MSSM Parameter determination via $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-$: NLO corrections

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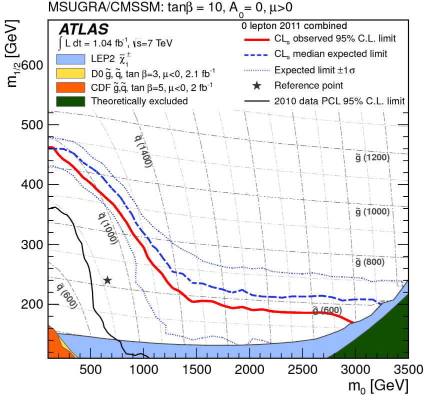
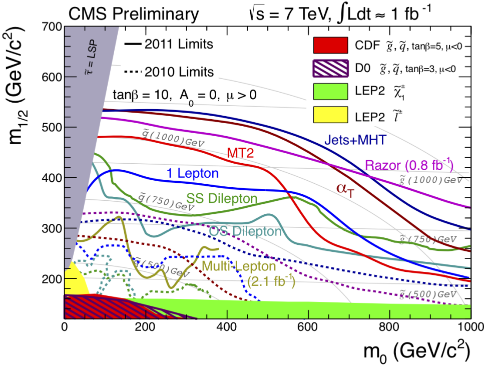
Outline

- Beyond the CMSSM
- The Chargino-Neutralino sector
- Parameter determination via $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-$
- Incorporating NLO corrections
- Results of fit for Chargino production@LC

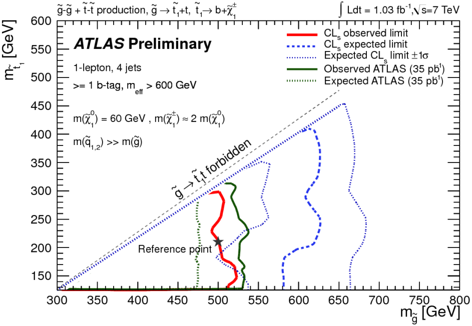
Status of the CMSSM at ATLAS and CMS



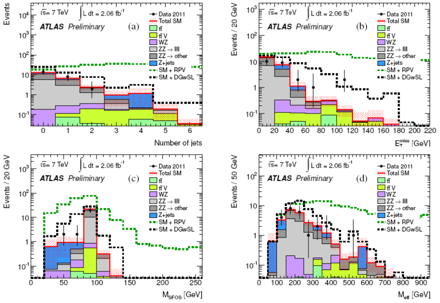


Beyond the CMSSM (e.g. at ATLAS)

Stop searches (ATLAS-CONF-2011-130)



4 leptons + E^T_{miss} at ATLAS (taken from ATLAS-CONF-2012-001)



$m_{\tilde{\chi}_1^\pm}$ 2 $m_{\tilde{\chi}_1^0}$, decays via virtual $W^\pm$ (BR=11%)

After applying $E^T_{\text{miss}} > 50$ GeV, 4 events, 1.7 ± 0.9 expected ...

Quick recap: Chargino and Neutralino Sector

$$\mathcal{L}_{\tilde{\chi}} = \overline{\tilde{\chi}_i^-}(\not{p}\,\delta_{ij} - \omega_L(U^* X V^\dagger)_{ij} - \omega_R(V X^\dagger U^T)_{ij})\tilde{\chi}_j^- + \frac{1}{2}\overline{\tilde{\chi}_i^0}(\not{p}\,\delta_{ij} - \omega_L(N^* Y N^\dagger)_{ij} - \omega_R(N Y^\dagger N^T)_{ij})\tilde{\chi}_j^0$$

$$X = \begin{pmatrix} M_2 & \sqrt{2} M_W \sin\beta \\ \sqrt{2} M_W \cos\beta & \mu \end{pmatrix}$$

diagonalised via $\mathbf{M}_{\tilde{\chi}^+} = U^* X V^\dagger$

[0] where we define $\omega_{L/R} = \frac{1}{2}(1 \mp \gamma_5)$

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$$Y = \begin{pmatrix} M_1 & 0 & -M_Z c_\beta s_W & M_Z s_\beta s_W \\ 0 & M_2 & M_Z c_\beta c_W & -M_Z s_\beta c_W \\ -M_Z c_\beta s_W & M_Z c_\beta c_W & 0 & -\mu \\ M_Z s_\beta s_W & -M_Z s_\beta c_W & -\mu & 0 \end{pmatrix}$$

diagonalised via $\mathbf{M}_{\tilde{\chi}^0} = N^* Y N^\dagger$

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Chargino production@LC

Parameter determination at tree-level:

