International Workshop on Future Linear Colliders

LCWS13

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Determining SUSY parameters from chargino production: including NLO corrections

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in collaboration with Aoife Bharucha, Gudrid Moortgat-Pick, Krzysztof Rolbiecki and Georg Weiglein

Motivation

Fantastic first three years of LHC runs with plenty of data

- from the „rediscovery" of the SM
  - to precise SM measurements
    - culminated with the discovery of a Higgs ~ 125 GeV
      - Nobel prize to Higgs and Englert

A new era has begun

- already quite precise measurements of H properties
  - great success of a weakly coupled SM
    - but unlikely that the SM is the ultimate theory

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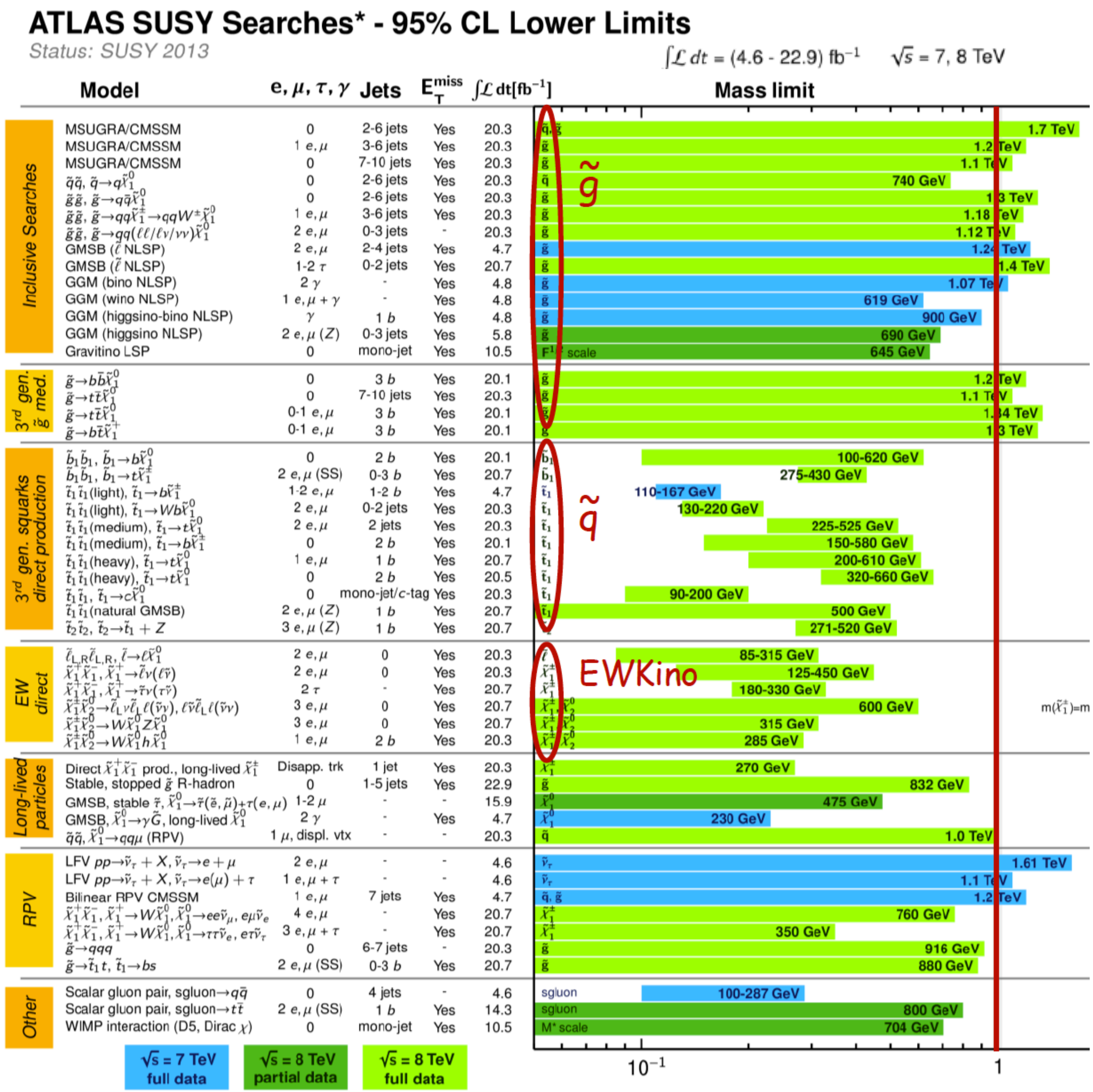
Supersymmetry – theoretically and experimentally most studied proposition for the beyond SM physics

