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SPA

SUPERSYMMETRY PARAMETER ANALYSIS

Convention and Project

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for the SPA Collaboration

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+ many authors
from America, Asia and Europe

SPA

SUPERSYMMETRY PARAMETER ANALYSIS

The SPA project is a joint study of theorists and experimentalists working on LHC and Linear Collider phenomenology. The study focuses on the supersymmetric extension of the Standard Model. The main targets are

- High-precision determination of the supersymmetry Lagrange parameters at the electroweak scale
- Extrapolation to a high scale to reconstruct the fundamental parameters and the mechanism for supersymmetry breaking

The SPA convention and the SPA Project are described in the report SPA.draft.ps.

Coordinators

This list contains the coordinators from Europe only; for each sector, the coordinators from America and Asia will be added soon.

- **Chairpersons:**
  J. Kalinowski, H.-U. Martyn
- **Theory:**
  G. Bélanger (dark matter, precision data), A. Djouadi (dark matter, precision data), A. Freitas (sleptons), J. Guasch (masses/widths), J. Kalinowski (charginos/neutralinos), W. Majerotto (charginos/neutralinos), W. Hollik (masses/widths), W. Porod (extrapolation to high scales), M. Spira (squarks/gluinos), G. Weiglein (SUSY Higgs)
- **Experiment:**
  G. Blair (extrapolation to high scales), K. Desch (SUSY Higgs), H.-U. Martyn (sparticle properties, LC), G. Polesello (squarks/gluinos, LHC)
- **Coordination Program Code:**
  W. Kilian

Outline

- Introduction and Motivation
- SPA Convention
- Program Repository
- Theoretical and Experimental Tasks
- Reference Point SPS1a$'$
- Summary and Outlook

- SUSY forms a bridge between EW and GUT scale
- LHC will see SUSY if at low energy scale
- LC and LHC$\oplus$LC for precision studies
- Reconstruction of fundamental SUSY theory and breaking mechanism

from experiment:

$\rightarrow$ precision analyses of masses and couplings including higher orders

from theory:

$\rightarrow$ accurate theoretical predictions to match exp. data

$\rightarrow$ loop contributions Lagrangian param $\leftrightarrow$ observables

$\rightarrow$ RGEs for extrapolation to high scales

Precision analysis required for

- Indirect tests of the MSSM
  $\rightarrow$ virtual SUSY effects in precision observables

- Precision studies for SUSY particles
  $\rightarrow$ determination of masses & couplings
  $\rightarrow$ reconstruction of model parameters

- Direct versus indirect tests
  $\rightarrow$ precision observables for precisely measured SUSY parameters
  $\rightarrow$ consistency check

Processes with external

(i) standard particles

(ii) Higgs bosons, especially light Higgs h^0

(iii) SUSY particles
– the chargino and neutralino sector
– the sfermion sector

Detailed analysis for SPS1a benchmark scenario: potential of LHC (300 fb^{-1}) alone and LHC $+$ LC

	LHC	LHC+LC
$\Delta m_{\tilde{\chi}_1^0}$	4.8	0.05 (input)
$\Delta m_{\tilde{l}_R}$	4.8	0.05 (input)
$\Delta m_{\tilde{\chi}_2^0}$	4.7	0.08
$\Delta m_{\tilde{q}_L}$	8.7	4.9
$\Delta m_{\tilde{q}_R}$	11.8	10.9
$\Delta m_{\tilde{g}}$	8.0	6.4
$\Delta m_{\tilde{b}_1}$	7.5	5.7
$\Delta m_{\tilde{b}_2}$	7.9	6.2
$\Delta m_{\tilde{l}_L}$	5.0	0.2 (input)
$\Delta m_{\tilde{\chi}_4^0}$	5.1	2.23

LHC+LC accuracy limited by LHC jet energy scale resolution

SPS 1a benchmark scenario:

favorable scenario for both LHC and LC

$\Rightarrow$ LC input improves accuracy significantly

Charginos: Charged gauginos + higgsinos

$$\psi^R = \begin{pmatrix} -i\,\lambda^- \\ \psi^2_{H_1} \end{pmatrix}, \quad \psi^L = \begin{pmatrix} -i\,\lambda^+ \\ \psi^1_{H_2} \end{pmatrix}, \quad \lambda^\pm = \tfrac{1}{\sqrt{2}}(\lambda^1 \mp i\lambda^2)$$

Mass matrix :

