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;
(2003), 525; work in progress: Alboteanu/Alwall/Kilian/Plehn/JR;
Kalinowski/Kilian/JR/Robens/Rolbiecki

Uppsala, May 16th, 2008
Challenging the Standard Model

- describes microcosm (too well?)
- 28 free parameters

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Fit</th>
<th>$\sigma^{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_{\nu_{e}}$</td>
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<td>0.02768</td>
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<tr>
<td>$m_{Z}$ [GeV]</td>
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<td>91.1875</td>
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<tr>
<td>$\Gamma_{Z}$ [GeV]</td>
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<td>2.4957</td>
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<tr>
<td>$m_{\text{had}}$ [nb]</td>
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<td>41.477</td>
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<td>$R_{b}$</td>
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<td>0.01645</td>
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<tr>
<td>$A_{b}$</td>
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<td>0.1481</td>
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<tr>
<td>$R_{b}$</td>
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<td>0.21586</td>
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<tr>
<td>$R_{c}$</td>
<td>0.1721</td>
<td>0.1722</td>
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<td>$A_{s}$</td>
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<td>$A_{f}$</td>
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<tr>
<td>$A_{l}$</td>
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<td>0.668</td>
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<tr>
<td>$A_{l}(\text{SLD})$</td>
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<td>0.1481</td>
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<tr>
<td>$\sin^{2}(\theta_{f})$</td>
<td>0.2324</td>
<td>0.2314</td>
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<tr>
<td>$m_{W}$ [GeV]</td>
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<td>80.374</td>
</tr>
<tr>
<td>$\Gamma_{W}$ [GeV]</td>
<td>2.140</td>
<td>2.091</td>
</tr>
<tr>
<td>$m_{t}$ [GeV]</td>
<td>170.9</td>
<td>171.3</td>
</tr>
</tbody>
</table>

- Form of Higgs potential?
Challenging the Standard Model

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Hierarchy problem

chiral symmetry: \( \delta m_f \propto v \ln(\Lambda^2/v^2) \)

no symmetry for quantum corrections to Higgs mass

\[ \delta M_H^2 \propto \Lambda^2 \sim M_{\text{Planck}}^2 = (10^{19})^2 \text{ GeV}^2 \]

20000 GeV^2 = \( \frac{1}{1000000000000000000000000000000000000} \) GeV^2
Open questions & Loose ends

– Unification of all interactions (?)

– Baryon asymmetry $\Delta N_B - \Delta N_{\bar{B}} \sim 10^{-9}$
  missing CP violation

– Flavour: three generations

– Tiny neutrino masses: $m_\nu \sim \frac{v^2}{M}$

– Dark Matter:
  - stable
  - weakly interacting
  - $m_{DM} \sim 100$ GeV

– Quantum theory of gravitation

– Cosmic inflation

– Dark Energy
  (Cosmological constant?)
Old (and New) Ideas for New Physics (since $\sim 1970$)

1. **Substructure/New strong interactions**
   - Technicolour: Higgs as a bound state of strongly-interacting partons

2. **Symmetries for cancellation of quantum corrections**
   - **Supersymmetry:** Spin-statistics $\Rightarrow$ corrections from bosons and fermions cancel each other
   - Little-Higgs/Moose models: global symmetries $\Rightarrow$ corrections from like-statistics particles cancel each other

3. **Non-trivial space-time structure eliminates hierarchy**
   - Large extra dimensions: Gravity appears only weak
   - Warped extra dimensions (Randall-Sundrum): Gravity only weak in our world

4. **Ignoring the hierarchy**
   - Anthropic principle: parameters have their values, *because we* (can) measure them
Supersymmetry (SUSY)

Wess/Zumino, 1974

- (uniquely) connects gauge and space-time symmetries
- Multiplets of fermions and bosons with equal masses
\[ \Rightarrow \text{SUSY broken in nature} \]

- To each particle add a superpartner
- Minimal Supersymmetric Standard Model (MSSM)
- Mass eigenstates:
  - Charginos: \[ \tilde{\chi}^\pm = \tilde{H}^\pm, \tilde{W}^\pm \]
  - Neutralinos: \[ \tilde{\chi}^0 = \tilde{H}, \tilde{Z}, \tilde{\gamma} \]
SUSY: Successes and Drawbacks

