Off-Shell and Interference Effects for SUSY Particle Production

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We show that the narrow-width approximation is insufficient for describing production of supersymmetric particles at the ILC. Especially when cuts are taken into account to extract signals using the narrow-width approximation can be wrong by an order of magnitude.

1 Precision SUSY measurements

Supersymmetry (SUSY) is the best-motivated solution to the hierarchy problem. If SUSY is realized in Nature, the LHC is likely to find sparticles during the next couple of years. The precision spectroscopy of the new particles will then be the major goal of future particle physics experiments. The aim is to perform mass measurements to get the spectrum (edges in decay chains), to access the spin of all new particles via angular/spin correlations, and finally to perform coupling measurements to verify SUSY by the relations among the couplings. Therefore, we need precise predictions SUSY processes: for their own determination as well as because they are background for (more difficult) SUSY processes. We need parameter values as precise as possible in order to reverse the renormalization-group evolution and get a handle on the GUT parameters [2, 3]. Corrections to (SUSY) processes (at the ILC) can be grouped into six categories [4]: 1) Loop corrections to SUSY production and decay processes; 2) nonfactorizable, maximally resonant photon exchange between production and decay; 3) real radiation of photons/gluons; 4) off-shell kinematics for the signal process (see also [5]); 5) irreducible background from all other SUSY processes; 6) reducible, experimentally indistinguishable SM background processes. Topics 1) and 3) are addressed in [6].

2 Complexity and Approximations

Generic SUSY processes have an incredible complexity: e.g. $e^+e^- \to b\bar{b}e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$ (which is just an exclusive final state for $\tilde{\chi}_2^0\tilde{\chi}_2^0$ production) has 66,478 diagrams already at tree level. Entangled in these amplitudes are different signal diagrams: $e^+e^- \to \tilde{\chi}_i^0\tilde{\chi}_j^0, \tilde{b}_i\tilde{b}_j, \tilde{e}_i\tilde{e}_j$. To disentangle them in simulations or a real data analysis, one has to use cuts and to consider SM backgrounds (here e.g. $e^+e^- \to b\bar{b}e^+e^-\nu_i\bar{\nu}_i$). There are much more complicated processes for LHC, and even for ILC. To deal with this complexity one needs to use multi-particle event generators [7].

There are three different levels of approximations used for describing such processes like $A_1A_2 \to P^{(*)} \to F_1F_2$: the narrow-width approximation $\sigma(A_1A_2 \to P) \times \mathrm{BR}(P \to F_1F_2)$ (on-shell production times branching ratio), the Breit-Wigner approximation $\sigma(A_1A_2 \to P) \times \frac{M_P^2\Gamma_P^2}{(s-M_P^2)^2+\Gamma_P^2M_P^2} \times \mathrm{BR}(P \to F_1F_2)$ (folding in a finite width propagator), and the full

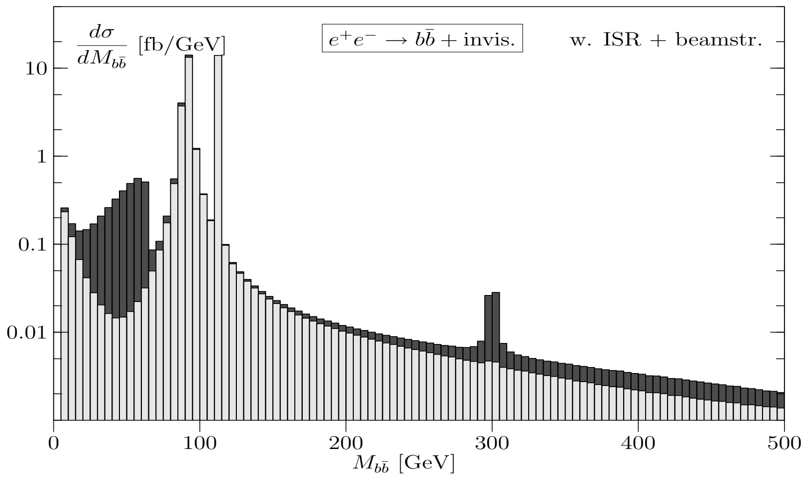

Figure 1: The $b\bar{b}$ invariant mass spectrum for the full process $e^+e^- \to b\bar{b}+\not{E}$ with ISR and beamstrahlung. The SM background ($Z \to \nu\bar{\nu}$) with the Z, h peaks is light gray. Dark gray represents all MSSM processes, with two peaks from heavy neutralino and heavy Higgs decays.