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

Diagonalization :

$$\chi_j^R = U_{jk}\,\psi_k^R\,, \quad \chi_j^L = V_{jk}\,\psi_k^L\,, \quad U^*\,X\,V^\dagger = \begin{pmatrix} m_{\tilde\chi_1^+} & 0 \\ 0 & m_{\tilde\chi_2^+} \end{pmatrix}$$

Neutralinos: Neutral gauginos + higgsinos

$$\psi^{0\top} = \left(-i\lambda',\, -i\lambda^3,\, \psi^1_{H_1},\, \psi^2_{H_2}\right)$$

Mass matrix :

$$Y = \begin{pmatrix} M_1 & 0 & -M_Z\, s_W \cos\beta & M_Z\, s_W \sin\beta \\ 0 & M_2 & M_Z\, c_W \cos\beta & -M_Z\, c_W \sin\beta \\ -M_Z\, s_W \cos\beta & M_Z\, c_W \cos\beta & 0 & -\mu \\ M_Z\, s_W \sin\beta & -M_Z\, c_W \sin\beta & -\mu & 0 \end{pmatrix}$$

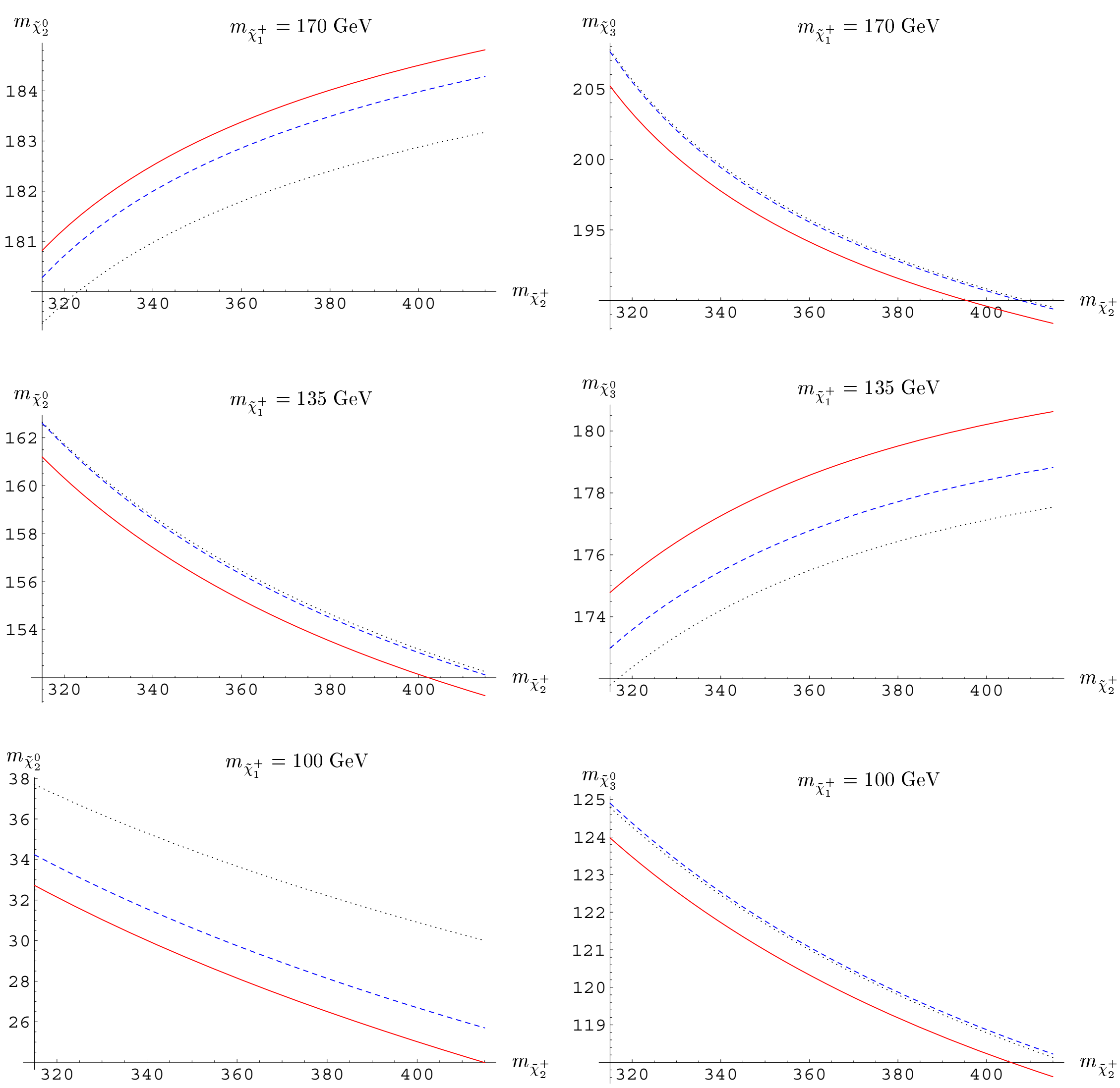
Diagonalization :

