Monte Carlo Simulations for NLO Chargino Production at the ILC

based on hep-ph/0607127, hep-ph/0610401

Tania Robens
in collaboration with W. Kilian, J. Reuter

RWTH Aachen

LCWS 2007, DESY Hamburg

Chargino and Neutralino sector: Reconstruction of SUSY parameters

- Charginos $\widetilde{\chi}_i^{\pm}$ and Neutralinos $\widetilde{\chi}_i^0$:
  superpositions of gauge and Higgs boson superpartners
- Chargino/ Neutralino sector:

  $$\tan\beta,\ \mu \text{ (Higgs sector)},\ M_1,\ M_2 \text{(soft breaking terms)}$$

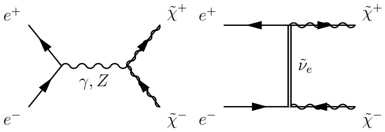
  can be reconstructed from

  $$\text{masses of } \widetilde{\chi}_1^{\pm},\ \widetilde{\chi}_2^{\pm},\ \widetilde{\chi}_1^0,\ 2\ \sigma \text{ in the } \widetilde{\chi}^{\pm} \text{ sector}$$

  (Choi ea 98, 00, 01)
- low-scale parameters + evolution to high scales (RGEs):
  $\Rightarrow$ hint at SUSY breaking mechanism (Blair ea, 02)
- requires high precision in ew-scale parameter determination

Chargino production at the ILC

- Charginos: (typically) light in the MSSM
  $\Rightarrow$ easily accessible at colliders (ILC/ LHC) $\Leftarrow$
- LO production at the ILC:



- decays: typically long decay chains

  e.g. $e^+ e^- \rightarrow \widetilde{\chi}_1^+ \widetilde{\chi}_1^- \rightarrow \tilde{\tau}_1^+ \tilde{\tau}_1^- \nu_\tau \bar{\nu_\tau} (\rightarrow \tau^+ \tau^- \nu_\tau \bar{\nu_\tau} \widetilde{\chi}_1^0 \widetilde{\chi}_1^0)$

Experimental accuracy and theoretical next-to-leading-order (NLO) corrections

- experimental errors: obtained from simulation studies (LHC/ ILC study, Weiglein ea, 04)
- generate "experimental data" with known SUSY input parameters
- errors: combination of statistical and systematic errors

combined **LHC + ILC:** ‰

same $\mathcal{O}$ errors from fitting routines determining SUSY parameters

- **Theory**:
  Full NLO SUSY corrections for $\sigma(ee \rightarrow \tilde{\chi}\tilde{\chi})$ at ILC:
  in the % regime (Fritzsche ea 04, Öller ea 04, 05)

$\Rightarrow$ include complete NLO contributions in analyses $\Leftarrow$

Experimental accuracy and theoretical next-to-leading-order (NLO) corrections

- experimental errors: obtained from simulation studies (LHC/ ILC study, Weiglein ea, 04)
- generate "experimental data" with known SUSY input parameters
- errors: combination of statistical and systematic errors

combined **LHC + ILC:** ‰

same $\mathcal{O}$ errors from fitting routines determining SUSY parameters

- **Theory**:
  Full NLO SUSY corrections for $\sigma(ee \rightarrow \widetilde{\chi}\,\widetilde{\chi})$ at ILC:
  in the % regime (Fritzsche ea 04, Öller ea 04, 05)

  $\Rightarrow$ include complete NLO contributions in analyses$\Leftarrow$

From σ_{tot} to Monte Carlo event generators

- experiments: see final decay products
- need to compare with simulated event samples
- also: important irreducible background effects (e.g. Hagiwara ea, 05)

$\longrightarrow$ talk by Jürgen Reuter

$\Rightarrow$ include NLO results in Monte Carlo Generators $\Leftarrow$

- MC Generator WHIZARD (W. Kilian, LC-TOOL-2001-039):
- so far: LO Monte Carlo Event Generator for $2 \longrightarrow n$ particle processes
- includes various physical models (SM, MSSM, non-commutative geometry, little Higgs models), initial state radiation, parton shower models,...

From σ_{tot} to Monte Carlo event generators

- experiments: see final decay products
- need to compare with simulated event samples
- also: important irreducible background effects

(e.g. Hagiwara ea, 05)

$\longrightarrow$ talk by Jürgen Reuter

$\Rightarrow$ include NLO results in Monte Carlo Generators $\Leftarrow$

- MC Generator WHIZARD (W. Kilian, LC-TOOL-2001-039):
- so far: LO Monte Carlo Event Generator for $2 \longrightarrow n$ particle processes
- includes various physical models (SM, MSSM, non-commutative geometry, little Higgs models), initial state radiation, parton shower models,...