So far the LHC results do not show any direct sign of supersymmetry!



D.Teyssier

But we should have expected it: LEP data, precision flavour data, gauge coupling unification were pointing in that direction

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But we should have expected it: LEP data, precision flavour data, gauge coupling unification were pointing in that direction

Deviations from the SM Higgs couplings may be small

Need high precision measurements: a new Linear Collider would be an ideal place for such measurements

Since LHC restrictions on charginos, neutralinos and 3rd generation sfermions are less restrictive, chances are that they might be within a reach of a LC

Does the LHC exclude SUSY Particles at the ILC?

Sven Heinemeyer, IFCA (CSIC, Santander)

Tokyo, 11/2013

NO!

Be ready for new discoveries and measurements at the LC

Outline

- Chargino and neutralino sectors
- Parameter determination from chargino production at LO
- NLO corrections
- Fit strategy and numerical results at NLO
- Summary and outlook

see: Bharucha, JK, Moortgat-Pick, Rolbiecki, Weiglein
Eur.Phys.J. C73 (2013) 2446

Chargino and neutralino sectors

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

chargino mass-eigenstates $M_{\tilde{\chi}^+} = U^* X V^\dagger$

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

$s_\beta = \sin\beta$

neutralino mass-eigenstates $M_{\tilde{\chi}^0} = N^* Y N^\dagger$

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

Parameter determination from –inos at LO

Strategy at tree-level

- production cross sections with polarized beams
- masses of accessible charginos and neutralinos
- fit $M_1, \quad M_2, \quad \mu, \quad \tan\beta$
- and predict masses of heavy charginos and neutralinos

SUSY Parameters				Mass Predictions		
M_1	M_2	μ	$\tan\beta$	$m_{\tilde{\chi}_2^\pm}$	$m_{\tilde{\chi}_3^0}$	$m_{\tilde{\chi}_4^0}$
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

Desch, JK, Moortgat-Pick, Nojiri, Polesello hep-ph/0312069

- A_{FB} gives sensitivity to sneutrino mass

Desch, JK, Moortgat-Pick, Rolbiecki, Stirling hep-ph/0607104

→ precision $\mathcal{O}(1\%)$ level

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Recent analysis of the higgsino scenario ➔ see talk by H. Sert

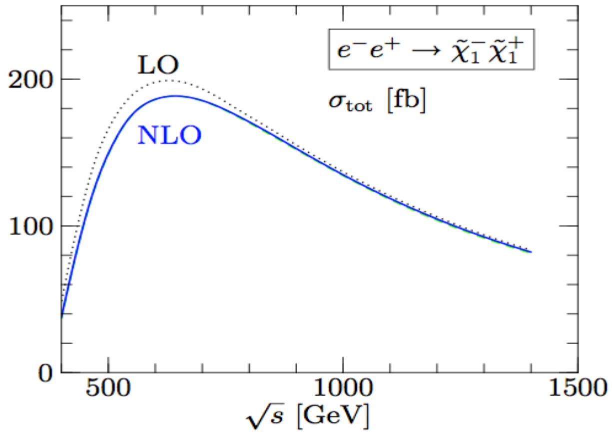
@ 2 ab^{-1}	input	lower	upper
M_1 [TeV]	1.7	$\sim$ 1.0 (-0.4)	$\sim$ 6.0
M_2 [TeV]	4.4	$\sim$ 2.5 (3.5)	$\sim$ 8.5
μ [GeV]	165.7	166.2	170.1

