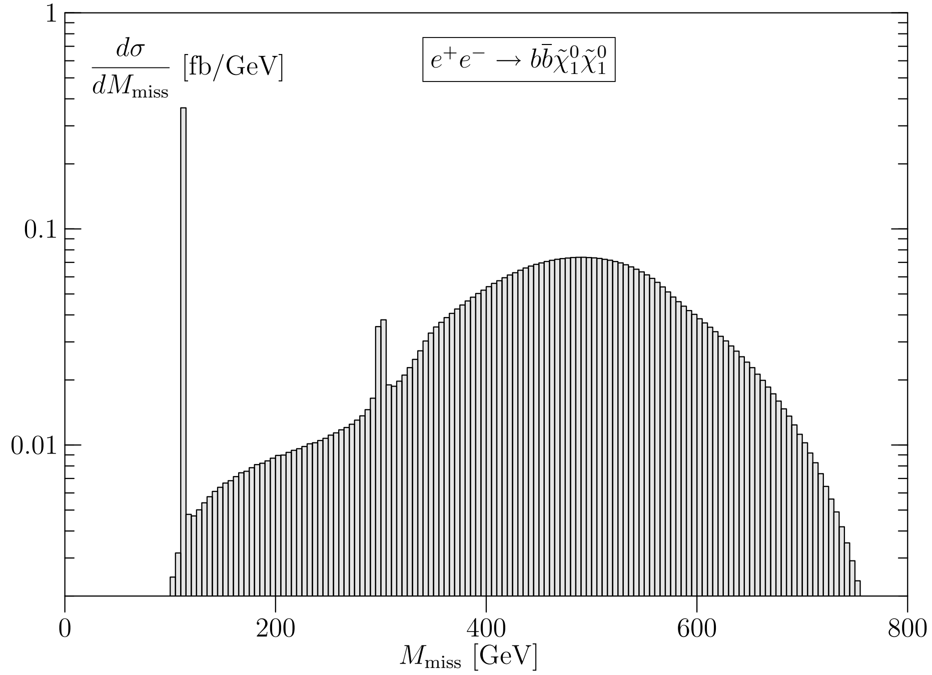


⇒ Remove Higgs Z, and neutralinos by cuts on $M_{b\bar{b}}$.

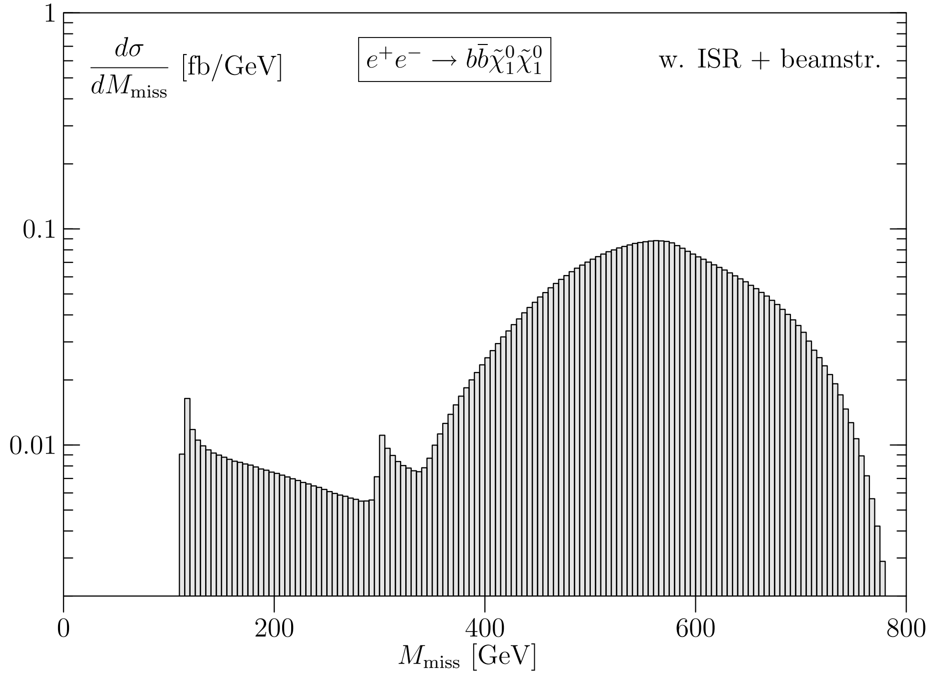
ISR and beamstrahlung

All Higgses can decay into $\tilde{\chi}_1^0\tilde{\chi}_1^0$, so expect peaks in $M_{\rm miss}$.