NLO cross section contributions

σ_{tot} contributions and dependencies:

- σ_{born}
- virtual $\mathcal{O}(\alpha)$ corrections: $\sigma_{\text{virt}}(\lambda)$
- emission of soft/ hard collinear/ hard non-collinear photons:

  $\sigma_{\text{soft}}(\Delta E_\gamma, \lambda) + \sigma_{\text{hc}}(\Delta E_\gamma,\, \Delta\theta_\gamma) + \sigma_{2\to 3}(\Delta E_\gamma, \Delta\theta_\gamma)$
- higher order initial state radiation: $\sigma_{\text{ISR}} - \sigma_{\text{ISR}}^{\mathcal{O}(\alpha)}(Q)$

  λ: photon mass , ΔE_γ: soft cut , $\Delta\theta_\gamma$: collinear angle

Including FormCalc $\mathcal{O}(\alpha)$ results in WHIZARD

- use FeynArts / FormCalc generated code for

$$
\begin{array}{rcl}
\mathcal{M}_{\text{virt}}(\lambda) & : & \text{virtual corrections} \\
f_s(\Delta E_\gamma, \lambda) & : & \text{soft photon factor} \\
(\mathcal{M}_{\text{born}} & : & \text{born contribution})
\end{array}
$$

- fixed order: integrate over effective matrix element:

$$|\mathcal{M}_{\text{eff}}|^2(\Delta E_\gamma) = (1 + f_s(\Delta E_\gamma, \lambda))\, |\mathcal{M}_{\text{born}}|^2 + 2\, Re(\mathcal{M}_{\text{born}}\, \mathcal{M}^*_{\text{virt}}(\lambda))$$

ΔE_γ: soft photon cut, λ: photon mass

- in practice: create library from FormCalc code, link this to WHIZARD

(1): Fixed $\mathcal{O}(\alpha)$ contributions

- integrate $|\mathcal{M}_{\text{eff}}|^2$ (born/ virtual/ soft photonic part)
- hard collinear photons: collinear approximation ($\mathcal{M}_{\text{born}}$)
- hard non-collinear photons: explicit $e\,e \rightarrow \widetilde{\chi}\,\widetilde{\chi}\,\gamma$ process ($\mathcal{M}_{\text{born}}^{2\rightarrow 3}$)
- corresponds to analytic results in literature (Fritzsche ea/ Öller ea)

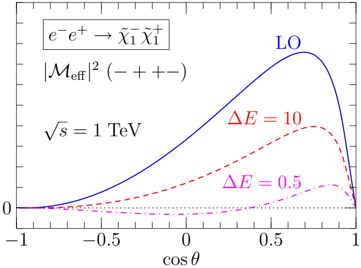
(1): Fixed $\mathcal{O}(\alpha)$ contributions

- integrate $|\mathcal{M}_{\text{eff}}|^2$ (born/ virtual/ soft photonic part)
- $+$ hard collinear photons: collinear approximation ($\mathcal{M}_{\text{born}}$)
- $+$ hard non-collinear photons: explicit $e\,e \rightarrow \tilde{\chi}\,\tilde{\chi}\,\gamma$ process ($\mathcal{M}_{\text{born}}^{2\rightarrow 3}$)
- corresponds to analytic results in literature (Fritzsche ea/ Öller ea)

problem: too low energy cuts: $|\mathcal{M}_{\text{eff}}|^2 < 0$ $\Rightarrow$ use negative weights or set $\mathcal{M}_{\text{eff}} = 0$

event generator specific problem

($\sigma_{\text{tot}} \geq 0$)



$\mathcal{M}^2$ behaviour, different cuts [GeV]

(2): Resumming leading logs to all orders

- idea: subtract $\mathcal{O}(\alpha)$ soft + virtual collinear contributions in $\mathcal{M}_{\text{eff}}$:

$$|\widetilde{\mathcal{M}}_{\text{eff}}|^2 = (1 + f_s(\Delta E_\gamma))\,|\mathcal{M}_{\text{born}}|^2 + 2\,Re(\mathcal{M}_{\text{born}}\,\mathcal{M}^*_{\text{virt}}) - 2\,f_s^{ISR,\mathcal{O}(\alpha)}(\Delta E_\gamma)\,|\mathcal{M}_{\text{born}}|^2$$