- Spontaneous SUSY breaking in the MSSM (MeV superpartners)
- Breaking in “hidden sector”
- Breaking mechanism induces 100 new parameters
- Solves hierarchy problem:
  \[
  \delta M_H \propto F \log(\Lambda^2)
  \]

- Fundamental scalars natural
- Form of Higgs potential
- Light Higgs \( M_H = 90 \pm 50 \text{ GeV} \)
- Discrete \( R \)-parity
  - SM particles even, SUSY partners odd
  - Prevents too rapid proton decay
  - Lightest SUSY particle (LSP) stable
- Dark matter: \( \tilde{\chi}_1^0 \)
- Unification of coupling constants
SUSY: Successes and Drawbacks

spontaneous SUSY breaking in the MSSM \( \mathcal{E} \) (MeV superpartners)

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Orthodoxist: "SUSY will be discovered, even if non-existent"
Revolutionist: "SUSY is already dead"
LHC search for new particles

Decay products from heavy particles:
- high-$p_T$ jets
- many hard leptons

Production of colored states
weakly interact. particles only in decays

Dark matter $\Leftrightarrow$ discrete parity $(R, T, \ K K)$

- new particles only in pairs $\Rightarrow$ high energies, (long) decay chains
- Dark matter $\Rightarrow$ much missing energy in the detector ($E_T$)

Different models/decay chains — identical signatures
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- many hard leptons

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Different models/decay chains — identical signatures
(SUSY) Observables/Precision Measurements

- **Mass (difference) of new particles:** endpoints of decay spectra

- **Spin of new particles:** angular distributions, correlations . . .

- **Model discrimination:** (Precise) measurements of coupling constants
  - Reverse RG evolution: get a handle on GUT parameters
  - **SPA project**  [http://spa.desy.de/spa](http://spa.desy.de/spa)

- **Precise prediction for signals and backgrounds:**
  - background to other (more difficult) SUSY processes
  - Consideration of kinematical cuts
  - Exclusive multi-particle final states: $2 \rightarrow 4$ to $2 \rightarrow 10$
  - Quantum corrections: real and virtual
Classification of corrections to (SUSY) processes

Corrections to the SUSY processes fall into six categories:

- off-shell kinematics for the signal process
  see also Berdine ea., 2007

- irreducible background from all other SUSY processes
  see above

- reducible, experimentally indistinguishable SM background processes
  see above

- Loop corrections to SUSY production and decay processes

- nonfactorizable, maximally resonant gluon [photon] exchange between production and decay

- real radiation of gluons [photons]
  see above
Classification of approximations in (SUSY) processes

Some generic SUSY process:

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

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

- Entanglement of different signal diagrams \( e^+ e^- \rightarrow \tilde{\chi}^0_i \tilde{\chi}^0_j, b_i \bar{b}_j, \tilde{e}_i \tilde{\bar{e}}_j \)
- 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:

| 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 \( \text{not} \) featured by ISAJET, PYTHIA, HERWIG, SUSYGEN
The Multi-Particle Generator WHIZARD

- Optimized helicity amplitudes: completely avoids redundancies
- Iterative adaptive multi-channel phase space \((\text{viable for } 2 \rightarrow 10)\)
- Unweighted events \((\text{formats: binary, HEPEVT, ATHENA, LHA, STDHEP})\)
- Graphical analysis tool
- Very high level of Complexity:

\[
\begin{align*}
  ee \rightarrow t\bar{t}H & \rightarrow b\bar{b}b\bar{b}jj\ell\nu \quad (110,000 \text{ diagrams}) \\
  ee \rightarrow ZHH & \rightarrow ZWWWW \rightarrow bb + 8j \quad (12,000,000 \text{ diagrams}) \\
  pp & \rightarrow \ell\ell + nj, n = 0, 1, 2, 3, 4, \ldots \quad (2,100,000 \text{ diagrams with 4 jets + flavors}) \\
  pp & \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 bbbb \quad (32,000 \text{ diagrams, 22 color flows, } \sim 10,000 \text{ PS channels}) \\
  pp & \rightarrow VVjj \rightarrow jj\ell\ell\nu\nu \quad \text{incl. anomalous TGC/QGC} \\
  \text{Test case } gg & \rightarrow 9g \quad (224,000,000 \text{ diagrams})
\end{align*}
\]

