SUSY parameter determination at LHC and ILC

Snowmass, 23/08/05
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- Introduction
- SUSY measurements
- Reconstruction of the fundamental parameters
- Conclusions

Introduction

FITTINO (P. Bechtle, K. Desch, P. Wienemann and SFITTER (R. Lafaye, T. Plehn, D. Z.): tools to determine supersymmetric parameters from measurements

The workhorses:

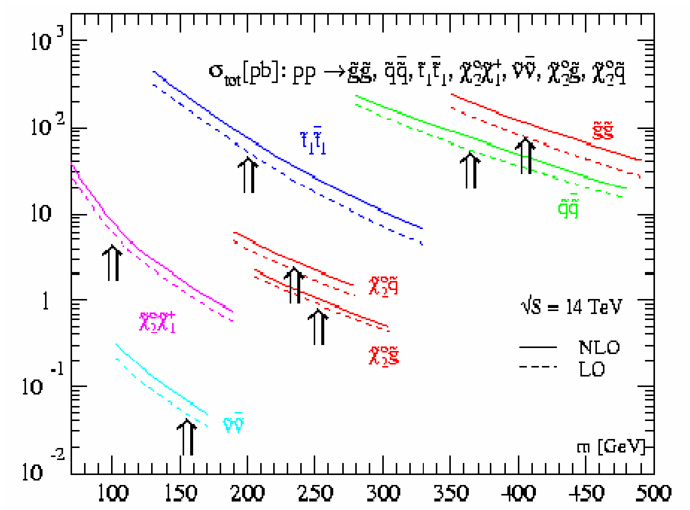
- **Mass spectra generated by SOFTSUSY, SPHENO, SUSPECT**
- **Branching ratios by MSMLIB, SPHENO**
- **e+e- cross sections by SPHENO**
- **NLO proton cross sections by Prospino2.0**

More details on technique etc: talk by Philip Bechtle on Wednesday

Models:

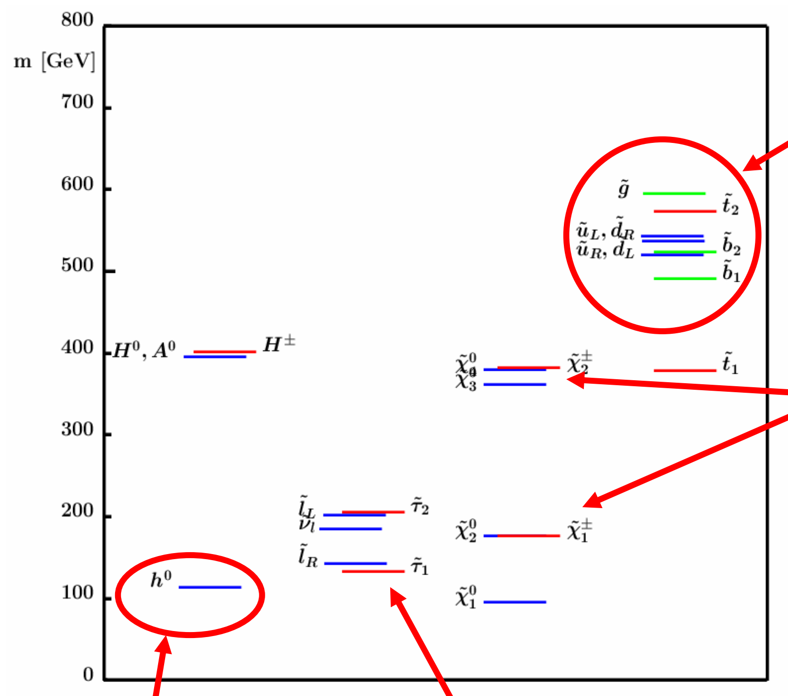
- **MSSM (minimal supersymmetric extension SM)**
- **mSUGRA (minimal supergravity)**
- **GMSB**
- **AMB**
- **NMSSM**

Beenakker et al



SPS1a and SPA1

m_0 = 100GeV $m_{1/2}$ = 250GeV A_0 = -100GeV tanβ =10 sign(μ)=+
favourable for LHC and ILC (Complementarity)



Moderately heavy gluinos and squarks

Heavy and light gauginos

Higgs at the limit of LEP reach

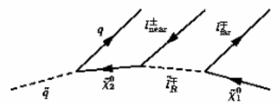
light sleptons

"Physics Interplay of the LHC and ILC"
Editor G. Weiglein hep-ph/0410364

$\tilde{\tau}_1$ lighter than lightest $\chi^\pm$:
- $\chi^\pm$ BR 100% $\tau\tilde{\nu}$
- χ_2 BR 90% $\tau\tilde{\tau}$
- cascade:

$\tilde{q}_L \to \chi_2\, q \to \tilde{\ell}_R\, \ell\, q \to \ell\, \ell$
visible

LHC:



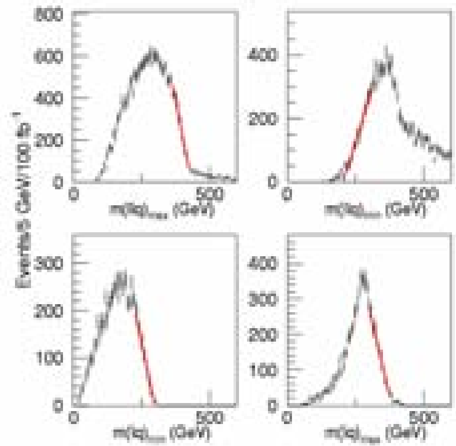
$$(m^2_{ll})^{edge} = \frac{(m^2_{\tilde\chi^0_2} - m^2_{\tilde l_R})(m^2_{\tilde l_R} - m^2_{\tilde\chi^0_1})}{m^2_{\tilde l_R}}$$

$$(m^2_{qll})^{edge} = \frac{(m^2_{\tilde q_L} - m^2_{\tilde\chi^0_2})(m^2_{\tilde\chi^0_2} - m^2_{\tilde\chi^0_1})}{m^2_{\tilde\chi^0_2}}$$

$$(m^2_{ql})^{edge}_{min} = \frac{(m^2_{\tilde q_L} - m^2_{\tilde\chi^0_2})(m^2_{\tilde\chi^0_2} - m^2_{\tilde l_R})}{m^2_{\tilde\chi^0_2}}$$

$$(m^2_{ql})^{edge}_{max} = \frac{(m^2_{\tilde q_L} - m^2_{\tilde\chi^0_2})(m^2_{\tilde l_R} - m^2_{\tilde\chi^0_1})}{m^2_{\tilde l_R}}$$

$$(m^2_{qll})^{thres} = [(m^2_{\tilde q_L} + m^2_{\tilde\chi^0_2})(m^2_{\tilde\chi^0_2} - m^2_{\tilde l_R})(m^2_{\tilde l_R} - m^2_{\tilde\chi^0_1}) - (m^2_{\tilde q_L} - m^2_{\tilde\chi^0_2})\sqrt{(m^2_{\tilde\chi^0_2} + m^2_{\tilde l_R})^2(m^2_{\tilde l_R} + m^2_{\tilde\chi^0_1})^2 - 16 m^2_{\tilde\chi^0_2} m^4_{\tilde l_R} m^2_{\tilde\chi^0_1}} + 2m^2_{\tilde l_R}(m^2_{\tilde q_L} - m^2_{\tilde\chi^0_2})(m^2_{\tilde\chi^0_2} - m^2_{\tilde\chi^0_1})]/(4m^2_{\tilde l_R} m^2_{\tilde\chi^0_2})$$



	Mass, ideal	"LHC"	"LC"	"LHC+LC"
$\tilde\chi^\pm_1$	179.7		0.55	0.55
$\tilde\chi^\pm_2$	382.3	–	3.0	3.0
$\tilde\chi^0_1$	97.2	4.8	0.05	0.05
$\tilde\chi^0_2$	180.7	4.7	1.2	0.08
$\tilde\chi^0_3$	364.7		3-5	3-5
$\tilde\chi^0_4$	381.9	5.1	3-5	2.23
$\tilde e_R$	143.9	4.8	0.05	0.05
$\tilde e_L$	207.1	5.0	0.2	0.2
$\tilde\nu_e$	191.3	–	1.2	1.2
$\tilde\mu_R$	143.9	4.8	0.2	0.2
$\tilde\mu_L$	207.1	5.0	0.5	0.5
$\tilde\nu_\mu$	191.3	–		
$\tilde\tau_1$	134.8	5-8	0.3	0.3
$\tilde\tau_2$	210.7	–	1.1	1.1
$\tilde\nu_\tau$	190.4	–	–	–
$\tilde q_R$	547.6	7-12	–	5-11
$\tilde q_L$	570.6	8.7	–	4.9
$\tilde t_1$	399.5		2.0	2.0
$\tilde t_2$	586.3		–	
$\tilde b_1$	515.1	7.5	–	5.7
$\tilde b_2$	547.1	7.9	–	6.2
$\tilde g$	604.0	8.0	–	6.5
h^0	110.8	0.25	0.05	0.05
H^0	399.8		1.5	1.5
A^0	399.4		1.5	1.5
$H^\pm$	407.7	–	1.5	1.5

