Status of the Event Generator WHIZARD – SUSY Simulations at the ILC and Radiative Corrections

Jürgen Reuter

University of Freiburg

ALCPG/GDE 07, Fermilab, October 23, 2007
The need for Multi-Particle Event Generators

New collider environments more complicated

Very complicated signal/background processes

New physics:

- DM: Conserved discrete parity: pair production, decay chains
- Complicated, quasi-degenerate spectrum at the Terascale
- High-multiplicity final states

ILC allows for precision measurements at least at per cent-level

Need for Multi-Particle Event Generators

JR, Snowmass 05; Hagiwara et al., 06; Hewett, 07; Kilian/Kobel/Mader/JR/Schumacher

- BSM processes do not factorize into $2 \rightarrow 2$ production/decay
- Interferences of several (partially) resonant diagram groves
- Off-shell effects violate Breit-Wigner approximation

Berdine/Kauer/Rainwater 07; Berdine/Kauer/JR/Rainwater
Sbottom production at the ILC

- In contrast to the LHC: Electroweak production
  \( \sqrt{s} = 800 \text{ GeV} \)

- 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: \( e^+ e^- \rightarrow b\bar{b} \nu_i \bar{\nu}_i \) (47 diagrams)

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<thead>
<tr>
<th>Channel</th>
<th>( \sigma_{\to 2} ) [fb]</th>
<th>( \sigma \times BR ) [fb]</th>
<th>( \sigma_{BW} ) [fb]</th>
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<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>
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</tr>
<tr>
<td>( hA )</td>
<td>0.002</td>
<td>0.001</td>
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</tr>
<tr>
<td>HA</td>
<td>5.653</td>
<td>0.320</td>
<td>0.314</td>
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<tr>
<td>( \tilde{\chi}_1^0 \tilde{\chi}_2^0 )</td>
<td>69.109</td>
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<tr>
<td>( \tilde{\chi}_1^0 \tilde{\chi}_3^0 )</td>
<td>24.268</td>
<td>3.675</td>
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<tr>
<td>( \tilde{\chi}_1^0 \tilde{\chi}_4^0 )</td>
<td>19.337</td>
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<tr>
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Off-shell decay $\tilde{\chi}_3^0 \rightarrow (\tilde{b}_1)_{off} \tilde{b} \rightarrow b\bar{b}\tilde{\chi}_1^0$ 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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$e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow b \tilde{b}_1$$\tilde{\chi}_1^0$$\tilde{\chi}_1^0$ w. ISR + beamstr.

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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.
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\(\tilde{b}_1 \to b\tilde{\chi}_1^0\) decay kinematics affected

\[ \frac{d\sigma}{dE_b} \text{ [fb/GeV]} \]

\[ e^+e^- \to bb\tilde{\chi}_1^0\tilde{\chi}_1^0 \]

\(\text{w. ISR + beamstr.}\)

\[ e^+e^- \to b\tilde{b}_1^* \to bb\tilde{\chi}_1^0\tilde{\chi}_1^0 \]

\[ \text{w. ISR + beamstr.} \]

150 GeV < \(M_{bb}\) < 250 GeV

350 GeV < \(M_{bb}\) < 800 GeV

\[ e^+e^- \to \tilde{b}_1\tilde{b}_1^* \to bb\tilde{\chi}_1^0\tilde{\chi}_1^0 \]
The Multi-Particle Generator WHIZARD

Very high level of Complexity:

- $e^+ e^- \rightarrow t\bar{t}H \rightarrow b\bar{b}b j j \ell \nu$ (110,000 diagrams)
- $e^+ e^- \rightarrow ZHH \rightarrow ZW W W W \rightarrow bb + 8j$ (12,000,000 diagrams)
- $pp \rightarrow \ell\ell + nj, n = 0, 1, 2, 3, 4, \ldots$ (2,100,000 diagrams with 4 jets + flavors)
- $pp \rightarrow \tilde{\chi}^0_1 \tilde{\chi}^0_1 bbb (32,000 diagrams, 22 color flows, \sim 10,000 PS channels)
- $pp \rightarrow VV jj \rightarrow jj\ell\ell\nu\nu$ incl. anomalous TGC/QGC
- Test case $gg \rightarrow 9g$ (224,000,000 diagrams)

Current versions:

- WHiZard 1.51 / O’Mega 000.011beta \(\Omega\) \rightarrow joint version:

WHIZARD 1.99 release date: somehow this or next week

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

New web address:

http://whizard.event-generator.org

- Standard reference for 1.99 + upcoming versions:

Kilian/Ohl/JR, 0708.4233

Major upgrade this fall/winter: WHIZARD 2.0.0
Technical details about WHIZARD

Status of WHIZARD 1.99: Installation

- Download tar-ball from http://whizard.event-generator.org
- unpack, do configure, make install that’s it!
- OK, granted: specify locations of external packages and O’Caml language (part of many Linux distributions, http://caml.inria.fr)

WHIZARD is written in Fortran 90/95. Compiler status?