- WHiZard 1.51 / O’Mega 000.011beta \(\Omega\) \rightarrow joint version: WHIZARD 1.92 release date: 2008, April, 29th

one grand unified package \(\text{incl. VAMP, Circe, Circe 2, WHiZard, O’Mega}\)

New web address: http://whizard.event-generator.org
Standard Reference for 1.92 + new versions: Kilian/Ohl/JR, 0708.4233

Major upgrade this summer: WHIZARD 2.0.0
Implemented Physics Content

Structured beams:
- For Tevatron/LHC: PDFs from LHAPDF (or PDFLIB)
- Parton Shower ($k_\perp$ ordered)
- For ILC physics:
  ISR, polarization, beamstrahlung, photon collider spectra (CIRCE/CIRCE 2)

external (user-defined) beam spectra can be read in

Supported Physics Models:

- Test models: QED, QCD
- SM ($R_\xi$ gauge, ...)
- Littlest/Simplest Little Higgs, Little Higgs Models with $T$ parity
- Moose models: 3-site model
- MSSM, NMSSM, extended SUSY models, incl. gravitinos (SLHA/SLHA2)
- Graviton resonances, Universal extra dimensions, Randall-Sundrum
- Noncommutative Standard Model
- Higher-dimensional operators, SM effective field theory extensions
- Anomalous triple and quartic gauge couplings
- K-matrix/Padé unitarization, unitarized resonances

Alboteanu/Kilian/JR
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: $\sigma(2 \rightarrow 2, s), \sigma(2 \rightarrow 3, s) \sim \text{const or } 1/s$
- Gauge invariance: Ward- and Slavnov-Taylor identities
- Supersymmetry: Ward-/Slavnov-Taylor identities
- Comparison of codes ($O(600)$ processes):

Reference: [http://whizard.event-generator.org/susy_comparison.html](http://whizard.event-generator.org/susy_comparison.html)

<table>
<thead>
<tr>
<th>Process</th>
<th>status</th>
<th>Madgraph/Helas</th>
<th>Whizard/O’Mega</th>
<th>Sherpa/A’Megic</th>
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<td></td>
<td></td>
<td>0.5 TeV</td>
<td>2 TeV</td>
<td>0.5 TeV</td>
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<tr>
<td>$\tilde{\tau}_1 \tilde{\tau}_1^*$</td>
<td>⚫</td>
<td>257.57(7)</td>
<td>79.63(4)</td>
<td>257.32(1)</td>
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<td>$\tilde{\tau}_2 \tilde{\tau}_2^*$</td>
<td>⚫</td>
<td>46.55(1)</td>
<td>66.86(2)</td>
<td>46.368(2)</td>
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<td>$\tilde{\nu}_1 \tilde{\nu}_1^*$</td>
<td>⚫</td>
<td>95.50(3)</td>
<td>19.00(1)</td>
<td>94.637(3)</td>
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<tr>
<td>$\tilde{\tau}_1 \tilde{\tau}_2^*$</td>
<td>⚫</td>
<td>502.26(7)</td>
<td>272.01(8)</td>
<td>502.27(2)</td>
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<tr>
<td>$\tilde{\chi}_0^0 \tilde{\chi}_1^0$</td>
<td>⚫</td>
<td>249.94(2)</td>
<td>26.431(1)</td>
<td>249.954(3)</td>
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<tr>
<td>$\tilde{\chi}_0^0 \tilde{\chi}_2^0$</td>
<td>⚫</td>
<td>69.967(3)</td>
<td>9.8940(3)</td>
<td>69.969(2)</td>
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<td>$\tilde{\chi}_0^0 \tilde{\chi}_3^0$</td>
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<td>17.0387(3)</td>
<td>0.7913(1)</td>
<td>17.0394(1)</td>
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<td>185.09(3)</td>
<td>45.15(1)</td>
<td>185.093(6)</td>
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<td>$h^0 h^0$</td>
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<td>0.3533827(3)</td>
<td>0.0001242(2)</td>
<td>0.35339(2)</td>
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<tr>
<td>$A^0 A^0$</td>
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<td>0.07975(3)</td>
<td>—</td>
<td>0.079758(6)</td>
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<td>$Z h^0$</td>
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<td>59.591(3)</td>
<td>3.1803(8)</td>
<td>59.589(3)</td>
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<td>$Z A^0$</td>
<td>⚫</td>
<td>2.9915(4)</td>
<td>4.682(5)</td>
<td>2.99162(9)</td>
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</table>
Parameter point under consideration