Mass determination for 300fb^{-1} (thus 2014) LHC: Toy MC from edges, thresholds to masses

Polesello et al: use of χ_1 from ILC (high precision) in LHC analyses improves the mass determination

MSUGRA with masses

MSUGRA is a good testing ground for the techniques of fitting and sensitivity, but not more

Two separate questions:

- **do we find the right point?**
    - **need and unbiased starting point**
- **what are the errors?**

Start	SPS1a	LHC	ILC	LHC+ILC
m_0	100	**1TeV**	**1TeV**	**1TeV**
$m_{1/2}$	250	**1TeV**	**1TeV**	**1TeV**
tanβ	10	**50**	**50**	**50**
A0	-100	**0GeV**	**0GeV**	**0GeV**

	SPS1a	ΔLHC	ΔILC	ΔLHC+ILC
m_0	100	**3.9**	**0.09**	**0.08**
$m_{1/2}$	250	**1.7**	**0.13**	**0.11**
tanβ	10	**1.1**	**0.12**	**0.12**
A0	-100	**33**	**4.8**	**4.3**

- **Convergence to central point**
- **errors from LHC %**
- **errors from ILC 0.1%**
- **LHC+ILC: slight improvement**
- **low mass scalars dominate m_0**

Sign(μ) fixed

Masses versus Edges (LHC)

Variable	Value (GeV)	Errors Stat. (GeV)	Scale (GeV)	Total
$m_{\ell\ell}^{max}$	77.07	0.03	0.08	0.08
$m_{\ell\ell q}^{max}$	428.5	1.4	4.3	4.5
$m_{\ell q}^{low}$	300.3	0.9	3.0	3.1
$m_{\ell q}^{high}$	378.0	1.0	3.8	3.9
$m_{\ell\ell q}^{min}$	201.9	1.6	2.0	2.6
$m_{\ell\ell b}^{min}$	183.1	3.6	1.8	4.1
$m(\ell_L) - m(\tilde{\chi}_1^0)$	106.1	1.6	0.1	1.6
$m_{\ell\ell}^{max}(\tilde{\chi}_4^0)$	280.9	2.3	0.3	2.3
$m_{\tau\tau}^{max}$	80.6	5.0	0.8	5.1
$m(\tilde{g}) - 0.99 \times m(\tilde{\chi}_1^0)$	500.0	2.3	6.0	6.4
$m(\tilde{q}_R) - m(\tilde{\chi}_1^0)$	424.2	10.0	4.2	10.9
$m(\tilde{g}) - m(\tilde{b}_1)$	103.3	1.5	1.0	1.8
$m(\tilde{g}) - m(\tilde{b}_2)$	70.6	2.5	0.7	2.6

	SPS1a	ΔLHC masses	ΔLHC edges
m_0	100	**3.9**	**1.2**
$m_{1/2}$	250	**1.7**	**1.0**
$\tan\beta$	10	**1.1**	**0.9**
A0	-100	**33**	**20**

Sign(μ) fixed

- **use of masses improves parameter determination!**
- **edges to masses is not a simple “coordinate” transformation:**

Δm_0	**Effect on $m\ell_R$**	**Effect on $m\ell\ell$**
1GeV	**0.7/5=0.14**	**0.4/0.08=5**

Similar effect for $m_{1/2}$

need correlations to obtain the ultimate precision from masses….

Total Error and down/up effect

Theoretical errors (mixture of c2c and educated guess):

Higgs	sleptons	Squarks,gluinos	Neutralinos, charginos
3GeV	1%	**3%**	**1%**

Higgs error: Sven Heinemeyer et al.