- works w/ (almost) all commercial compiler: Intel, Lahey, NAG, Pathscale
- Portland has a severe compiler bug
- compiles with g95
- compiles with gfortran 4.3.0 (will be part of new Linux SuSe 11.0, Debian 4.1, ...)
- lots of Fortran2003 features coming (No need for reprogramming in C++)

Basic facts:

- Helicity amplitudes
- Iterative adaptive multi-channel phase space (viable for $2 \rightarrow 10$)
- Unweighted events (formats: binary, HEPEVT, ATHENA, LHA, STDHEP)
- Graphical analysis tool
Implemented Physics Content

Structured beams:

For Tevatron/LHC: PDFs from LHAPDF (or PDFLIB)
For ILC physics:
  ▶ ISR (implemented: Skrzypek/Jadach, Kuraev/Fadin)
  ▶ arbitrarily polarized beams
  ▶ beamstrahlung (CIRCE), photon collider spectra (CIRCE 2)
  ▶ external (user-defined) beam spectra can be read in

Supported Physics Models:

  ▶ Test models: QED, QCD
  ▶ SM
  ▶ Littlest/Simplest Little Higgs, Little Higgs Models with $T$ parity
  ▶ Moose models: 3-site model
  ▶ MSSM, NMSSM, extended SUSY models, incl. gravitinos (SLHA)
  ▶ Graviton resonances, Extra dimensions
  ▶ Noncommutative Standard Model
  ▶ Higher-dimensional operators, SM effective field theory extensions
  ▶ Anomalous triple and quartic gauge couplings
  ▶ K-matrix/Padé unitarization, unitarized resonances  Kilian/JR
Comparison of Automated Tools for Perturbative Interactions in SuperSymmetry


<table>
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<tr>
<th>Process</th>
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<th>0.5 TeV</th>
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<td>(\tilde{\tau}_1 \tilde{\tau}_1^*)</td>
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<td>257.57(7)</td>
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<tr>
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<tr>
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<td>0.26438(2)</td>
<td>—</td>
<td>0.264389(5)</td>
<td>—</td>
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<th>Madgraph/Helas</th>
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<th>2 TeV</th>
<th>Whizard/O'Mega</th>
<th>0.5 TeV</th>
<th>2 TeV</th>
<th>Sherpa/A'Megic</th>
<th>0.5 TeV</th>
<th>2 TeV</th>
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<tr>
<td>(\tilde{\chi}_1 \tilde{\chi}_1)</td>
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<td>185.09(3)</td>
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<td>26.515(1)</td>
<td>—</td>
<td>26.5162(6)</td>
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<tr>
<td>(\tilde{\chi}_3 \tilde{\chi}_3)</td>
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<td>0.0001242(2)</td>
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<td>(h^0 H^0)</td>
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<td>0.0001242(2)</td>
<td>0.0001242(2)</td>
<td>0.00012422(3)</td>
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<td>(h^0 H^0)</td>
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<td>—</td>
<td>0.005167(4)</td>
<td>—</td>
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<td>—</td>
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<tr>
<td>(A^0 A^0)</td>
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<tr>
<td>(Z h^0)</td>
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<td>(A^0 h^0)</td>
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<td>—</td>
<td>0.0051434(4)</td>
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<td>(A^0 H^0)</td>
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<td>—</td>
<td>1.4880(2)</td>
<td>—</td>
<td>1.48793(9)</td>
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<tr>
<td>(H^+ H^-)</td>
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<td>5.2344(6)</td>
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<td>5.2344(2)</td>
<td>—</td>
<td>5.2345(3)</td>
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</table>
Upcoming Features

WHIZARD version 2.0.0 coming out this fall/winter

- (More) Automatized installation tool
- New syntax for defining cuts, scales and analyses: allows for arbitrary functions of kinematical variables
- fancier (and faster) color structures from O’Mega
- WHIZARD uses O’Mega info for better/faster phase space generation
- Cascade decays (apply with great care!!!) WHIZARD calls itself recursively, breaks double decay chains down into subprocesses
- Leading order (QCD) parton shower
  (so only fragmentation/hadronization and PDFs by external routines)
- Dark matter relic density calculator
- Support for ROOT data format
- TAUOLA interface

All points close to finalization; Major restructuring of the code
Upcoming Features / Future Features