Following discussions do not depend on the special parameter point
SUGRA-inspired point, non-universal right-handed scalar masses
tan $\beta = 20$

<table>
<thead>
<tr>
<th>Particle</th>
<th>$M$ [GeV]</th>
<th>$\Gamma$ [GeV]</th>
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</thead>
<tbody>
<tr>
<td>$h$</td>
<td>114.45</td>
<td>0.0050</td>
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<td>$H$</td>
<td>300.15</td>
<td>2.2924</td>
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<tr>
<td>$A$</td>
<td>300.00</td>
<td>2.7750</td>
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<tr>
<td>$H^\pm$</td>
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<tr>
<td>$\tilde{b}_1$</td>
<td>295.36</td>
<td>0.5395</td>
</tr>
<tr>
<td>$\tilde{b}_2$</td>
<td>399.92</td>
<td>3.4956</td>
</tr>
<tr>
<td>$\tilde{e}_L$</td>
<td>205.02</td>
<td></td>
</tr>
<tr>
<td>$\tilde{e}_R$</td>
<td>205.65</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>Particle</th>
<th>$M$ [GeV]</th>
<th>$\Gamma$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{\chi}_1^0$</td>
<td>46.84</td>
<td>—</td>
</tr>
<tr>
<td>$\tilde{\chi}_2^0$</td>
<td>112.41</td>
<td>0.00005</td>
</tr>
<tr>
<td>$\tilde{\chi}_3^0$</td>
<td>148.09</td>
<td>0.01162</td>
</tr>
<tr>
<td>$\tilde{\chi}_4^0$</td>
<td>236.77</td>
<td>1.0947</td>
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<tr>
<td>$\tilde{\chi}_1^{\pm}$</td>
<td>106.60</td>
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</tr>
<tr>
<td>$\tilde{\chi}_2^{\pm}$</td>
<td>237.25</td>
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<tr>
<td>$\tilde{\mu}_1$</td>
<td>413.84</td>
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</tr>
<tr>
<td>$\tilde{\mu}_2$</td>
<td>978.88</td>
<td></td>
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</tbody>
</table>

- (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: $b \rightarrow s\gamma$, $B_s \rightarrow \mu^+\mu^-$, $\Delta\rho$, $g_\mu - 2$, CDM
- Focus on $\text{BR}(\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0) = 43.2\%$
Sbottom production at the LHC

\[ \tilde{b}_1 \text{ production with subsequent decay } \tilde{b}_1 \to \tilde{\chi}_1^0 b \]

Parton-level distributions

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

Cuts: \( p_{T,b} > 20 \text{ GeV}, \mid \eta_b \mid < 4, \text{ and } \Delta R_{bb} > 0.4. \)

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-\(p_{T,b}\) is cut out

(Un)lucky case!!
Real corrections: Bottom-jet radiation

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

\[ g \rightarrow b\bar{b}\text{-splitting, } b\text{-ISR as combinatorial background} \]

\[ pp \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 b\bar{b}\bar{b}\bar{b} : \text{ 32112 diagrams, 22 color flows, } \sim 4000 \text{ PS channels} \]

\[ \sigma(pp \rightarrow b\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0) = 1177 \text{ fb} \quad \rightarrow \quad \sigma(pp \rightarrow b\bar{b}\bar{b}\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0) = 130.7 \text{ fb} \]

Forward discrimination of ISR and decay jets difficult:

Only the most forward jet considerably softer
Real corrections: Bottom-jet radiation

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

\[
pp \rightarrow \tilde{\chi}^0_1 \tilde{\chi}^0_1 b \bar{b} \bar{b} \bar{b} : \quad 32112 \text{ diagrams, 22 color flows, } \sim 4000 \text{ PS channels}
\]

\[
\sigma(pp \rightarrow b \bar{b}\tilde{\chi}^0_1 \tilde{\chi}^0_1) = 1177 \text{ fb} \quad \rightarrow \quad \sigma(pp \rightarrow b \bar{b}b\bar{b}\tilde{\chi}^0_1 \tilde{\chi}^0_1) = 130.7 \text{ fb}
\]