- Analyse $\sigma^{\pm}_{L/R}\{i,j\}$ i.e. L/R polarised $\tilde{\chi}^+_i \tilde{\chi}^-_j$ production cross-section[1]
- From $\sigma^{\pm}_{L/R}\{1,1\}$ determine M_2, μ and $\tan\beta$[2]
- M_1 then extracted from the neutralino sector
- Assume $\sqrt{s} \leq 500$ GeV, $500\,\mathrm{fb}^{-1}$, $P_{e^-} = \mp 80\%$ and $P_{e^+} = \pm 60\%$

[1] K. Desch, J. Kalinowski, G. A. Moortgat-Pick, M. M. Nojiri and G. Polesello, [arXiv:hep-ph/0312069].

[2] Input SPS1a: $M_1 = 99.13$ GeV, $M_2 = 192.7$ GeV, $\mu = 352.4$ GeV and $\tan\beta = 10$

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SUSY Parameters				Mass Predictions		
M_1	M_2	μ	$\tan\beta$	$m_{\tilde{\chi}^\pm_2}$	$m_{\tilde{\chi}^0_3}$	$m_{\tilde{\chi}^0_4}$
99.1 ± 0.2	192.7 ± 0.6	352.8 ± 8.9	10.3 ± 1.5	378.8 ± 7.8	359.2 ± 8.6	378.2 ± 8.1

Table: SUSY parameters with 1σ errors derived from the analysis of the assumed LC data collected at the first phase of operation. Shown are also the predictions for the heavier chargino/neutralino masses.

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Why incorporate loop effects?

SUSY loop effects known to be **large**:

- Fundamental parameter determination possible in chargino and neutralino sector at LC to percent level, loop effects critical such that **theory meets experimental accuracy**
- Sensitivity to parameters arising via loops, e.g. stop sector

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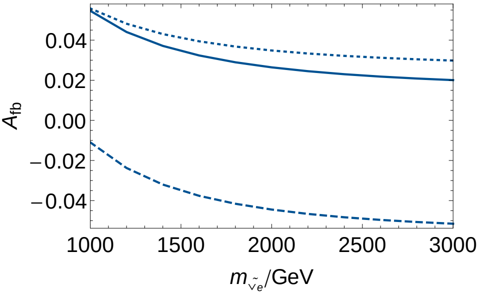

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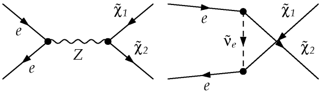
Parameter determination at NLO:

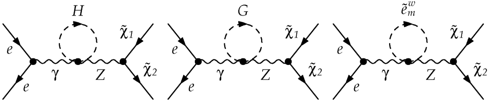
- Use NLO corrected masses and cross-sections
- Use A_{fb} as additional measurement
- Fit to M_1, M_2, μ, $\tan\beta$, + stop sector $m_{\tilde{t}_1}$, $m_{\tilde{t}_2}$ and $\cos\theta_t$

Example diagrams for $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-$ at one-loop

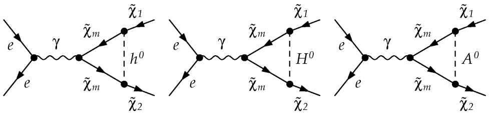
Tree:



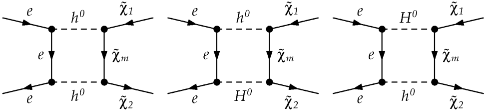
Self-energy:



Vertex:

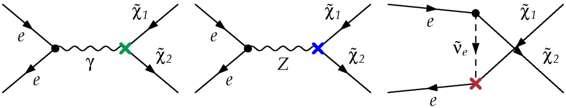


Box:



Calculate using `FeynArts, FormCalc, LoopTools`

Getting finite results: selected counter-terms



Renormalize $\gamma\tilde{\chi}_i^+\tilde{\chi}_j^-$, $Z\tilde{\chi}_i^+\tilde{\chi}_j^-$ and $e\tilde{\nu}_e\tilde{\chi}_i^+$ vertices[3]