$$\chi_i^0 = N_{ij}\,\psi_j^0\,, \quad N^* Y N^\dagger = \begin{pmatrix} m_{\tilde\chi_1^0} & 0 & 0 & 0 \\ 0 & m_{\tilde\chi_2^0} & 0 & 0 \\ 0 & 0 & m_{\tilde\chi_3^0} & 0 \\ 0 & 0 & 0 & m_{\tilde\chi_4^0} \end{pmatrix}$$

pole masses

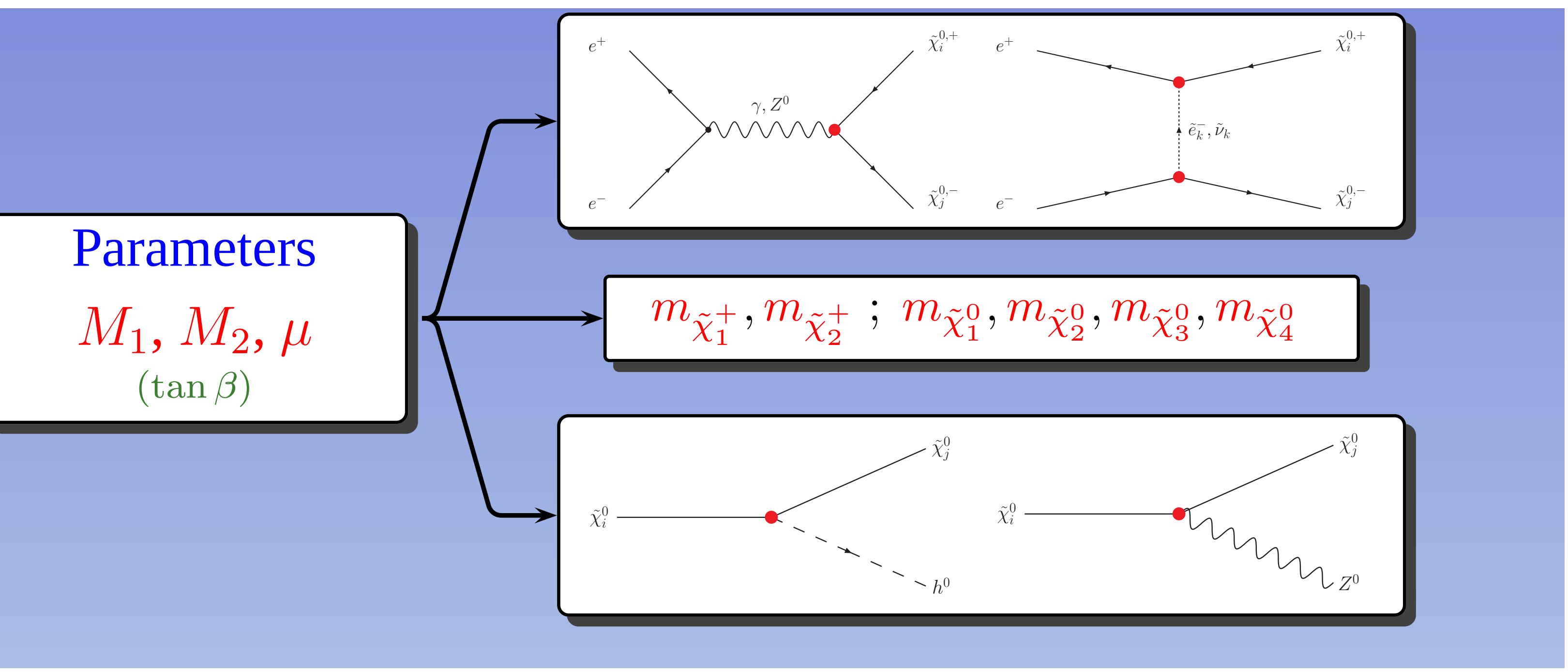
$[M_{\tilde{f}} = 300\,\text{GeV},\ \tan\beta = 10]$