	SPS1a	ΔLHC+ ILCexp	ΔLHC+ ILCth
m_0	100	**0.08**	**1.2**
$m_{1/2}$	250	**0.11**	**0.7**
tanβ	10	**0.12**	**0.7**
A0	-100	**4.3**	**17**

Including theory errors reduces sensitivity by an order of magnitude

	SPS1a	SoftSUSYup	ΔLHC+LC
m_0	100	**95.2**	**1.1**
$m_{1/2}$	250	**249.8**	**0.5**
tanβ	10	**9.82**	**0.5**
A0	-100	**-97**	**10**

Running down/up

- **spectrum generated by SUSPECT**
- **fit with SOFTSUSY (B. Allanach)**
- **central values shifted (natural)**
- **m_0 not compatible (to be checked)**
- **theoretical errors are important**

SLHC+ILC

SPS1a results LHC 300fb^{-1}

- SLHC 3000fb^{-1}
- Some improvement
- limitation: energy scale

Variable	Value (GeV)	Errors Stat. (GeV)	Errors Scale (GeV)	Errors Total
$m_{\ell\ell}^{max}$	77.07	0.03	0.08	0.08
$m_{\ell\ell q}^{max}$	428.5	1.4	4.3	4.5
$m_{\ell q}^{low}$	300.3	0.9	3.0	3.1
$m_{\ell q}^{high}$	378.0	1.0	3.8	3.9
$m_{\ell\ell q}^{min}$	201.9	1.6	2.0	2.6
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$m_{\ell\ell}^{max}(\tilde{\chi}_4^0)$	280.9	2.3	0.3	2.3
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$m(\tilde{g}) - 0.99 \times m(\tilde{\chi}_1^0)$	500.0	2.3	6.0	6.4
$m(\tilde{q}_R) - m(\tilde{\chi}_1^0)$	424.2	10.0	4.2	10.9
$m(\tilde{g}) - m(\tilde{b}_1)$	103.3	1.5	1.0	1.8
$m(\tilde{g}) - m(\tilde{b}_2)$	70.6	2.5	0.7	2.6

SLHC
0.08
4.3
3
3.8
2.1
2.1
0.5
0.8
1.8
6
5.3
1.1
1.1

	SPS1a	ΔLHC before	ΔSLHC	ΔLHC+ILC	ΔSLHC+ILC
m_0	100	1.2	0.7	0.08	0.07
$m_{1/2}$	250	1.0	0.6	0.11	0.11
tanβ	10	0.9	0.7	0.12	0.12
A0	-100	20	10	4.4	3.8

SLHC:

- factor 2 improvement
- SLHC+ILC marginal wrt LHC+ILC

MSUGRA beyond masses

Add the Higgs coupling measurements at LHC
Add the cross section measurements at ILC
Higgs branching ratios ILC

- improvement in A0 for LHC
- error reduction factor 2 in LHC+ILC

	SPS1a'	ΔLHC edges	ΔLHC all	ΔLHC+ILC
m_0	70	**1.2**	**1.4**	**0.07**
$m_{1/2}$	250	**1.7**	**1.0**	**0.07**
$\tan\beta$	10	**1.1**	**1.3**	**0.04**
A0	-300	**33**	**16**	**2.5**

	LHC	ΔLHC	LHC+ILC	ΔLHC+ILC
m_0	**70.4**	**1.4**	**67.9**	**0.08**
$m_{1/2}$	**250.7**	**1.0**	**251.6**	**0.07**
$\tan\beta$	**9.9**	**1.3**	**11.5**	**0.04**
A0	**-298**	**16**	**-162**	**2.7**
χ^2	**0.5**		**3667**	

- **Small deviation from MSUGRA:**
- **1st and 2^{nd} separated from 3^{rd}**
- **L separated from R sfermions**

clear separation of % deviations from MSUGRA via χ^2

Between MSUGRA and the MSSM

Start with MSUGRA, then loosen the unification criteria, less restricted model defined at the GUT scale:

- **$\tan\beta$, A0, $m_{1/2}$, $m_0^{sleptons}$, $m_0^{squarks}$, m_H^2 , μ**
- **experimental errors only**

Sfitter-team and Sabine Kraml

	SPS1a	LHC	ΔLHC
$m_0^{sleptons}$	100	**100**	**4.6**
$m_0^{squarks}$	100	**100**	**50**
m_H^2	10000	**9932**	**42000**
$m_{1/2}$	250	**250**	**3.5**
$\tan\beta$	10	**9.82**	**4.3**
A0	-100	**-100**	**181**

- **Higgs sector undetermined**
  - **only h (m_Z) seen**
- **slepton sector the same as MSUGRA**
  - **light scalars dominate determination of m_0**
- **smaller degradation in other parameters, but still % precision**

The highest mass states do not contain the maximum information in the scalar sector, but they do in the Higgs sector!