@ 2 ab^{-1}	input	lower	upper
M_1 [TeV]	5.3	$\sim$ 3	no
M_2 [TeV]	9.5	$\sim$ 7	$\sim$ 15
μ [GeV]	167.2	165.2	167.4

Berggren, Bruemmer, List, Moortgat-Pick, Robens, Rolbiecki, Sert 1307.3566

Need for NLO corrections

- SUSY loop corrections known to be sizable



Fritzsche, Hollik hep-ph/0407095
Oeller, Eberl, Majerotto hep-ph/0504109
Kilian, Reuter, Robens hep-ph/0607127
Robens, JK, Rolbiecki, Kilian,Reuter 0803.4161

see also S.Heinemeyer's talk

- Sensitivity to parameters arising via loops, e.g. stop sector
- New effects at loop level, e.g. CP asymmetries in production of non-diagonal chargino pairs

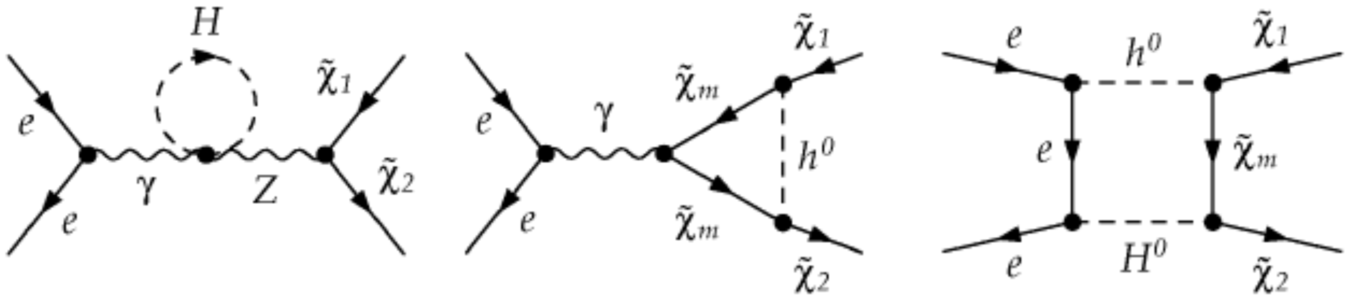
Osland, Vereshagin 0704.2165
Rolbiecki, JK 0709.2994

- Expected experimental accuracies better than 1%

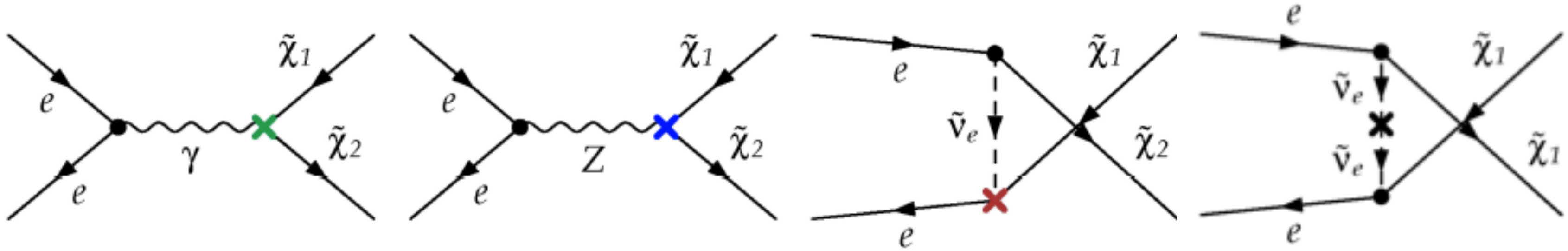
➔ loop effects critical that theory meets experiment