$M_{\chi_1^0} = 110\,\text{GeV}$

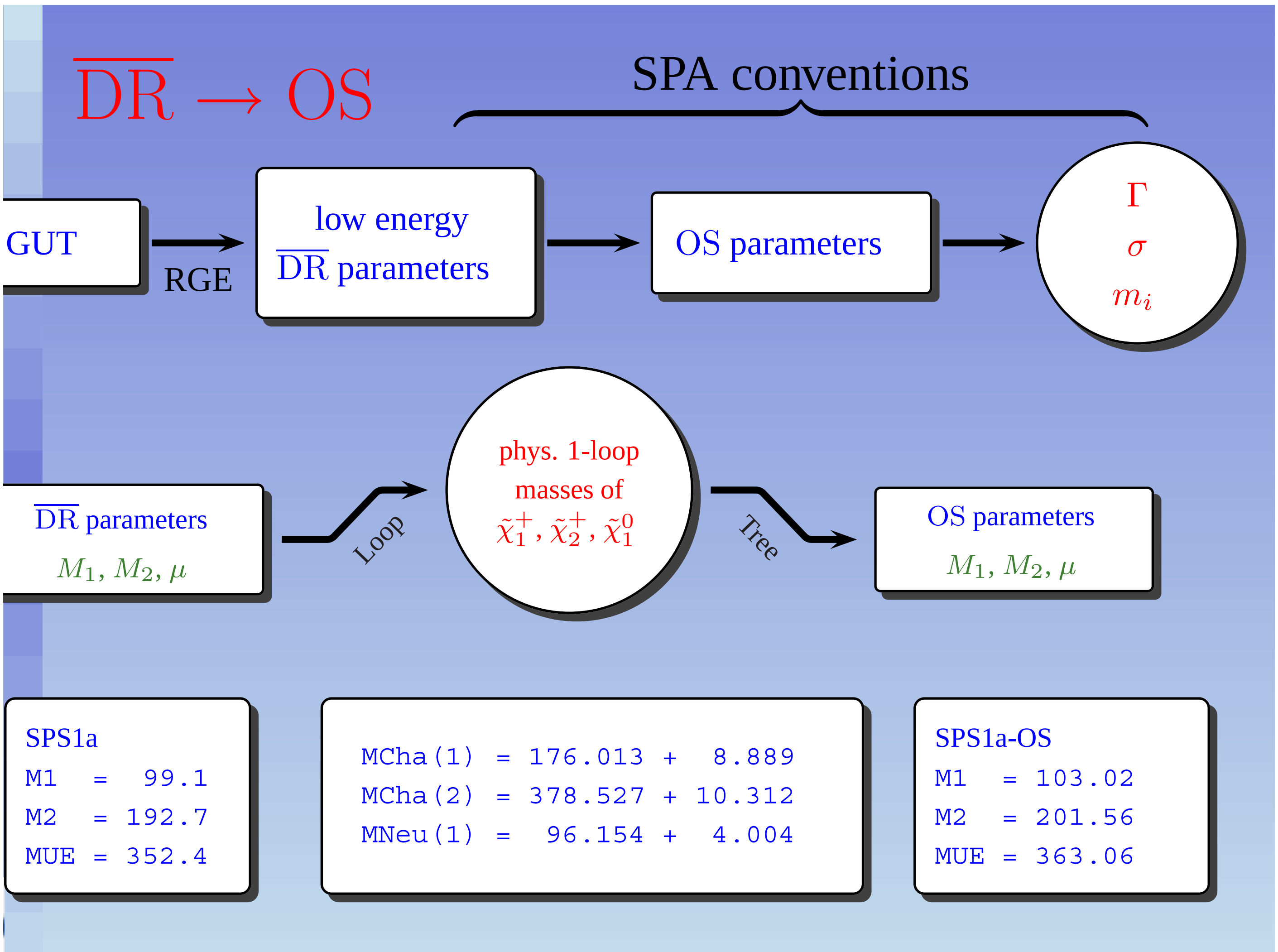


Born

complete 1-loop



Parameters
M_1, M_2, μ
$(\tan\beta)$
e^+
e^-
γ, Z^0
$\tilde{\chi}_i^{0,+}$
$\tilde{\chi}_j^{0,-}$
$\tilde{e}_k^-, \tilde{\nu}_k$
$m_{\tilde{\chi}_1^+}, m_{\tilde{\chi}_2^+}$; $m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_3^0}, m_{\tilde{\chi}_4^0}$
$\tilde{\chi}_i^0$
$\tilde{\chi}_j^0$
h^0
Z^0