Channel	$\sigma_{2\to 2}$	$\sigma \times$ BR	$\sigma_{\rm BW}$
Zh	20.574	1.342	1.335
ZH	0.003	0.000	0.000
HA	5.653	0.320	0.314
$\tilde{\chi}^0_1\tilde{\chi}^0_2$	69.109	13.078	13.954
$\tilde{\chi}^0_1\tilde{\chi}^0_3$	24.268	3.675	4.828
$\tilde{\chi}^0_1\tilde{\chi}^0_4$	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
$Z\bar{\nu}\nu$	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

Channel	$\sigma_{\rm BW}$	$\sigma^{\rm cut}_{\rm BW}$
Zh	1.335	0.009
HA	0.314	0.003
$\tilde{\chi}^0_1\tilde{\chi}^0_2$	13.954	0.458
$\tilde{\chi}^0_1\tilde{\chi}^0_3$	4.828	0.454
$\tilde{\chi}^0_1\tilde{\chi}^0_4$	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
$Z\bar{\nu}\nu$	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

Table 1: Main subprocesses for sbottom production at an 800 GeV ILC using the three level of complexity mentioned in the text. Left: before the cuts, right: after the cuts. Upper table is signal processes, lower one SM backgrounds. All processes in femtobarn.

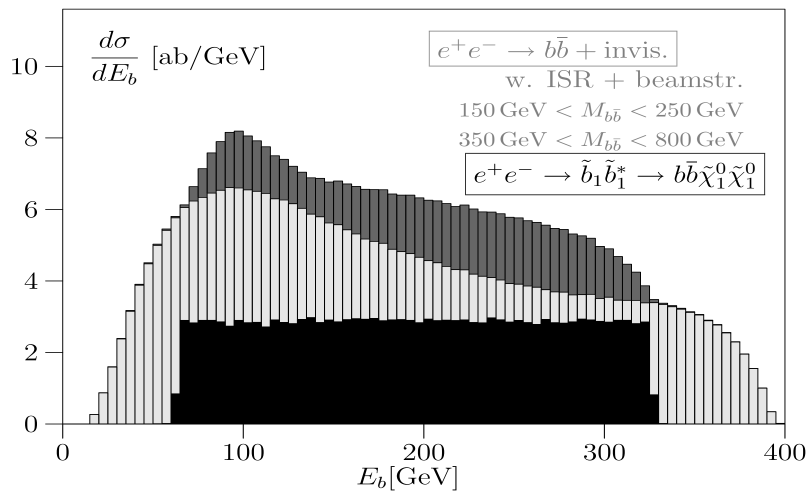

Figure 2: The E_b spectrum of $e^+e^- \to b\bar{b}+\not{E}$, including all interferences and off-shell effects, plus ISR and beamstrahlung. The light gray histogram is the SM background, dark gray the sum of SUSY processes, including the cuts. We also show the idealized case (red) of on-shell sbottom production without ISR or beamstrahlung.

matrix elements: $\sigma(A_1 A_2 \to F_1 F_2)$. That last level is not featured by event generators like ISAJET, PYTHIA, HERWIG, SUSYGEN.

The simulations presented here have been performed with the multi-purpose event generator `WHIZARD` [8], which is well-suited for physics beyond the SM [9]. Especially, the MSSM implementation has been thoroughly tested [4], e.g. in a comparison with the other two MSSM multi-particle generators, `Madgraph` and `Sherpa`. The reference data can be found at `http://whizard.event-generator.org/susy_comparison.html`.