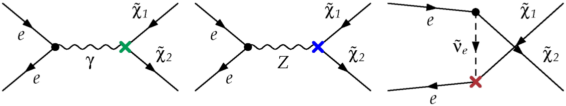
$$\delta\Gamma^L_{\tilde{\chi}_i^+\tilde{\chi}_j^-\gamma} = \frac{ie}{2}\left(\delta_{ij}\left(2\delta Z_e + \delta Z_{\gamma\gamma}\right) - \frac{\delta Z_{Z\gamma}}{c_W s_W} C^L_{\tilde{\chi}_i^+\tilde{\chi}_j^- Z} + \delta Z^L_{ij} + \delta \bar{Z}^L_{ij}\right),$$

$$\delta\Gamma^L_{\tilde{\chi}_i^+\tilde{\chi}_j^- Z} = \frac{-ie}{c_W s_W}\left(\delta C^L_{\tilde{\chi}_i^+\tilde{\chi}_j^- Z} + C^L_{\tilde{\chi}_i^+\tilde{\chi}_j^- Z}\left(\delta Z_e - \frac{\delta c_W}{c_W} - \frac{\delta s_W}{s_W} + \frac{\delta Z_{ZZ}}{2}\right)\right.$$
$$\left. - \delta_{ij}\frac{c_W s_W}{2}\delta Z_{\gamma Z} + \frac{1}{2}\sum_{n=1,2}\left(\delta Z^L_{nj} C^L_{\tilde{\chi}_i^+\tilde{\chi}_n^- Z} + C^L_{\tilde{\chi}_n^+\tilde{\chi}_j^- Z}\delta \bar{Z}^L_{in}\right)\right)$$

$$\delta\Gamma^L_{\tilde{\nu}_e e^+\tilde{\chi}_i^-} = \frac{ie\delta_{ij}}{s_W}\left(C^L_{\tilde{\nu}_e e^+\tilde{\chi}_i^-}\left(\delta Z_e - \frac{\delta s_W}{s_W} + \frac{1}{2}\left(\delta Z_{\tilde{\nu}_e} + \delta Z_e^{R*}\right)\right.\right.$$
$$\left.\left. + \frac{1}{2}\left(\delta Z^L_{1i} U^*_{12} + \delta Z^L_{2i} U^*_{22}\right)\right) + \delta C^L_{\tilde{\nu}_e e^+\tilde{\chi}_i^-}\right).$$

[3] as in A. Bharucha, A. Fowler, G. Moortgat-Pick, G. Weiglein, [arXiv:12XX.XXXX [hep-ph]]

Getting finite results: selected counter-terms



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$$\left. - \delta_{ij}\frac{c_W s_W}{2}\delta Z_{\gamma Z} + \frac{1}{2}\sum_{n=1,2}\left(\delta Z^L_{nj} C^L_{\tilde\chi_i^+\tilde\chi_n^- Z} + C^L_{\tilde\chi_n^+\tilde\chi_j^- Z}\delta\bar Z^L_{in}\right)\right)$$

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Parameter renormalisation:

- $X + \delta X$, $Y + \delta Y \Rightarrow M_1 + \delta M_1$, $M_2 + \delta M_2$, $\mu + \delta\mu$ etc.

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where s_β denotes $\sin\beta$ etc. ($\overline{\mathrm{DR}}$ renormalisation for $\tan\beta$)

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  where s_β denotes $\sin\beta$ etc. ($\overline{\mathrm{DR}}$ renormalisation for $\tan\beta$)
- More physical masses than independent parameters $\Rightarrow$ can only choose **three masses on-shell**[4]:
  - $\tilde{\chi}^\pm_{1,2}$, $\tilde{\chi}^0_{1(2/3)}$: NCC(b/c)
  - $\tilde{\chi}^0_{1,2}$, $\tilde{\chi}^\pm_2$: NNC
  - $\tilde{\chi}^0_{1,2}$, $\tilde{\chi}^0_3$: NNN

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- $\Delta m_{\tilde{\chi}_i} = \frac{m_{\tilde{\chi}_i}}{2} \mathrm{Re}[\hat{\Sigma}^L_{ii}(m^2_{\tilde{\chi}_i}) + \hat{\Sigma}^R_{ii}(m^2_{\tilde{\chi}_i})] + \frac{1}{2} \mathrm{Re}[\hat{\Sigma}^{SL}_{ii}(m^2_{\tilde{\chi}_i}) + \hat{\Sigma}^{SR}_{ii}(m^2_{\tilde{\chi}_i})] = 0,$

  results in renormalisation conditions fixing $\delta|M_1|$, $\delta|M_2|$, $\delta|\mu|$