Only marginal differences in $p_T, b$, PDF: Maximum at lower value

\begin{align*}
\text{shifted to lower } p_T : \text{ light particles balance out event}
\end{align*}
Big Off-Shell/Interference Effects at LHC

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: $\Gamma/M$ enhanced by $1/\beta^n$
- Interference of non-resonant contributions

Large effects occur:

- Effective BRs (defined via excl. final states) deviate by up to $O(100 \%)$
- Charge asymmetries in decays: e.g. $\tilde{g}\tilde{g} \rightarrow b\bar{b}_1^* b\bar{b}_1^* / \bar{b} b_1 \bar{b}_1$
- Chirality asymmetries: e.g. $\tilde{g}\tilde{g} \rightarrow \tilde{q}_L \tilde{q}_L j j / \tilde{q}_R \tilde{q}_R j j$
Sbottom production at the ILC

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

<table>
<thead>
<tr>
<th>Channel</th>
<th>( \sigma_{2\rightarrow2} ) [fb]</th>
<th>( \sigma \times \text{BR} ) [fb]</th>
<th>( \sigma_{\text{BW}} ) [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Zh )</td>
<td>20.574</td>
<td>1.342</td>
<td>1.335</td>
</tr>
<tr>
<td>( ZH )</td>
<td>0.003</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>( hA )</td>
<td>0.002</td>
<td>0.001</td>
<td>0.000</td>
</tr>
<tr>
<td>( HA )</td>
<td>5.653</td>
<td>0.320</td>
<td>0.314</td>
</tr>
<tr>
<td>( \tilde{\chi}^0_1\tilde{\chi}^0_2 )</td>
<td>69.109</td>
<td>13.078</td>
<td>13.954</td>
</tr>
<tr>
<td>( \tilde{\chi}^0_1\tilde{\chi}^0_3 )</td>
<td>24.268</td>
<td>3.675</td>
<td>4.828</td>
</tr>
<tr>
<td>( \tilde{\chi}^0_1\tilde{\chi}^0_4 )</td>
<td>19.337</td>
<td>0.061</td>
<td>0.938</td>
</tr>
<tr>
<td>( \tilde{b}_1\tilde{b}_1 )</td>
<td>4.209</td>
<td>0.759</td>
<td>0.757</td>
</tr>
<tr>
<td>( \tilde{b}_1\tilde{b}_2 )</td>
<td>0.057</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>Sum</td>
<td>19.238</td>
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<th>( \sigma_{\text{BW}} ) [fb]</th>
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<tr>
<td>( ZZ )</td>
<td>202.2</td>
<td>12.6</td>
<td>13.1</td>
</tr>
<tr>
<td>( Zh )</td>
<td>20.6</td>
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<tr>
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<td>626.1</td>
<td>109.9</td>
<td>111.4</td>
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<tr>
<td>( \tilde{h}\tilde{\nu} )</td>
<td>170.5</td>
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<td>76.4</td>
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<tr>
<td>Sum</td>
<td>186.5</td>
<td>187.7</td>
<td></td>
</tr>
</tbody>
</table>

| Exact   | 19.624                          | 190.1                           |
| w/ISR   | 22.552                          | 174.2                           |

- 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)
- Irreducible SM background: $e^+ e^- \rightarrow b\bar{b} \nu_i \bar{\nu}_i$ ($WW$ fusion, $Zh, ZZ$)
  (47 diagrams)

<table>
<thead>
<tr>
<th>Channel</th>
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<th>$\sigma \times BR$ [fb]</th>
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<tr>
<td>$h\tilde{\nu}$</td>
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- Use widths to the same order as your process
Results

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

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

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

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Results: Isolation of the Signal

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<td>$Z\bar{\nu}\nu$</td>
<td>111.4</td>
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<td>$h\bar{\nu}\nu$</td>
<td>76.4</td>
<td>0.002</td>
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<td>0.0</td>
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<td>0.937</td>
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<tr>
<td>$\tilde{b}_1\tilde{b}_2$</td>
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$\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$ decay kinematics affected

$\frac{d\sigma}{dE_b} [fb/GeV]$, $e^+e^- \rightarrow bb\tilde{\chi}_1^0\tilde{\chi}_1^0$

w. ISR + beamstr.
Results: Isolation of the Signal

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

de\[d\sigma \over dE_b\] [fb/GeV]
\[e^+e^- \rightarrow bb\tilde{\chi}^0_1\tilde{\chi}^0_1\]
w. ISR + beamstr.