Future features, 2008ish

- NLO parton shower with correct matching to hard matrix elements
- New manual
- Graphical User Interface (partially already there)
- Standardized interface to FeynArts/FormCalc/LoopTools
- Full-fledged parallelization (partially under way)
- Own algebraic tool for deriving Feynman rules from Lagrangians
- Web interface
Status of SUSY NLO calculations (for ILC processes)

1) Consistent renormalization procedure (DR)  
   Stöckinger, 2005

2) Higgs observables  
   - effective potential approx. + RGE  
     Carena/Garcia/Nierste/Wagner, 1999  
   - full 1-loop calculation  
     Degrassi et al., 2005; Heinemeyer et al., 2004-6  
   - leading 2-loop pieces  
     Rzehak et al., 2005

3) Charginos and Neutralinos  
   - full 1-loop: renormalization/spectrum  
     Fritzsch/Hollik, 2004; Eberl/Majerotto/Öller, 2004  
   - pair production and 2-body decays  
     Fritzsch/Hollik, 2004; Eberl/Majerotto/Öller, 2004  
   - 3-body decays  
     Kovaric/Rolbiecki et al.

4) Sfermions  
   - 1-loop: renormalization and mass spectrum  
     Hollik/Rzehak, 2005  
   - $e^+ e^- \rightarrow \tilde{q}\tilde{q}^*, \tilde{\ell}\tilde{\ell}^+$  
     Arhrib/Hollik, Kovaric et al., Freitas et al., 2002-2004  
   - 2-body decays  
     Guasch/Hollik/Solà, 2004

5) Unified framework for codes/calculation: SPA convention  
   SPA, 2005

6) Full matrix elements, Off-shell and Interference effects  
   - all particles, all processes, all colliders  
     JR et al., 2005; Hagiwara et al., 2006
Classification of NLO corrections

- Loop corrections to SUSY production and decay processes
- Nonfactorizable, maximally resonant photon exchange between production and decay
- Real radiation of photons
- Off-shell kinematics for the signal process
- Irreducible background from all other SUSY processes
- Reducible, experimentally indistinguishable SM background processes

Multi-pole approximation, justified from EW SM processes

Denner et al., 0006307, 0502063, 0604011.
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Implemented in Sherpa, Smadgraph, WHIZARD thoroughly checked

Hagiwara et al., 0512260; JR et al., 0512012

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Multi-pole approximation, justified from EW SM processes

Denner et al., 0006307, 0502063, 0604011.
SUSY (NLO) Simulations for the ILC
Example: NLO Chargino Production at the ILC

For the rest: always SPS1a’

SUGRA-scenario with \( \text{sgn } \mu = 1 \)

- \( m_0 = 70 \text{ GeV} \)
- \( m = 250 \text{ GeV} \)
- \( \tan \beta = 10 \)
- \( A_0 = -300 \text{ GeV} \)

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

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

Chargino masses and widths:

<table>
<thead>
<tr>
<th>( \tilde{\chi}_1^+ )</th>
<th>( M )</th>
<th>( \Gamma )</th>
<th>( \Gamma / M )</th>
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<tbody>
<tr>
<td>183.7 GeV</td>
<td>0.077 GeV</td>
<td>0.00042</td>
<td></td>
</tr>
<tr>
<td>415.4 GeV</td>
<td>3.1 GeV</td>
<td>0.0075</td>
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\[ e^- e^+ \rightarrow \tilde{\chi}_1^- \tilde{\chi}_1^+ \]

\[ \frac{d\sigma}{d\cos \theta} \text{ [fb] (LO)} \]

\[ \sqrt{s} = 1 \text{ TeV} \]

\[ \cos \theta \text{ angle between } e^- \text{ and } \tilde{\chi}_1^- \]

- Born helicity amplitudes known analytically
- Implemented in narrow width approx. in many programs
- Full (tree-level) processes in Sherpa, SMadgraph, WHIZARD

- No massless \( t \)-channel particles \( \Rightarrow \) neglect \( m_e \) for phase space

- to clarify notation

\[ \sigma_{\text{Born}}(s) = \int d\Gamma_2 \left| \mathcal{M}_{\text{Born}}(s, \cos \theta) \right|^2 \]
Virtual Corrections

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

(Semi-)automatized calculation with \texttt{FeynArts/FormCalc}

Hahn et al., 9007565, 0012260, 0105349; Fritzsche, 05; Fritzsche/Hollik, 0407095

Independent check of numerical results

Regulators:

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

Interference of Born and virtual corrections

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

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)