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Parameters

Parameter	Value	Parameter	Value
$\|M_1\|$	125 GeV	M_2	250 GeV
$\|\mu\|$	180 GeV	M_{H^+}	1000 GeV
$\|M_3\|$	1 TeV	$\tan\beta$	10
$M_{\tilde{q}_{12}}$	1.5 TeV	$M_{\tilde{f}_3}$	400/800 GeV

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Weak 3rd gen. LHC constraints

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Weak LHC constraints on charginos and neutralinos

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Rates of chargino/neutralino production

At example point....

Large σ → $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-$

Threshold scans → $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_3^0$, $e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_3^0$

	$(60\%, -80\%)$	$(-60\%, 80\%)$	$(0, 0)$
Process	cross section [fb]		
$e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-$	1450	155	515
$e^+e^- \to \tilde{\chi}_1^\pm\tilde{\chi}_2^\mp$	35	36	23
$e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0$	1.5	0.1	0.5
$e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0$	2.8	4.4	2.6
$e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_3^0$	88	72	53
$e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_4^0$	0.1	0	0
$e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_2^0$	0.2	0	0.1
$e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_3^0$	155	112	91
$e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_4^0$	0	0	0
$e^+e^- \to \tilde{\chi}_3^0\tilde{\chi}_3^0$	0.2	0.1	0.1
$e^+e^- \to \tilde{\chi}_3^0\tilde{\chi}_4^0$	11	8.6	6.6
$A_{FB}(\ell)$	-2.6%	-4.7%	-3%
$A_{FB}(\tilde{\chi}_1)$	-2.2%	-9.3%	-3%

Fitting $e^+e^- \to \tilde{\chi}^+_i \tilde{\chi}^-_j$@LC ($\mathcal{L} = 200\ \mathrm{fb}^{-1}$ and $\varepsilon = 15\%$)

Observable	Tree value	Loop correction	Error
$m_{\tilde{\chi}^\pm_1}$	149.6	–	0.2
$m_{\tilde{\chi}^\pm_2}$	292.3	–	2.0
$m_{\tilde{\chi}^0_1}$	106.9	–	0.2
$m_{\tilde{\chi}^0_2}$	164.0	2.0	1.0
$m_{\tilde{\chi}^0_3}$	188.6	-1.5	1.0
$\sigma(\tilde{\chi}^+_1\tilde{\chi}^-_1)^{350}_{(-0.8,0.6)}$	2347.5	-291.3	$1.3/\varepsilon$
$\sigma(\tilde{\chi}^+_1\tilde{\chi}^-_1)^{350}_{(0.8,-0.6)}$	224.4	7.6	$0.4/\varepsilon$
A^{350}_{FB}	-2.2%	6.8%	0.8%
$\sigma(\tilde{\chi}^+_1\tilde{\chi}^-_1)^{500}_{(-0.8,0.6)}$	1450.6	-24.4	$1.0/\varepsilon$
$\sigma(\tilde{\chi}^+_1\tilde{\chi}^-_1)^{500}_{(0.8,-0.6)}$	154.8	12.7	$0.3/\varepsilon$
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Masses from the continuum

Fitting $e^+e^- \to \tilde{\chi}_i^+\tilde{\chi}_j^-$@LC ($\mathcal{L} = 200\ \text{fb}^{-1}$ and $\varepsilon = 15\%$)

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A^{500}_{FB}	-2.6%	5.3%	1%

Masses from threshold scans

Fit Results: $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-$@LC (preliminary)

Errors

$\sim 0.5\%$

Parameter	NLO result $\pm 1\sigma (\pm 2\sigma)$	LO result $\pm 1\sigma$
$M_1/$ GeV	125.0 ± 0.6 (± 1.2)	122.0 ± 0.5
$M_2/$ GeV	250.0 ± 1.6 (± 3.0)	260.7 ± 1.4
$\mu/$ GeV	180.0 ± 0.7 (± 1.3)	176.5 ± 0.5
$\tan\beta$	10.0 ± 1.3 (± 2.6)	27.0 ± 9.0
$m_{\tilde{\nu}}/$ GeV	1500 ± 20 (± 40)	2230 ± 50
$m_{\tilde{t}_2}/$ GeV	800^{+220}_{-170} $(^{+540}_{-280})$	–