$e^+e^- \rightarrow \tilde{b}_1\tilde{b}_1^* \rightarrow bb\tilde{\chi}^0_1\tilde{\chi}^0_1$

$\frac{d\sigma}{dE_b}$ [ab/GeV]
$e^+e^- \rightarrow bb + invis.$
w. ISR + beamstr.
150 GeV $< M_{bb} < 250$ GeV
350 GeV $< M_{bb} < 800$ GeV
Going to Next-to-Leading Order

For the rest: always SPS1a' SUGRA-scenario with

\[ m_0 = 70 \text{ GeV} \quad m_{1/2} = 250 \text{ GeV} \quad \tan \beta = 10 \quad \text{sgn} \mu = 1 \quad A_0 = -300 \text{ GeV} \]

Chargino masses and widths:

| \( \tilde{\chi}^+_1 \) | 183.7 GeV | 0.077 GeV | 0.00042 |
| \( \tilde{\chi}^+_2 \) | 415.4 GeV | 3.1 GeV | 0.0075 |

SPS1a'-preferred decay (2-step cascade):

\[ \tilde{\chi}_1^+ \rightarrow \tilde{\tau}_1 \nu \rightarrow \tau^+ \tilde{\chi}_1^0 \nu \]

- Born helicity amplitudes known analytically (Choi et al., 9812236, 0002033)
- Implemented in narrow width approximation in many programs
Virtual Corrections

Virtual corrections from SUSY and SM particles: self energies, vertex corrections, box diagrams (as usual)

(Semi-)automatized calculation with **FeynArts/FormCalc**

Hahn et al., 9807565, 0012260, 0105349 ; Fritzsche, ; Fritzsche/Hollik, 0407095

Independent check of numerical results

Öller/Eberl/Majerotto, 0504109

Regulators:

- Electron mass $m_e$ for collinear photon radiation
- Fictitious photon mass $\lambda$ for infrared divergencies

Interference of Born and virtual corrections

\[
\sigma_{\text{virt}}(s, \lambda^2, m_e^2) = \int d\Gamma_2 \left[ 2 \text{Re} \left( \mathcal{M}_{\text{Born}}(s)^* \mathcal{M}_{1\text{-loop}}(s, \lambda^2, m_e^2) \right) \right]
\]

 Eliminate dependence on $\lambda$ by

- neglecting power corrections in $\lambda$
- Adding real (1st order) photon radiation with $E_\gamma < \Delta E_\gamma$
- Correction (terms $\propto \log \Delta E_\gamma$) is shifted into soft-photon factor
Virtual Corrections

Virtual corrections from SUSY and SM particles: self energies, vertex corrections, box diagrams (as usual)

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Soft-photon factor:

$$f_{\text{soft}} = -\frac{\alpha}{2\pi} \sum_{i,j = e^\pm, \tilde{\chi}^\pm} \int_{|k| \leq \Delta E_{\gamma}} \frac{d^3k}{2\omega_k} \frac{(\pm)p_ip_j Q_i Q_j}{(p_ik)(p_jk)}$$
Real and Collinear Photons

“Virtual + Soft”

\[
\sigma_{v+s}(s, \Delta E_\gamma, m_e^2) = \int d\Gamma_2 \left[ f_{\text{soft}}(\frac{\Delta E_\gamma}{\lambda}) |M_{\text{Born}}(s)|^2 + 2\text{Re} (M_{\text{Born}}(s)^* M_{1\text{-loop}}(s, \lambda^2, m_e^2)) \right]
\]

for simulation choose \( \Delta E_\gamma \leq \Delta E_\gamma^{\text{exp}} \)

Real radiation (i.e. the process \( e^- e^+ \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \gamma \)):

\[
\sigma_{2 \rightarrow 3}(s, \Delta E_\gamma, m_e^2) = \int_{\Delta E_\gamma} d\Gamma_3 |M_{2\rightarrow 3}(s, m_e^2)|^2.
\]

