Off-Shell and Interference Effects for SUSY Particle Production

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

DESY, June 1st, 2007
SUSY Precision measurements

Motivation for SUSY: see Tuesday’s Symposium

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

Precise parameter values: Reverse the renormalization-group evaluation and get a handle on GUT parameters (⇒ P. Zerwas’ talk)
⇒ SPA project http://spa.desy.de/spa
Classification of corrections to (SUSY) processes

Corrections to the SUSY processes fall into six categories:

- Loop corrections to SUSY production and decay processes
  Kilian/JR/Robens, EPJ C48 (2006), 389, see T. Robens’ talk

- Nonfactorizable, maximally resonant photon exchange between production and decay

- Real radiation of photons [gluons]
  Kilian/JR/Robens, EPJ C48 (2006), 389, see T. Robens’ talk

- Off-shell kinematics for the signal process
  see also Berdine/Rainwater/Kauer, 2007

- Irreducible background from all other SUSY processes

- Reducible, experimentally indistinguishable SM background processes
Classification of approximations in (SUSY) processes

Some generic SUSY process:

\[ e^+ e^- \rightarrow b\bar{b} e^+ e^- \tilde{\chi}_1^0 \tilde{\chi}_1^0 \]

66478 diagrams. (It’s just \( e^+ e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 \! \))

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

Process \( A_1 A_2 \rightarrow P(*) \rightarrow F_1 F_2 \), 3 different levels:

| Level               | Formula                                                                 |
|---------------------|-------------------------------------------------------------------------|
| Narrow width        | \( \sigma(A_1 A_2 \rightarrow P) \times \text{BR}(P \rightarrow F_1 F_2) \) |
| Breit-Wigner        | \( \sigma(A_1 A_2 \rightarrow P) \times \frac{M_P^2 \Gamma_P^2}{(s-M_P^2)^2+\Gamma_P^2 M_P^2} \times \text{BR}(P \rightarrow F_1 F_2) \) |
| Full matrix element | \( \sigma(A_1 A_2 \rightarrow F_1 F_2) \)                                 |

last level not featured by ISAJET, PYTHIA, HERWIG, SUSYGEN
The generator generator O’Mega $\Omega$ / Whizard

Matrix Element Generator O’Mega:

Optimized helicity amplitudes: avoiding all redundancies

Multi-purpose Event Generator Whizard:

– 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 this summer: Whizard 2.0/O’Mega 1.0 (LHC approaching!!)
  ▶ 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 $2 \rightarrow 2$ processes for ILC)
– Future features: Parton Shower/Matrix Element matching
Tests and Checks of MSSM implementation

- MSSM: doubled spectrum, 100 parameters, 5000 vertices
- Unitarity checks: $\sigma(2 \rightarrow 2, s), \sigma(2 \rightarrow 3, s) \sim const$ or $1/s$
- Gauge invariance: Ward- and Slavnov-Taylor identities
- Supersymmetry: Ward-/Slavnov-Taylor identities

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

Comparison of codes ($\mathcal{O}(600)$ processes):

| Process | status | Madgraph/Helas | | Whizard/O'Mega | | Sherpa/A'Megic |
|---------|--------|----------------|-----------------|-----------------|-----------------|
|         | 0.5 TeV | 2 TeV          | 0.5 TeV | 2 TeV | 0.5 TeV | 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) |
| $\tilde{\chi}^0_1 \tilde{\chi}^0_1$ | ● | 249.94(2) | 26.43(1) | 249.954(9) | 26.431(1) | 249.96(1) | 26.431(1) |
| $\tilde{\chi}^0_2 \tilde{\chi}^0_2$ | ● | 69.967(3) | 9.8940(3) | 69.969(2) | 9.8940(4) | 69.968(3) | 9.8937(5) |
| $\tilde{\chi}^0_1 \tilde{\chi}^0_2$ | ● | 17.0387(3) | 0.7913(1) | 17.0394(1) | 0.79136(2) | 17.040(1) | 0.79137(5) |
| $\tilde{\chi}^+ \tilde{\chi}^-$ | ● | 185.09(3) | 45.15(1) | 185.093(6) | 45.147(2) | 185.10(1) | 45.151(2) |

Reference: [http://james.physik.uni-freiburg.de/~reuter/susy_comparison.html](http://james.physik.uni-freiburg.de/~reuter/susy_comparison.html)
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] | \( \Gamma \) [GeV] | Particle | \( M \) [GeV] | \( \Gamma \) [GeV] |
|----------|--------------|----------------|----------|--------------|----------------|
| \( h \)  | 114.45       | 0.0050         | \( \tilde{\chi}^0_1 \) | 46.84        | —              |
| \( H \)  | 300.15       | 2.2924         | \( \tilde{\chi}^0_2 \) | 112.41       | 0.00005        |
| \( A \)  | 300.00       | 2.7750         | \( \tilde{\chi}^0_3 \) | 148.09       | 0.01162        |
| \( H^\pm \) | 310.96      |                | \( \tilde{\chi}^0_4 \) | 236.77       | 1.0947         |
| \( \tilde{b}_1 \) | 295.36     | 0.5395         | \( \tilde{\chi}^{\pm}_1 \) | 106.60       |                |
| \( \tilde{b}_2 \) | 399.92     | 3.4956         | \( \tilde{\chi}^{\pm}_2 \) | 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
- \( m_{\tilde{q}} \sim 430\text{ GeV} \)
- Light sbottoms accessible at the ILC
- Low-energy data-compatible: \( b \to s\gamma, B_s \to \mu^+\mu^-, \Delta\rho, g_\mu - 2, \text{CDM} \)
- Focus on \( \text{BR}(\tilde{b}_1 \to b\tilde{\chi}^0_1) = 43.2\% \)
Sbottom production at the ILC