Beyond SPS1a at LHC

Fittino and Sfitter are not restricted to SPS1a

m_0 =1400 GeV $m_{1/2}$ = 180 GeV

A_0=700 GeV tanβ = 51 μ > 0

Study motivated by:

Wim de Boer: astro-ph/0408272 (talk yesterday and this afternoon)

Dominant Processes at the LHC:

- $g + g \rightarrow \tilde{g} + \tilde{g} (50\%)$
- $q + \bar{q} \rightarrow \tilde{\chi}_2^0 + \tilde{\chi}_1^{\pm} (20\%)$
- $f + \bar{f} \rightarrow \tilde{\chi}_1^- + \tilde{\chi}_1^+ (10\%)$

Tri-lepton signal promissing

Measurements:

- Higgs masses h,H,A
- mass difference χ_2-χ_1
- mass difference $\tilde{g}$- χ_2

Sufficient for MSUGRA

m_0 =1400 ± (50 – 530)GeV

$m_{1/2}$ = 180 ± (2-12) GeV

A_0 =700 ± (181-350) GeV

tanβ= 51 ± (0.33-2)

Uncertainties:

- b quark mass
- t quark mass
- Higgs mass prediction

MSSM

Fit the low energy parameters

LHC ILC LHC+ILC

	LHC	LC	LHC+LC	SPS1a
$\tan\beta$	10.22±9.1	10.26±0.3	10.06±0.2	10
M_1	102.45±5.3	102.32±0.1	102.23±0.1	102.2
M_2	191.8±7.3	192.52±0.7	191.79±0.2	191.8
M_3	578.67±15	fixed 500	588.05±11	589.4
$M_{\tilde{\tau}_L}$	fixed 500	197.68±1.2	199.25±1.1	197.8
$M_{\tilde{\tau}_R}$	129.03±6.9	135.66±0.3	133.35±0.6	135.5
$M_{\tilde{\mu}_L}$	198.7±5.1	198.7±0.5	198.7±0.5	198.7
$M_{\tilde{\mu}_R}$	138.2±5.0	138.2±0.2	138.2±0.2	138.2
$M_{\tilde{e}_L}$	198.7±5.1	198.7±0.2	198.7±0.2	198.7
$M_{\tilde{e}_R}$	138.2±5.0	138.2±0.05	138.2±0.05	138.2
$M_{\tilde{q}3_L}$	498.3±110	497.6±4.4	521.9±39	501.3
$M_{\tilde{t}_R}$	fixed 500	420±2.1	411.73±12	420.2
$M_{\tilde{b}_R}$	522.26±113	fixed 500	504.35±61	525.6
$M_{\tilde{q}2_L}$	550.72±13	fixed 500	553.31±5.5	553.7
$M_{\tilde{s}_R}$	529.02±20	fixed 500	531.70±15	532.1
$M_{\tilde{c}_R}$	526.21±20	fixed 500	528.90±15	529.3
$M_{\tilde{q}1_L}$	550.72±13	fixed 500	553.32±6.5	553.7
$M_{\tilde{u}_R}$	528.91±20	fixed 500	531.70±15	532.1
$M_{\tilde{d}_R}$	526.2±20	fixed 500	528.90±15	529.3
A_τ	fixed 0	-202.4±89.5	352.1±171	-253.5
A_t	-507.8±91	-501.95±2.7	-505.24±3.3	-504.9
A_b	-784.7±35603	fixed 0	-977±12467	-799.4
m_A	fixed 500	399.1±0.9	399.1±0.8	399.1
μ	345.21±7.3	344.34±2.3	344.36±1.0	344.3

MSSM fit:
bottom-up approach
24 parameters at the EW scale

LHC or ILC alone:
- **certains parameters must be fixed**

LHC+ILC:
- **all parameters fitted**
- **several parameters improved**

Caveat:
- **LHC errors ~ theory errors**
- **ILC errors << theory errors**

⇒SPA project: improvement of theory predictions and standardisation

Conclusions

- SFitter (and Fittino) will be essential to determine SUSY's fundamental parameters
  - mass differences, edges and thresholds are more sensitive than masses
  - the LHC will be able to measure the parameters at the level %
  - ILC will improve by a factor 10
  - LHC+ILC reduces the model dependence
  - Small deviations from MSUGRA easily detected
  - SLHC reduces errors by factor 2
  - MSSM can be probed at both colliders with sensitivities to different regions of the parameter space