(Semi-)automatized calculation with \texttt{FeynArts/FormCalc}

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

Soft-photon factor:

$$
f_{\text{soft}} = -\frac{\alpha}{2\pi} \sum_{i,j=e^\pm, \tilde{\chi}^\pm} \int_{|k| \leq \Delta E_\gamma} \frac{d^3k}{2\omega_k} \frac{(\pm)p_ip_j Q_i Q_j}{(p_i k)(p_j k)}
$$
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 $2 \to 3$ cross section:

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

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

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

$$\sigma_{\text{hard, coll}}(s, \Delta E_\gamma, \Delta \theta_\gamma, m_\gamma^2) = \int_{\Delta E_\gamma, \Delta \theta_\gamma} d\Gamma_3 |M_{2\to3}(s, m_\gamma^2)|^2$$

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

collinear structure functions (helicity conserving/flip):

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

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

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

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

Combining all parts:

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

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

with

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

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

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

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

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

All corrections defined as a generalized structure function ⇒ suitable for implementation in an event generator
Technical Details and Failure of Approach

Generate Born + $2 \to 3$ by O’Mega, convolute Born with generalized structure function (“user-defined structure function” in WHIZARD)

Sampling $\delta$-functions:

- splitting sampling region $[0, x_0] \cup [x_0, 1]$
- map first region as exactly as possible
- set $x = 1$ in the 2nd region ($\delta$-functions)
- reweighting according to

$$w(x > x_0) : w(x < x_0) = 1 : \int_0^{x_0} dx f(x; \Delta \theta_\gamma, \frac{m_e^2}{s})$$

For fixed-order simulation avoid double-counting:

$$f(x_1 < x_0, x_2 < x_0) \equiv 0$$  (strictly here)

Numerical agreement: WHIZARD and fixed-order calculation
Technical Details and Failure of Approach

For fixed-order simulation avoid double-counting:
\[ f(x_1 < x_0, x_2 < x_0) \equiv 0 \quad \text{(strictly here)} \]

Numerical agreement: WHIZARD and fixed-order calculation

In the soft-photon region: negative event weights

- 2 \rightarrow 2 and 2 \rightarrow 3 runs separately
- Lowering the cutoff from \[ \frac{\Delta E_{\gamma}}{\sqrt{s}} < 10^{-2} \] to \[ \frac{\Delta E_{\gamma}}{\sqrt{s}} < 10^{-3} \]: 2 \rightarrow 2
  NLO becomes negative, compensating the 2 \rightarrow 3
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

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

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)

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

Kilian/JR/Robens, 2006

Resummation approach eliminates problem of negative weights:

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

Final improvement:

- convoluting $2 \to 3$ part with ISR structure function
- add $2 \to 4$ part

\[
\sigma_{\text{tot,ISR}^+}(s, m_e^2) = \int dx_1 f_{\text{ISR}}(x_1; \Delta \theta_\gamma, \frac{m_e^2}{s}) \int dx_2 f_{\text{ISR}}(x_2; \Delta \theta_\gamma, \frac{m_e^2}{s}) \times \left( \int d\Gamma_2 |\tilde{\mathcal{M}}_{\text{eff}}(s; \Delta E_\gamma, \Delta \theta_\gamma, m_e^2)|^2 + \int_{\Delta E_\gamma, \Delta \theta_\gamma} d\Gamma_3 |\mathcal{M}_{2\to 3}(s)|^2 \right) \\
+ \int_{\Delta E_\gamma, i, \Delta \theta_\gamma, i} d\Gamma_4 |\mathcal{M}_{2\to 4}(s)|^2
\]
Choosing Cutoffs

▶ Collinear (angular) cutoff

Collinear approximation breaks down at $\theta_\gamma > 10^\circ$

Higher-order effects for emission angles below 0.1°

▶ Energy cutoff

Fixed order/semianalytic agree

Small angles: interference term overshoots

5 % correction from higher order $\gamma$ radiation

ILC statist. fluctuation: 2.5 %

$\Rightarrow \Delta E_\gamma \lesssim 0.5$ GeV
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

- Extended WHIZARD: 1st NLO SUSY MC Event Generator for the ILC
- All possible distributions available at NLO
- Matching of resummed soft-collinear photons and explicit NLO parts avoids negative weights
- Interface to FeynArts: all MSSM 2 → 2 processes for ILC available
- Open issues/Next step(s):
  - Include chargino decays
  - Resummation of Coulomb singularity: improved threshold behavior
  - Semiautomatized version / Program library

New version WHIZARD 1.99 → 2.0.0

http://whizard.event-generator.org

Functional cut/analysis syntax, more models, recursive cascades, improved phase space, parton shower, . . .

as usual: we’re open to users wish list!