Loop corrections

Loops



Counter-terms



calculated using FeynArts, FormCalc, LoopTools

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

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

see Bharucha, Fowler, Moortgat-Pick, Weiglein 1211.3134

Parameter renormalization

❖ the mass matrix in the chargino sector is renormalized as

$$X \to X + \delta X \qquad \text{where}$$

$$\delta X = \begin{pmatrix} \delta M_2 & \dfrac{\delta M_W^2 s_\beta}{\sqrt{2} M_W} + M_W s_\beta c_\beta^2 \delta t_\beta \\ \dfrac{\delta M_W^2 c_\beta}{\sqrt{2} M_W} - M_W c_\beta s_\beta^2 \delta t_\beta & \delta\mu \end{pmatrix}$$

❖ in the similar manner the mass matrix for neutralinos $Y \to Y + \delta Y$ which contains δM_1

❖ $\tan\beta$ renormalized in DRbar scheme

❖ more physical masses than independent parameters

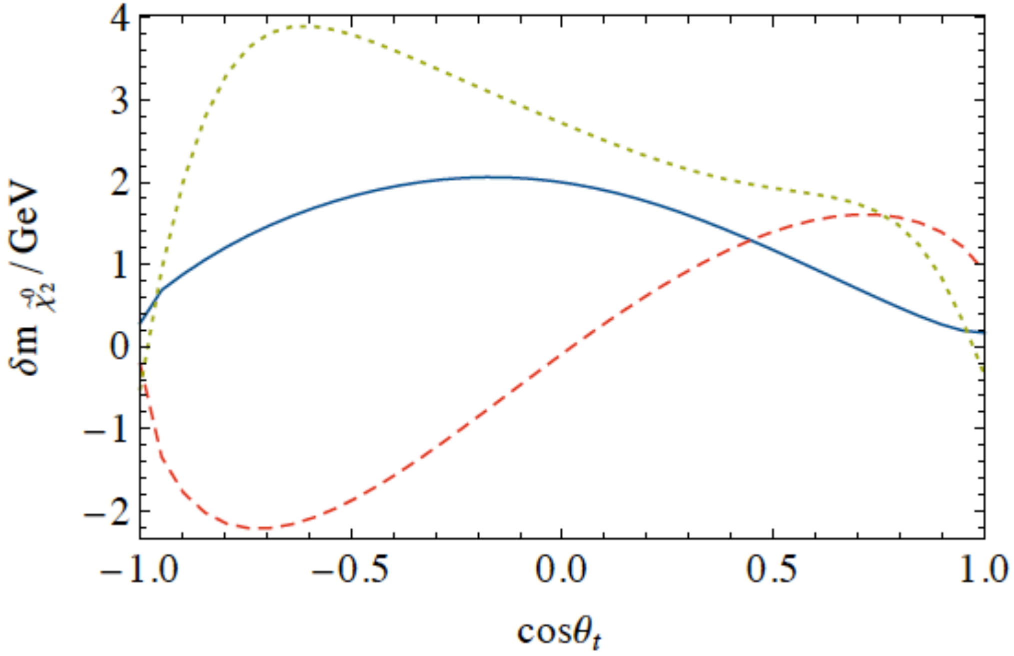
fix $\delta M_1,\ \delta M_2$ and $\delta\mu$ from three physical masses