However, these are diluted by ISR/beamstrahlung effects:



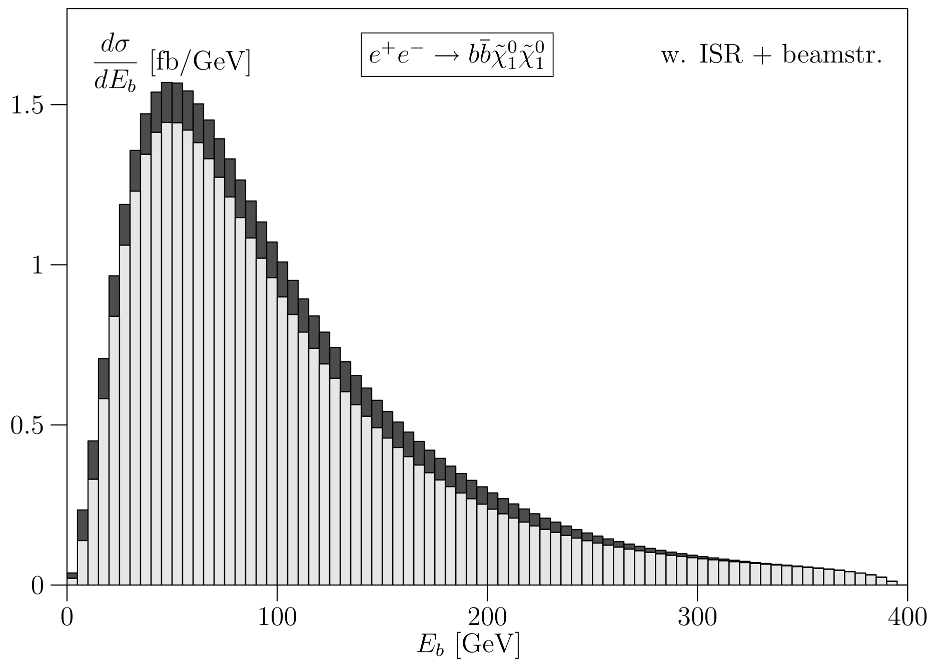
No radiation



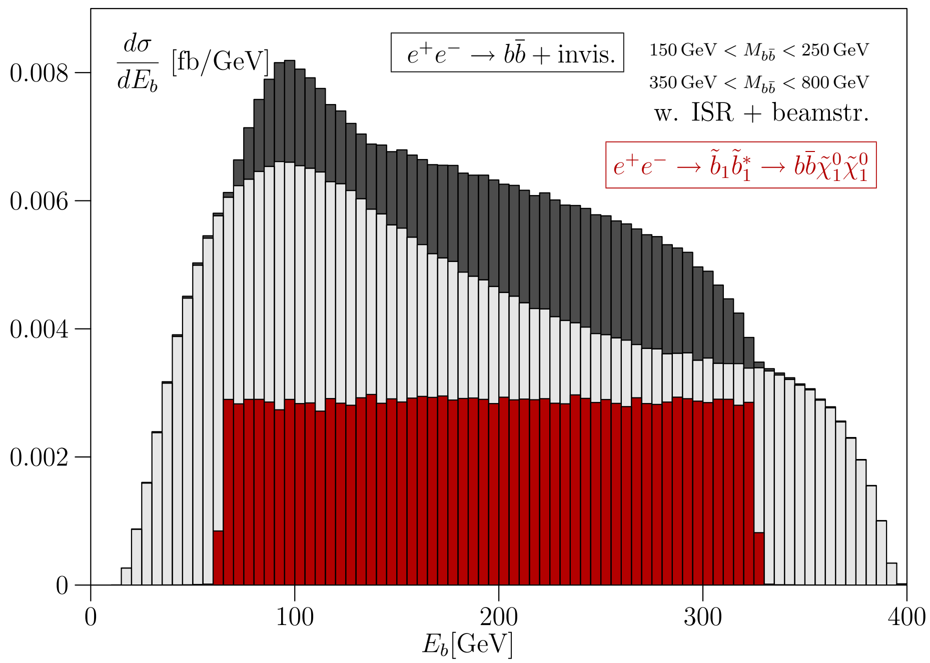
With radiation

The Result

The E_b spectrum should show a box shape with sharp edges.



No cuts



With cuts on $M_{b\bar{b}}$

Cross section after cuts:

SUSY $0.38\,\text{fb}$ (Breit-Wigner: $2.3\,\text{fb}$), SM bkgd $1.61\,\text{fb}$ (Breit-Wigner: $2.1\,\text{fb}$)

Conclusions

- Complete tree-level multi-particle event generators are now available for the MSSM: WHIZARD, MadEvent, Sherpa
- MSSM implementation and results thoroughly checked
- Off-shell effects in ILC processes (example: sbottom production):
  - Approximations are off by more than $10\,\%$: on-shell, Breit-Wigner, no ISR/Beamstrahlung
  - For quantitative estimate of background after cuts, Breit-Wigner approximation fails
  - New event generators solve these problems.

Future improvements needed: longer cascades, loops