- fold this with ISR structure function:

$$\int d\Gamma \int_0^1 dx_1 \int_0^1 dx_2\, f^{\text{ISR}}(x_1)\, f^{\text{ISR}}(x_2)\, |\widetilde{\mathcal{M}}_{\text{eff}}|^2(s, x_i))$$

- $f^{\text{ISR}}(x)$: Initial state radiation (Jadach, Skrzypek, Z.Phys. 1991)

$\Rightarrow$ describes collinear (real + virtual) photons in leading log accuracy $\Leftarrow$

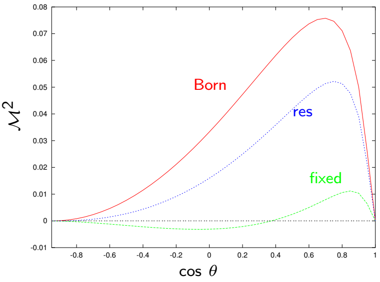
- $f_s^{\text{ISR},\mathcal{O}(\alpha)}$: soft integrated $\mathcal{O}(\alpha)$ contribution

Resumming: What do we get ??

- $\mathcal{O}(\alpha)$: equivalent to fixed order method

$\Rightarrow$ got rid of $|\mathcal{M}|^2 < 0$ effects !!

no negative weights



(-++-), $\Delta E_\gamma = 0.5$ GeV

- higher orders:
  higher order ISR for $|\mathcal{M}_{\text{born}}|^2$ as well as Re $(\mathcal{M}_{\text{born}}\,\mathcal{M}^*_{\text{virt}})$!!!

  $\Rightarrow$ new higher order effects $\Leftarrow$

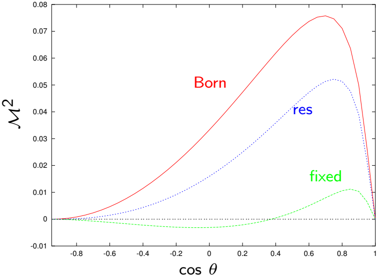
additional possibility: also fold hard noncollinear process with ISR

Resumming: What do we get ??

- $\mathcal{O}(\alpha)$: equivalent to fixed order method

$\Rightarrow$ got rid of $|\mathcal{M}|^2 < 0$ effects !!

no negative weights



(-++-),

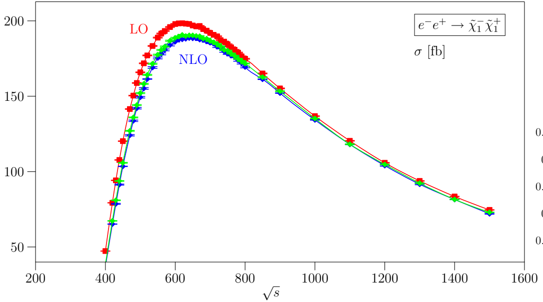
$\Delta E_\gamma = 0.5$ GeV

- higher orders:
  higher order ISR for $|\mathcal{M}_{\text{born}}|^2$ as well as Re $(\mathcal{M}_{\text{born}}\,\mathcal{M}^*_{\text{virt}})$!!!

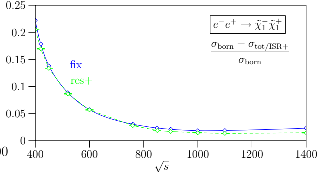
$\Rightarrow$ new higher order effects $\Leftarrow$

additional possibility: also fold hard noncollinear process with ISR

Results: cross sections



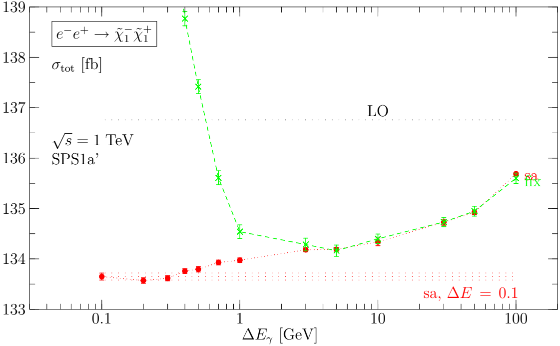
$\sigma(\sqrt{s})$



relative corrections

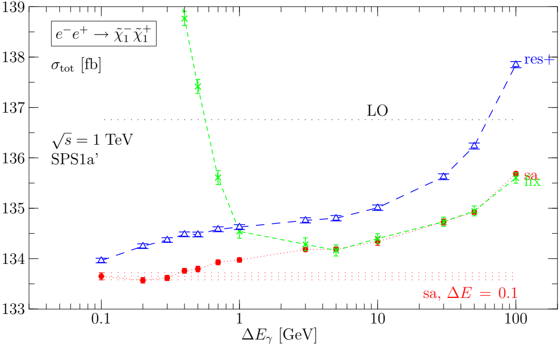
agrees with results in the literature (Fritzsche ea, Öller ea)