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

| Channel | $\sigma_{2\rightarrow2}$ [fb] | $\sigma \times BR$ [fb] | $\sigma_{BW}$ [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          |                  |

| Channel | $\sigma_{2\rightarrow2/3}$ [fb] | $\sigma \times BR$ [fb] | $\sigma_{BW}$ [fb] |
|---------|-----------------|-----------------|-----------------|
| $ZZ$    | 202.2           | 12.6            | 13.1            |
| $Zh$    | 20.6            | 1.9             | 1.9             |
| $ZH$    | 0.0             | 0.0             | 0.0             |

| Channel | $\sigma_{2\rightarrow2/3}$ [fb] | $\sigma \times BR$ [fb] | $\sigma_{BW}$ [fb] |
|---------|-----------------|-----------------|-----------------|
| $Z\tilde{\nu}\nu$ | 626.1           | 109.9           | 111.4           |
| $h\tilde{\nu}\nu$ | 170.5           | 76.5            | 76.4            |
| $H\tilde{\nu}\nu$ | 0.0             | 0.0             | 0.0             |
| Sum     | 186.5           | 187.7           |                  |

- Use widths to the same order as your process
Sbottom production at the ILC

In contrast to the LHC: Electroweak production

More channels contribute to $e^+ e^- \rightarrow b\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0$:

$e^+ e^- \rightarrow Zh, ZH, Ah, HA, \tilde{\chi}_1^0\tilde{\chi}_2^0, \tilde{\chi}_1^0\tilde{\chi}_3^0, \tilde{\chi}_1^0\tilde{\chi}_4^0, \tilde{b}_1\tilde{b}_1^*, \tilde{b}_1\tilde{b}_2^*$ (412 diagrams)

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| $\tilde{b}_1\tilde{b}_1$ | 4.209                      | 0.759                    | 0.757             |
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|----------|---------------------------------|--------------------------|-------------------|
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| $Zh$     | 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 w/ISR

| Channel  | $\sigma_{2\rightarrow2/3}$ [fb] | $\sigma \times BR$ [fb] | $\sigma_{BW}$ [fb] |
|----------|---------------------------------|--------------------------|-------------------|
| Exact    | 19.624                          |                          |                   |
| w/ISR    | 22.552                          |                          |                   |

Use widths to the same order as your process
Results

Off-shell decay $\tilde{\chi}^0_3 \rightarrow (\tilde{b}_1)_{off} \tilde{b} \rightarrow b\bar{b}\tilde{\chi}^0_1$ 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
Results

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

Cut out the resonances

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

$250 \text{ GeV} < M_{b\bar{b}} < 350 \text{ GeV}$
Results: Isolation of the Signal

| Channel | $\sigma_{BW}$ [fb] | $\sigma_{cut\ BW}$ [fb] |
|---------|-------------------|-------------------------|
| $Z\tilde{\nu}\nu$ | 111.4 | 2.114 |
| $h\tilde{\nu}\nu$ | 76.4 | 0.002 |
| $H\tilde{\nu}\nu$ | 0.0 | 0.000 |
| Sum | 187.7 | 2.117 |

| Channel | $\sigma_{BW}$ [fb] | $\sigma_{cut\ BW}$ [fb] |
|---------|-------------------|-------------------------|
| $Zh$ | 1.335 | 0.009 |
| $HA$ | 0.314 | 0.003 |
| $\tilde{\chi}_1\tilde{\chi}_2^0$ | 13.954 | 0.458 |
| $\tilde{\chi}_1\tilde{\chi}_3^0$ | 4.828 | 0.454 |
| $\tilde{\chi}_1\tilde{\chi}_4^0$ | 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 |

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

d$\sigma$/d$E_b$ [fb/GeV] $e^+e^- \rightarrow bb\tilde{\chi}_1\tilde{\chi}_1^0$
w. ISR + beamstr.
Results: Isolation of the Signal

| Channel       | \(\sigma_{BW} \) [fb] | \(\sigma_{cut}^{BW} \) [fb] |
|---------------|------------------------|-----------------------------|
| \(Z\bar{\nu}\nu\) | 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                       |

| Channel       | \(\sigma_{BW} \) [fb] | \(\sigma_{cut}^{BW} \) [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                       |
| \(\tilde{\chi}_1^0\tilde{\chi}_1^0\) | 0.757                | 0.451                       |
| \(\tilde{\chi}_1^0\tilde{\chi}_2^0\) | 0.002                | 0.001                       |
| Sum           | 22.129                 | 2.314                       |

\(\tilde{b}_1 \to b\tilde{\chi}_1^0\) decay kinematics affected
Summary & Outlook

Precision predictions for SUSY pheno are important

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

Factorization in $2 \rightarrow 2$ 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

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