“Total” cross section (fixed order):

\[
\sigma_{\text{tot}}(s, m_e^2) = \sigma_{\text{Born}}(s) + \sigma_{v+s}(s, \Delta E_\gamma, m_e^2) + \sigma_{2 \rightarrow 3}(s, \Delta E_\gamma, m_e^2)
\]

should not depend on \( \Delta E_\gamma \), but power corrections only in \( \sigma_{2 \rightarrow 3} \), not in \( \sigma_{v+s} \)
As usual, split $2 \rightarrow 3$ cross section:

$$\sigma_{2 \rightarrow 3(s, \Delta E_\gamma, m_e^2)} = \sigma_{\text{hard,non-coll}}(s, \Delta E_\gamma, \Delta \theta_\gamma) + \sigma_{\text{hard,coll}}(s, \Delta E_\gamma, \Delta \theta_\gamma, m_e^2)$$

$$x = 1 - 2E_\gamma/\sqrt{s}$$ electron energy fraction after radiation

Approximate collinear radiation by convoluting the Born cross section with a structure function

$$\sigma_{\text{hard,coll}}(s, \Delta E_\gamma, \Delta \theta_\gamma, m_e^2) = \int_{\Delta E_\gamma, \Delta \theta_\gamma} d\Gamma_3 |M_{2\rightarrow 3}(s, m_e^2)|^2$$

$$= \int_0^{x_0} dx f(x; \Delta \theta_\gamma, \frac{m_e^2}{s}) \int d\Gamma_2 |M_{\text{Born}}(x s, m_e^2)|^2.$$  

Collinear structure functions (helicity conserving and helicity flip):

Böhm/Dittmaier, 1993

$$f^+(x) = \frac{\eta}{4} \frac{1+x^2}{1-x}$$

$$f^-(x) = \frac{\alpha}{2\pi} (1 - x)$$

$$\eta := \frac{2\alpha}{\pi} \left[ \log \left( \frac{s}{4m_e^2} (\Delta \theta_\gamma)^2 \right)^2 - 1 \right]$$

Cutoff $\Delta E_\gamma \rightarrow x_0 = 1 - 2\Delta E_\gamma/\sqrt{s}$ (no power corrections in $\Delta \theta_\gamma$)
Simulation

Combining all parts:

\[ \sigma_{\text{tot}}(s, m_e^2) = \int dx \, f_{\text{eff}}(x_1, x_2; \Delta E_\gamma, \Delta \theta_\gamma, \frac{m_e^2}{s}) \int d\Gamma_2 \, |M_{\text{eff}}(s, x_1, x_2; m_e^2)|^2 \]

\[ + \int_{\Delta E_\gamma, \Delta \theta_\gamma} d\Gamma_3 \, |M_{2 \to 3}(s)|^2, \]

with

\[ f_{\text{eff}}(x_1, x_2; \Delta E_\gamma, \Delta \theta_\gamma, \frac{m_e^2}{s}) = \delta(1 - x_1) \delta(1 - x_2) \]

\[ + \delta(1 - x_1) \, f(x_2; \Delta \theta_\gamma, \frac{m_e^2}{s}) \, \theta(x_0 - x_2) \]

\[ + f(x_1; \Delta \theta_\gamma, \frac{m_e^2}{s}) \, \delta(1 - x_2) \, \theta(x_0 - x_1) \]

\[ |M_{\text{eff}}(s, x_1, x_2; m_e^2)|^2 = \left[ 1 + f_{\text{soft}}(\Delta E_\gamma, \frac{m_e^2}{s}) \, \theta(x_1, x_2) \right] |M_{\text{Born}}(s)|^2 \]

\[ + 2 \Re \left[ M_{\text{Born}}(s) \, M_{1\text{-loop}}(s, \frac{m_e^2}{s}) \right] \theta(x_1 - x_0) \theta(x_2 - x_0) \]

All corrections defined as a generalized structure function

⇒ suitable for implementation in an event generator
Resumming photons

Experimental resolution drives one into **negative weights region**

Soft-collinear region: \( E_\gamma < \Delta E_\gamma, \Delta \theta_\gamma < \theta_\gamma \): double logs

\[
\frac{\alpha}{\pi} \log \frac{E_\gamma^2}{s} \log \theta_\gamma \text{ invalidate perturbative series}
\]

In that region resummation of all orders is possible

\[
\sigma_{\text{Born+ISR}}(s, \Delta \theta_\gamma, m_e^2) = \int dx f_{\text{ISR}}(x; \Delta \theta_\gamma, \frac{m_e^2}{s}) \int d\Gamma_2 |M_{\text{Born}}(xs)|^2
\]