A closer look: ΔE_γ dependence of σ_{tot}



- semianalytic (FormCalc): tests soft approximation, shifts : 2 - 5 ‰ ($\Delta E_\gamma \leq 10\,\text{GeV}$)
- fixed order result (WHIZARD): same as 'sa' for $\Delta E_\gamma \geq 3\,\text{GeV}$, smaller values: $|\mathcal{M}_{\text{eff}}|^2 \leq 0$ effects

ΔE_γ dependence: resummation



$\sigma_{tot}(\Delta E_\gamma)$:

resummation includes higher order effects

5‰ difference to 'sa' for $\Delta E_\gamma \leq 10\,\mathrm{GeV}$

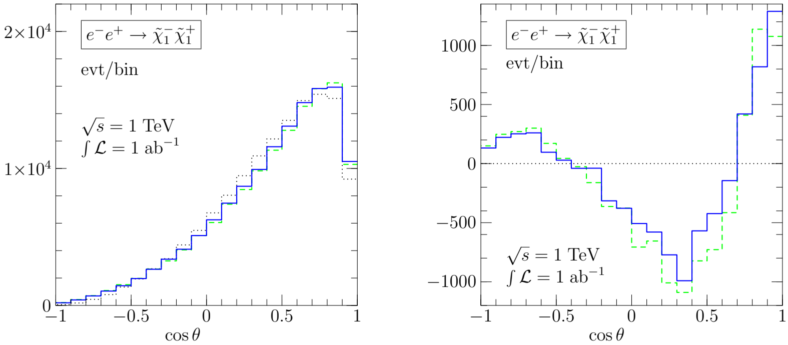
In summary:

shift in ΔE_γ leads to ‰ effects, match ILC accuracy

$\Rightarrow$ careful choice of ΔE_γ, method important

"best" choice: fully resummed version with low energy cut

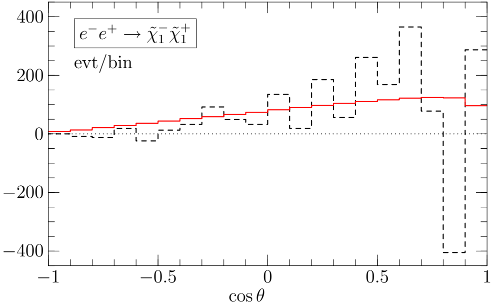
simulation results: angular distributions



Born, fixed order, resummation

!! more than 1 σ deviation !! $\sqrt{n_{\max}} \approx \mathcal{O}(10^2)$; nbins = 20

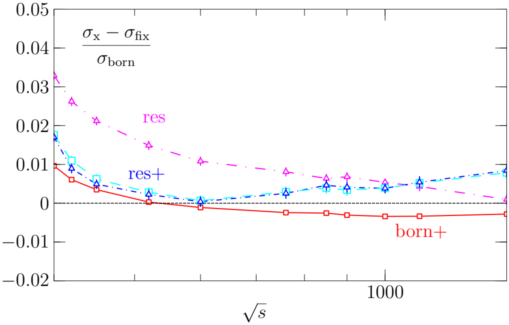
Angular distributions: higher orders



$N_{\mathrm{res},+} - N_{\mathrm{ex}}$
red: 1 standard dev from Born result

also higher order contributions statistically significant

$\sqrt{s}$ dependence of different higher order contributions



relative difference:

$$\frac{\sigma_x - \sigma_{fix}}{\sigma_{Born}}$$

Born+: only Born folded w ISR, resummation , fully resummed result

difference between Born+ and fully resummed result: multiple photon emission from interaction term