Fit Results: $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-$@LC (preliminary)

Using masses from threshold scans:

Improved Errors

Parameter	NLO result $\pm 1\sigma (\pm 2\sigma)$	NLO result $\pm 1\sigma (\pm 2\sigma)$
M_1/ GeV	$125 \pm 0.4\ (\pm 0.7)$	$125 \pm 0.3\ (\pm 0.7)$
M_2/ GeV	$250 \pm 0.6\ (\pm 1.1)$	$250 \pm 0.6\ (\pm 1.3)$
μ/ GeV	$180 \pm 0.4\ (\pm 0.8)$	$180 \pm 0.4\ (\pm 0.8)$
$\tan\beta$	$10.0 \pm 0.6\ (\pm 1.2)$	$10 \pm 0.5\ (\pm 1)$
$m_{\tilde{\nu}}$/ GeV	$1500 \pm 19\ (\pm 40)$	$1500 \pm 24\ (^{+60}_{-40})$
$\cos\theta_{\tilde{t}}$	–	$0 \pm 0.15\ (^{+0.4}_{-0.3})$
$m_{\tilde{t}_1}$/ GeV	–	$400^{+180}_{-120}\ (^{\text{at limit}}_{\text{at limit}})$
$m_{\tilde{t}_2}$/ GeV	$800^{+240}_{-160}\ (^{+700}_{-260})$	$800^{+300}_{-170}\ (^{+1000}_{-290})$

Sensitivity to additional parameters

Summary and Outlook

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- Tree-level parameter determination possible up to $\mathcal{O}(\%)$ level at a LC via $\tilde{\chi}^0/\tilde{\chi}^\pm$ production
- Full $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-$@NLO calculated
- Extract parameters $\mathbf{M_1}$, $\mathbf{M_2}$, μ, $\tan\beta$, $\mathbf{m_{\tilde{t}_i}}$ and $\cos\theta_{\mathbf{t}}$ from fit to **NLO** predictions for masses, polarised cross-sections and $A_{\rm fb}$
- Increased sensitivity to larger number of parameters compared to LO analyses
- Show **crucial** role played by improved determination of masses from threshold scans

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Outlook

- Study various other scenarios
- Investigate **sensitivity to** $\phi_{\mathbf{t}}$

Obtaining an IR finite result for e^+e^- to charginos

- Must include soft radiation as external charged particles, but this introduces a cut-off.
- Phase-space slicing method, divide the photonic corrections phase space into soft ($E < \Delta E$), collinear ($\theta < \Delta\theta$) and finite regions

$$\sigma^{\text{full}} = \sigma^{\text{tree}} + \sigma^{\text{virt+soft}} + \sigma^{\text{soft}} + \sigma^{\text{coll}}.$$

- Interested in weak SUSY corrections:

$$\sigma^{\text{weak}} = \sigma^{\text{virt+soft}}(\Delta E) - \frac{\alpha}{\pi}\sigma^{\text{tree}}\left(\log\frac{4\Delta E^2}{s}(L_e - 1 + \Delta_\gamma) + \frac{3}{2}L_e\right),$$

  where Δ_γ is given by the coefficient of the terms in the soft photon correction arising from final state radiation, and the interference between initial and final state radiation, which contain ΔE.
- Left with the “reduced genuine SUSY cross-section” as defined by the SPA convention
- Using `FormCalc`, can automatically include soft correction

Existing results for for e^+e^- to charginos

- Compared to existing results[5], where the corrections are calculated in the $\mathrm{SPS1a'}$ benchmark scenario.
- In Oller et al., 2005, different approaches adopted for the renormalisation of the chargino and neutralino mixing matrices, of $\tan\beta$ and of the electric charge. In addition the sneutrino mass must be shifted in order to allow the selectron mass to be chosen on-shell, as the selectron enters neutralino production which is studied in the same work
- Our results compare up to expected accuracy taking into account these differences in renormalisation approach
- Approach to chargino-neutralino renormalisation by Fritzsche, 2005 is comparable to ours, but differs in renormalisation of $\tan\beta$, our results found to be within a percent

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[5] W. Oller, H. Eberl and W. Majerotto, Phys. Rev. D **71** (2005) 115002 [arXiv:hep-ph/0504109] and T. Fritzsche, PhD Thesis, Cuvillier Verlag, Göttingen 2005, ISBN 3-86537-577-4