\( f_{\text{ISR}} \) includes all order soft-photon radiation (LLA), hard-collinear up to 3rd order

Skrzypek/Jadach, 1991

For collinear photons cancellation of infrared divergencies built in, main source of negative weights removed
Matching with NLO

Combine ISR-resummed LO with NLO, avoid double-counting
Subtract contribution of one soft photon (already in soft-photon factor)

\[
f_{\text{soft,ISR}}(\Delta E_\gamma, \Delta \theta_\gamma, m_e^2) = \frac{\eta}{4} \int_{x_0}^{1} dx \left( \frac{1 + x^2}{1 - x} \right) = \frac{\eta}{4} \left( 2 \ln(1 - x_0) + x_0 + \frac{1}{2} x_0^2 \right) .
\]

After this subtraction we have

\[
|\tilde{\mathcal{M}}_{\text{eff}}(\hat{s}; \Delta E_\gamma, \Delta \theta_\gamma, m_e^2)|^2 = \left[ 1 + f_{\text{soft}} \left( \frac{\Delta E_\gamma}{\lambda} \right) - 2 f_{\text{soft,ISR}}(\Delta E_\gamma, \Delta \theta_\gamma, \frac{m_e^2}{s} ) \right] |\mathcal{M}_{\text{Born}}(\hat{s})|^2
+ 2 \text{Re} \left[ \mathcal{M}_{\text{Born}}(\hat{s}) \mathcal{M}_{1\text{-loop}}(\hat{s}, \lambda^2, m_e^2) \right] ,
\]

contains Born, virtual + soft contr. with LL part of virtual and soft-coll. removed

New “s+v” term (contains also soft/coll. corrections to Born/1-loop interference)

\[
\sigma_{\text{v+s,ISR}}(s, \Delta E_\gamma, \Delta \theta_\gamma, m_e^2 )
= \int dx_1 f_{\text{ISR}}(x_1; \Delta \theta_\gamma, \frac{m_e^2}{s}) \int dx_2 f_{\text{ISR}}(x_2; \Delta \theta_\gamma, \frac{m_e^2}{s}) \int d\Gamma_2 |\tilde{\mathcal{M}}_{\text{eff}}(\hat{s}; \Delta E_\gamma, \Delta \theta_\gamma, m_e^2)|^2
\]
Simulation

Resummation approach eliminates problem of negative weights:

Only source for negative weights: soft-noncollinear region, does not cause problems

Final improvement:

- convoluting $2 \rightarrow 3$ part with ISR structur function
- add $2 \rightarrow 4$ part

$$
\sigma_{\text{tot,ISR+}}(s, m_e^2) = \int dx_1 f_{\text{ISR}}(x_1; \Delta \theta_\gamma, \frac{m_e^2}{s}) \int dx_2 f_{\text{ISR}}(x_2; \Delta \theta_\gamma, \frac{m_e^2}{s}) \\
\times \left( \int d\Gamma_2 |\widetilde{M}_{\text{eff}}(\hat{s}; \Delta E_\gamma, \Delta \theta_\gamma, m_e^2)|^2 + \int_{\Delta E_\gamma, \Delta \theta_\gamma} d\Gamma_3 |M_{2\rightarrow3}(\hat{s})|^2 \right) \\
+ \int_{\Delta E_\gamma, i, \Delta \theta_\gamma, i} d\Gamma_4 |M_{2\rightarrow4}(s)|^2
$$
Results and Distributions

NLO corrections -5% (Xsec max.)
-2% (-1.5%) fixed-order (resummed) @ 1 TeV

Binned distribution of chargino scattering angle
Cutoffs: $\Delta \theta_\gamma = 1^\circ$, $\Delta E_\gamma = 3$ GeV (fixed-order)
$K$-factor approach insufficient
Summary and Outlook

- LHC: new era of physics
- 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 LHC/ILC: WHIZARD
  http://whizard.event-generator.org
  - First BSM signal vs. bkgd. jet studies
  - Next step(s): Reconsider all edge structures [LHC]:
    Alboteanu/Alwall/Plehn/JR/Schumann
- Extended WHIZARD: 1st NLO SUSY MC Generator for the ILC
  FeynArts/FormCalc interface: all MSSM $2 \to 2$ processes for ILC
- QCD NLO simulations: GOLEM/WHIZARD collab.