$\overline{\text{DR}} \rightarrow \text{OS}$
SPA conventions
GUT
RGE
low energy
$\overline{\text{DR}}$ parameters
OS parameters
Γ
σ
m_i
$\overline{\text{DR}}$ parameters
M_1, M_2, μ
Loop
phys. 1-loop
masses of
$\tilde{\chi}_1^+, \tilde{\chi}_2^+, \tilde{\chi}_1^0$
Tree
OS parameters
M_1, M_2, μ
SPS1a
M1 = 99.1
M2 = 192.7
MUE = 352.4
MCha(1) = 176.013 + 8.889
MCha(2) = 378.527 + 10.312
MNeu(1) = 96.154 + 4.004
SPS1a-OS
M1 = 103.02
M2 = 201.56
MUE = 363.06

SPA CONVENTION

- The masses of the SUSY particles and Higgs bosons are defined as pole masses.
- All SUSY Lagrangian parameters, mass parameters and couplings, including $\tan\beta$, are given in the $\overline{DR}$ scheme and defined at the scale $\tilde{M} = 1$ TeV.
- Gaugino/higgsino and scalar mass matrices, rotation matrices and the corresponding angles are defined in the $\overline{DR}$ scheme at $\tilde{M}$, except for the Higgs system in which the mixing matrix is defined in the on-shell scheme, the scale parameter chosen as the light Higgs mass.
- The Standard Model input parameters of the gauge sector are chosen as G_F, α, M_Z and $\alpha_s^{\overline{MS}}(M_Z)$. All lepton masses are defined on-shell. The t quark mass is defined on-shell; the b, c quark masses are introduced in $\overline{MS}$ at the scale of the masses themselves while taken at a renormalization scale of 2 GeV for the light u, d, s quarks.
- Decay widths / branching ratios and production cross sections are calculated for the set of parameters specified above.

Renormalization schemes

$\overline{\mathrm{DR}}$ scheme:

- Loop integrals: $\frac{2}{\epsilon} - \gamma + \log 4\pi + \log \mu^2 \to \log \mu^2_{\overline{\mathrm{DR}}}$
- \+ easy to implement
- – observables are scale dependent in finite order perturbation theory
- \+ natural choice for GUT-inspired parameter sets (mSUGRA)

OS scheme:

- renormalization constants fixed by physical conditions
- – renormalization constants complicated
- \+ observables are scale independent
- \+ well suited for calculations of cross sections and decay rates (e.g. pole masses $\to$ correct kinematical thresholds)

DRed/DReg and $\overline{MS}$/$\overline{DR}$

Clarification:

$\overline{DR}$ scheme		DRed regularization
$\Updownarrow$	$\neq$	$\Updownarrow$
Def. of UV cts $\Leftrightarrow$ choice of renormalization conditions $\Leftrightarrow$ renormalization scheme can be chosen even in DReg		choice of UV and IR regularization all renormalization conditions can be chosen

$\overline{MS}$ scheme		DReg regularization
$\Updownarrow$	$\neq$	$\Updownarrow$
Def. of UV cts		choice of UV and IR regularization

Separation of “QED corrections”