3 Results

For our study [4] of off-shell and interference effects and to test the quality of the Breit-Wigner approximation, we took a SUGRA-inspired parameter point with non-universal right-handed scalar masses and $\tan\beta = 20$. Note, that the following does not depend on this special point, however. This point features a light Higgs, directly above LEP limit [10], large (47 %) invisible Higgs decays to the LSP, $m_{\tilde{q}} \sim 430$ GeV, light sbottoms accessible at the ILC, and is compatible with all low-energy data: $b \to s\gamma$, $B_s \to \mu^+\mu^-$, $\Delta\rho$, $g_\mu - 2$, CDM. The sbottoms have masses of 295.36 and 399.92 GeV and widths of 0.5295 and 3.4956 GeV, respectively. The neutralino masses are 46.84, 112.41, 148.09 and 236.77 GeV, their widths 0, 0.00005, 0.01162 and 1.0947 GeV, respectively. The focus lies on $\mathrm{BR}(\tilde{b}_1 \to b\tilde{\chi}_1^0) = 43.2\%$, as we want to study sbottom production at an 800 GeV ILC.

In contrast to the LHC, at the ILC sbottoms are produced by electroweak interactions. Hence, much more channels contribute to the same exclusive final state, $e^+e^- \to b\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0$: $e^+e^- \to Zh, ZH, Ah, HA, \tilde{\chi}_1^0\tilde{\chi}_2^0, \tilde{\chi}_1^0\tilde{\chi}_3^0, \tilde{\chi}_1^0\tilde{\chi}_4^0, \tilde{b}_1\tilde{b}_1^*, \tilde{b}_1\tilde{b}_2^*$, altogether 412 diagrams. The irreducible SM background is $e^+e^- \to b\bar{b}\nu_i\bar{\nu}_i$ (WW fusion, Zh, ZZ, 47 diagrams). Important is to use widths to the same order as your process, i.e. tree level in our case. The left of Tab. 1 shows the cross sections of the contributing subprocesses in the three levels of complexity described above. The $b\bar{b}$ invariant mass spectrum (dark) including the SM background (light gray) is shown in Fig. 1. Light gray peaks stem from the Z and light Higgs resonance, while the dark gray peak comes from the heavy Higgses. The broad dark continuum at low energies results from heavy neutralinos. Hence, to isolate the SUSY signal it is mandatory to cut out the resonances, namely the two windows $M_{b\bar{b}} < 150$ GeV and $250\,\text{GeV} < M_{b\bar{b}} < 350$ GeV. The off-shell decay $\tilde{\chi}_3^0 \to (\tilde{b}_1)_{off}\bar{b} \to b\bar{b}\tilde{\chi}_1^0$ gives a broad continuum instead of a well-defined peak expected from subsequent 2-body decays; this causes some of the effects described below. ISR and beamstrahlung give corrections of the same order as off-shell effects and affect all p_{miss} observables. The corresponding plots can be found in [4]. The cross sections after application of the cuts are shown on the right of Tab. 1; note the difference between the exact result 0.487 fb and the Breit-Wigner approximation of 2.314 fb showing a deviation of an order of magnitude. Fig. 2 shows that the $\tilde{b}_1 \to b\tilde{\chi}_1^0$ decay kinematics is affected by the off-shell and interference effects, the SM backgrounds as well as ISR and beamstrahlung in a way that makes it much harder to precisly extract the sbottom mass as desired.

In summary, precision predictions for SUSY phenomenology are important, especially higher order virtual and real corrections. The factorization of processes into $2 \to 2$ production and decay is insufficient or even wrong. Off-shell effects and interferences affect the results, especially with cuts. Therefore one has to use full matrix elements (cf. [11]), available from multi-particle event generators where `WHIZARD` is especially well-suited for ILC.

4 Acknowledgments

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