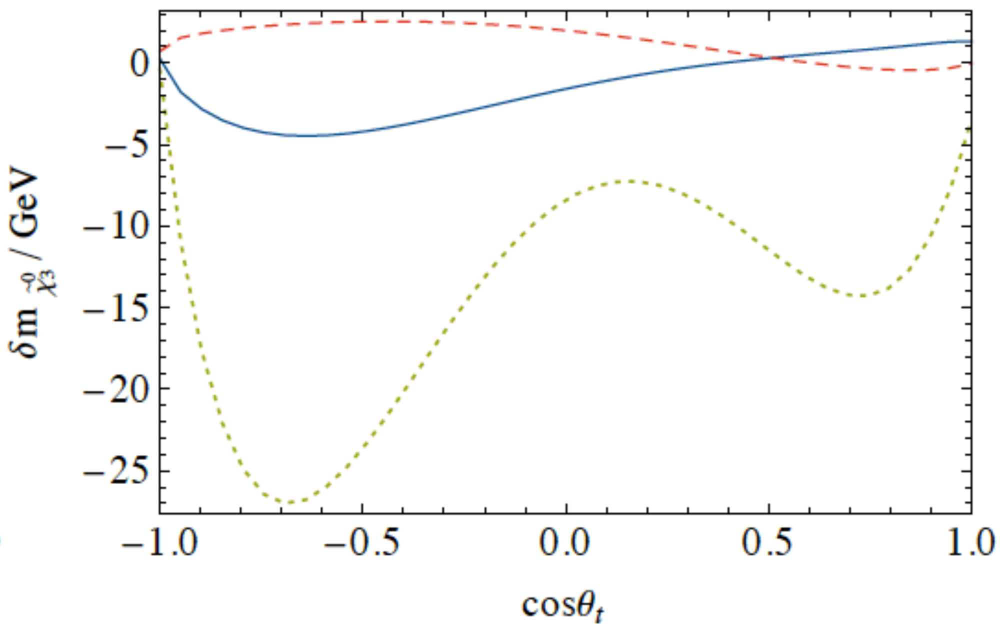
on-shell conditions

we use $\tilde{\chi}_1^0$, $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^\pm$ on-shell mass conditions (NCC)

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

heavier neutralino masses get loop corrections





Fit strategy

- As input for the fit take:
  - the masses of the charginos $(\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^{\pm})$ and neutralinos $(\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0)$
  - the light chargino production cross section $\sigma(\tilde{\chi}_1^+\tilde{\chi}_1^-)$ with polarised beams at $\sqrt{s} = 400$ and 500 GeV $\mathcal{L} = 200\ \mathrm{fb}^{-1}$
  - the forward-backward asymmetry A_{FB} at $\sqrt{s} = 400$ and 500 GeV
  - the Higgs boson mass, m_h
  - the branching ratio $\mathcal{B}(b \to s\gamma)$
  - the anomalous muon magnetic moment

- Perform a multi-dimensional fit using Minuit

$$\chi^2 = \sum_i \left| \frac{\mathcal{O}_i - \bar{\mathcal{O}}_i}{\delta \mathcal{O}_i} \right|^2$$

LHC compatible scenario

Parameter	Value	Parameter	Value
M_1	106	M_2	212
μ	180	M_{A^0}	500
M_3	1500	$\tan\beta$	12
$M_{e_{1,2}}$	125	M_{e_3}	106
M_{l_i}	180	M_{q_i}	1500
M_{u_3}	450	$A_{f_{1,2}}$	-1850

- light stops, other squarks and gluino heavy
- large stop mixing to get the Higgs mass 125 GeV
- light sleptons (accesible at both LHC and LC)
- gaugino-higgsino mixture and relatively heavy A0 to satisfy relic density, $b \to s\gamma$ and a_μ

Numerical results

Observable	Tree value	Loop correction	Error	
$m_{\tilde{\chi}_1^\pm}$	139.3	–	0.1	(0.2)
$m_{\tilde{\chi}_2^\pm}$	266.2	–	0.5	(2)
$m_{\tilde{\chi}_1^0}$	92.8	–	0.2	
$m_{\tilde{\chi}_2^0}$	148.5	2.4	0.5	(1)
$m_{\tilde{\chi}_3^0}$	189.7	-7.3	0.5	(1)
$\sigma(\tilde{\chi}_1^+\tilde{\chi}_1^-)^{400}_{(-0.8,0.6)}$	709.7	-85.1	0.7	
$\sigma(\tilde{\chi}_1^+\tilde{\chi}_1^-)^{400}_{(0.8,-0.6)}$	129.8	20.0	0.3	
A_{FB}^{400}	24.7%	-2.8%	1.4%	
$\sigma(\tilde{\chi}_1^+\tilde{\chi}_1^-)^{500}_{(-0.8,0.6)}$	560.0	-70.1	0.7	
$\sigma(\tilde{\chi}_1^+\tilde{\chi}_1^-)^{500}_{(0.8,-0.6)}$	97.1	16.4	0.3	
A_{FB}^{500}	39.2%	-5.8%	1.5%	
$b \to s\gamma$	$2.7 \cdot 10^{-4}$	–	$0.3 \cdot 10^{-4}$	
m_h	125	–	1	