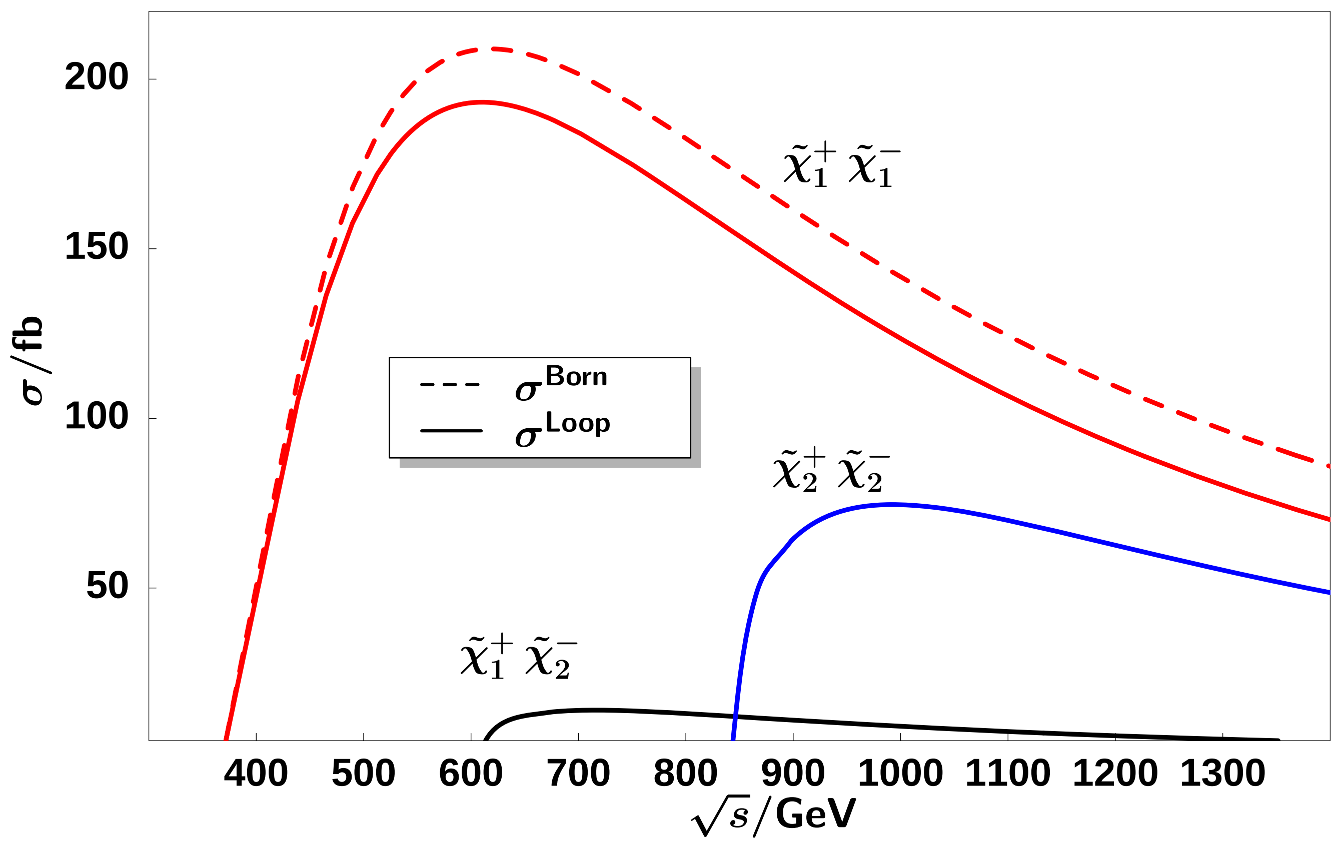
Full calculation inevitable

- separation of diagrams with virtual photons not UV-finite
- soft-photon bremsstrahlung necessary for IR-finite result
- hard bremsstrahlung for realistic treatments

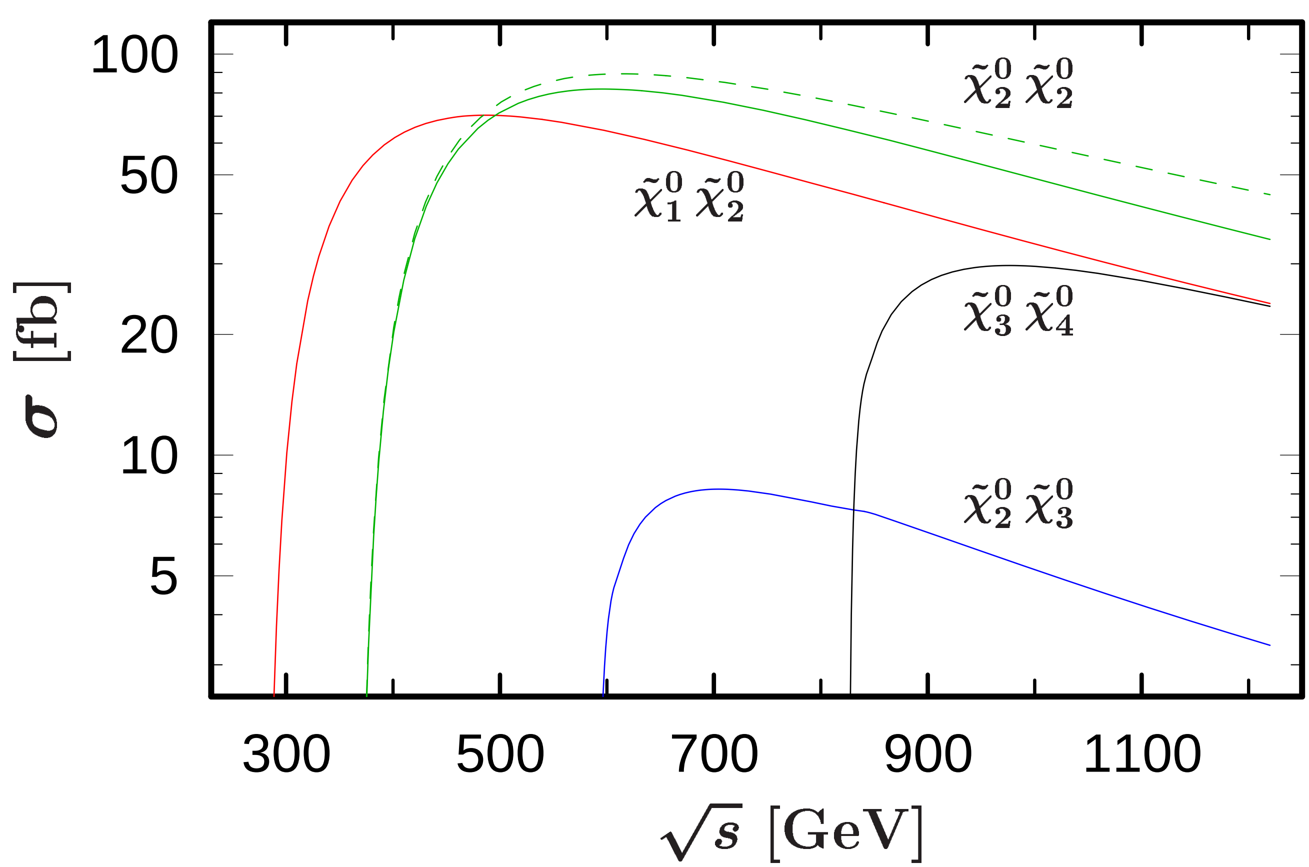
Reasonable separation $(L_e = \log \frac{s}{m_e^2},\ \Delta E = E_{\gamma\,\mathrm{soft}}^{\mathrm{max}})$:

$$
\begin{aligned}
\sigma &= \sigma_{\mathrm{QED}} + \sigma_{\mathrm{rem}}\,, \\
\sigma_{\mathrm{QED}} &= \sigma^{\mathrm{hard}} + \frac{\alpha}{\pi}\left[(L_e - 1)\log\frac{4\,\Delta E^{\,2}}{s} + \frac{3}{2}L_e\right]\sigma_0 \\
\sigma_{\mathrm{rem}} &= \sigma^{\mathrm{v+s}} - \frac{\alpha}{\pi}\left[(L_e - 1)\log\frac{4\,\Delta E^{\,2}}{s} + \frac{3}{2}L_e\right]\sigma_0
\end{aligned}
$$

- gauge invariant
- σ_{rem} free of large soft and collinear photon contributions



σ/fb
200
150
100
50
400
500
600
700
800
900
1000
1100
1200
1300
√s/GeV
σ^Born
σ^Loop
$\tilde{\chi}_1^+\,\tilde{\chi}_1^-$
$\tilde{\chi}_2^+\,\tilde{\chi}_2^-$
$\tilde{\chi}_1^+\,\tilde{\chi}_2^-$



σ [fb]
100
50
20
10
5
300
500
700
900
1100
√s [GeV]
$\tilde{\chi}_2^0\,\tilde{\chi}_2^0$
$\tilde{\chi}_1^0\,\tilde{\chi}_2^0$
$\tilde{\chi}_3^0\,\tilde{\chi}_4^0$
$\tilde{\chi}_2^0\,\tilde{\chi}_3^0$

chargino/neutralino sector

complete at one loop [MPI/Vienna] :
renormalization and mass spectrum
pair production in e^+e^- collisions

sfermion sector

OS renormalization, sfermion mass spectrum
[Hollik, Rzehak]