Summary and Outlook

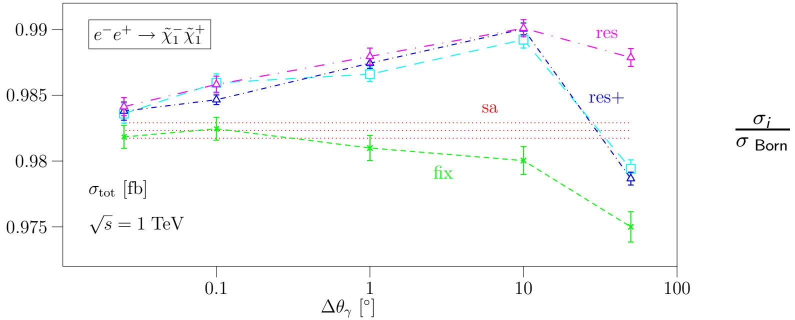
- Chargino/ neutralino sector of MSSM: high precision in SUSY paramater analysis at EW scale (‰ at ILC)
- same size/ larger NLO corrections

$\Rightarrow$ include NLO results in Monte Carlo Event generators

- resummation method for photons allows lower soft cuts/ inclusion of higher order contributions
- NLO as well as higher order contributions significant !!
- next steps: include NLO corrections to $\tilde{\chi}$ decays ($\rightarrow$ talk by K.Rolbiecki), non-factorizing contributions (start with photonic corrections in the double-pole approximation)
- general interface to FormCalc generated matrix elements: extendable to other processes...

cut dependencies: $\Delta\theta_\gamma$

tests: collinear photon approximation



σ_{tot} again larger for resummation method

for higher angles: second order ISR effects between 0.05^o and 0.1^o $(\mathcal{O}(‰))$

η, f_s, hard collinear approximation, $ISR^{\mathcal{O}(\alpha)}$

- $\eta = \frac{2\alpha}{\pi}\left(\log\left(\frac{Q^2}{m_e^2}\right) - 1\right)$ (Q = scale of process)
- $$f_s = -\frac{\alpha}{2\pi}\sum_{i,j=e^\pm}\int_{|\mathbf{k}|\leq\mathbf{\Delta E}}\frac{d^3k}{2\omega_k}\frac{(\pm)\,p_i\,p_j\,Q_i\,Q_j}{p_i\,k\,p_j\,k},$$

  (Denner 1992)

  $\omega_k = \sqrt{\mathbf{k^2} + \lambda^2}$, p_i initial/ final state momenta, k: γ momentum
- hard collinear factor ($\pm$ helicity conserving/ flipping):

  $$f^+(x) = \frac{\alpha}{2\pi}\frac{1+x^2}{(1-x)}\left(\ln\left(\frac{s\,(\Delta\theta)^2}{4\,m^2}\right) - 1\right), f^-(x) = \frac{\alpha}{2\pi}x.$$

  (Dittmaier 1993)
- $$f_s^{ISR,\mathcal{O}(\alpha)} = \left[\int_{x_0}^1 f_{ISR}(x)\,dx\right]_{\mathcal{O}(\alpha)} = \frac{\eta}{4}\left(2\ln(1-x_0) + x_0 + \frac{1}{2}x_0^2\right)$$

ISR in its full beauty (Skrzypek ea, 91)

$$
\begin{aligned}
\Gamma_{ee}^{LL}(x,Q^2) \;=\;& \frac{\exp(-\frac{1}{2}\eta\gamma_E+\frac{3}{8}\eta)}{\Gamma(1+\frac{\eta}{2})}\,\frac{\eta}{2}\,(1-x)^{(\frac{\eta}{2}-1)} \\
-\;& \frac{\eta}{4}(1+x)+\frac{\eta^2}{16}\Bigg(-2\,(1-x)\log(1-x)-\frac{2\log x}{1-x}+\frac{3}{2}(1+x)\log x-\frac{x}{2} \\
-\;& \frac{5}{2}\Bigg)+\left(\frac{\eta}{2}\right)^3\Bigg[-\frac{1}{2}(1+x)\left(\frac{9}{32}-\frac{\pi^2}{12}+\frac{3}{4}\log(1-x)+\frac{1}{2}\log^2(1-x)\right. \\
-\;& \left.\frac{1}{4}\log x\log(1-x)+\frac{1}{16}\log^2 x-\frac{1}{4}\mathrm{Li}_2(1-x)\right) \\
+\;& \frac{1}{2}\,\frac{1+x^2}{1-x}\left(-\frac{3}{8}\log x+\frac{1}{12}\log^2 x-\frac{1}{2}\log x\log(1-x)\right) \\
-\;& \frac{1}{4}(1-x)\left(\log(1-x)+\frac{1}{4}\right)+\frac{1}{32}(5-3x)\log x\Bigg]\;;\;\eta\;=\;\frac{2\,\alpha}{\pi}\left(\log\left(\frac{Q^2}{m_e^2}\right)-1\right)
\end{aligned}
$$