(when masses from continuum)

Numerical results

Parameter	Loop fit
M_1	$106 \pm 0.3\ (\pm 0.6)$
M_2	$212 \pm 0.5\ (\pm 1.0)$
μ	$180 \pm 0.6\ (\pm 1.2)$
$\tan\beta$	$12 \pm 0.6\ (\pm 1.3)$
$\cos\theta_{\tilde{t}}$	$0.15^{+0.08}_{-0.07}\ (^{+0.16}_{-0.14})$
$m_{\tilde{t}_1}$	$430^{+360}_{-130}\ (^{+900}_{-180})$
$m_{\tilde{t}_2}$	$1520^{+260}_{-260}\ (^{+490}_{-520})$

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with m_h and $b \to s\gamma$ constraints

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$\tan\beta$	$12 \pm 0.3\ (\pm 1.1)$
$\cos\theta_{\tilde{t}}$	$0.15^{+0.08}_{-0.06}\ (^{+0.16}_{-0.09})$
$m_{\tilde{t}_1}$	$430^{+170}_{-120}\ (^{+350}_{-170})$
$m_{\tilde{t}_2}$	$1520^{+110}_{-150}\ (^{+240}_{-270})$

Summary and outlook

Summary:

- Tree-level parameter determination possible to $\mathcal{O}(1\%)$ at a LC from chargino/neutralino production
- Full NLO calculation of chargino production at a LC
- Extract parameters $\mathrm{M_1}, \mathrm{M_2}, \mu, \tan\beta, \mathrm{m_{\tilde{t}_i}}$ and $\cos\theta_{\mathrm{t}}$ at NLO from polarized cross-sections, FB asymmetries and masses
- Sensitivity to larger set of parameters, in particular stop sector
- Crucial role played by mass measurements from threshold scans
- Improved sensitivity from including m_h and $b \to s\gamma$ in the fit

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Outlook:

- investigate sensitivity to CP phases, e.g. ϕ_t
- include other observables, e.g. A_{12}, $B \to \mu^+\mu^-$

Backups

Comparing fits using NLO and LO expressions

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

Impact of mass measurements on fit results

Parameter	Threshold fit	Continuum fit
M_1	125 ± 0.3 (± 0.7)	125 ± 0.6 (± 1.2)
M_2	250 ± 0.6 (± 1.3)	250 ± 1.6 (± 3)
μ	180 ± 0.4 (± 0.8)	180 ± 0.7 (± 1.3)
$\tan\beta$	10 ± 0.5 (± 1)	10 ± 1.3 (± 2.6)
$m_{\tilde{\nu}}$	1500 ± 24 $\left({}^{+60}_{-40}\right)$	1500 ± 20 (± 40)
$\cos\theta_{\tilde{t}}$	0 ± 0.15 $\left({}^{+0.4}_{-0.3}\right)$	–
$m_{\tilde{t}_1}$	400^{+180}_{-120} $\left({}^{\text{at limit}}_{\text{at limit}}\right)$	–
$m_{\tilde{t}_2}$	800^{+300}_{-170} $\left({}^{+1000}_{-290}\right)$	800^{+350}_{-220} $\left({}^{\text{at limit}}_{\text{at limit}}\right)$

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

slide borrowed from A.Bharucha