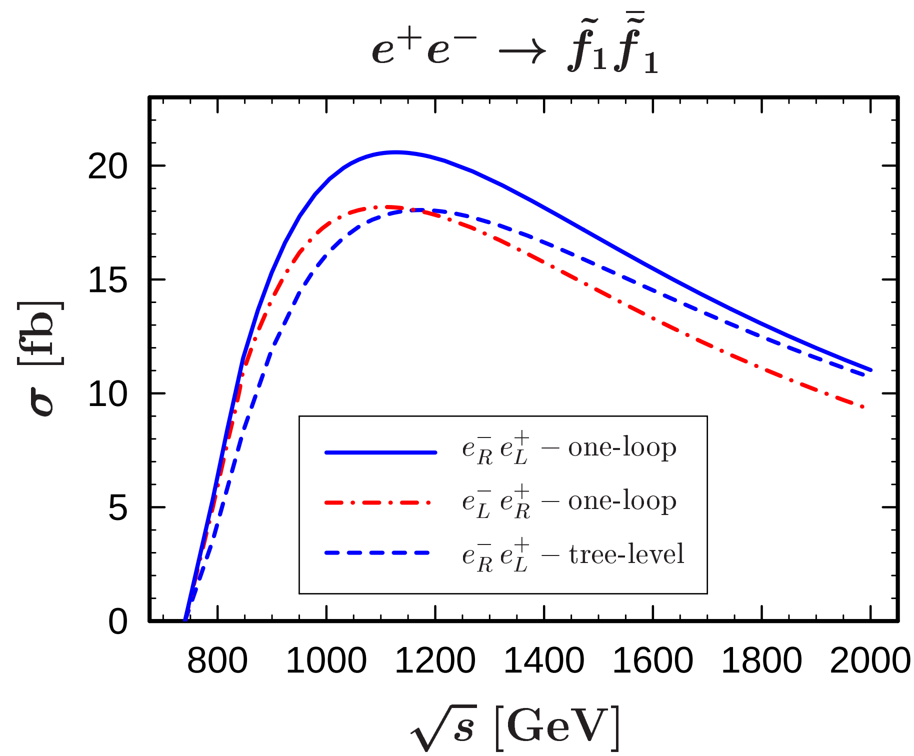
$$\begin{pmatrix} m_f^2 + M_L^2 + M_Z^2 c_{2\beta}(I_f^3 - Q_f s_W^2) & m_f(A_f - \mu\kappa) \\ m_f(A_f - \mu\kappa) & m_f^2 + M_{\tilde{f}_R}^2 + M_Z^2 c_{2\beta} Q_f s_W^2 \end{pmatrix}$$

sfermion pair production in e^+e^- collisions
complete at one-loop

[Arhrib, Hollik]	squarks, sleptons
[Kovarik, Weber, Eberl, Majerotto]	squarks
[Freitas, Miller, von Manteuffel, Zerwas]	sleptons

sfermion decays into fermions and -inos

complete at one-loop
[Guasch, Hollik, Solà]



example: $\tilde{f}_1 = \tilde{t}_1$ [from SPA draft]

Program Repository

- Scheme translation tools:

  $\overline{\text{DR}} \quad \leftrightarrow \quad \overline{\text{MS}} \quad \leftrightarrow \quad \text{on-shell}$

- Spectrum calculators:

  Higgs-boson masses, SUSY particle masses

- Other observables: decay rates, cross sections, low-energy observables, astrophysics, cosmology

- Event generators

- Analysis programs, fit programs

- Renormalization group equations

  $M_{\text{SUSY}} \quad \leftrightarrow \quad M_{\text{GUT}}$

The available codes implement various parts of the SPA setup. The following classes of programs have been defined in the SPA draft report:

1. **Scheme translation tools**
   (no codes listed so far)
2. **Spectrum calculators**
   - FeynHiggs maintained by S. Heinemeyer [Higgs sector only]
   - ISAJET/ISASUSY by H. Baer, F.E. Paige, S.D. Protopescu, and X. Tata (SLHA interface)
   - NMHDECAY by U. Ellwanger, J.F. Gunion and C. Hugonie [NMSSM Higgs sector only]
   - SOFTSUSY by B. Allanach
   - SPHENO by W. Porod
   - SUSPECT by A. Djouadi, J.-L. Kneur and G. Moultaka
3. **Calculation of other observables**
   (A) Decay tables
   - FeynHiggs maintained by S. Heinemeyer [Higgs sector only]
   - NMHDECAY by U. Ellwanger, J.F. Gunion and C. Hugonie [NMSSM Higgs sector only]
   - SDECAY by M. Mühlleitner, A. Djouadi and Y. Mambrini
   - SPHENO by W. Porod

   (B) Cross sections
   - FeynHiggs maintained by S. Heinemeyer [Higgs sector only]
   - ISAJET/ISASUSY by H. Baer, F.E. Paige, S.D. Protopescu, and X. Tata (SLHA interface)
   - PROSPINO2 maintained by T. Plehn (see also: PROSPINO1 by W. Beenakker, R. Höpker, and M. Spira)
   - PYTHIA by T. Sjöstrand, L. Lönnblad, P. Skands, and S. Mrenna (SLHA interface)
   - SPHENO by W. Porod
   - WHIZARD by W. Kilian (uses O’Mega by T. Ohl and J. Reuter)

   (C) Low-energy observables
   - FeynHiggs maintained by S. Heinemeyer [Higgs sector only; computes Δ&rho and (g-2)_μ]
   - SUSPECT by A. Djouadi, J.-L. Kneur and G. Moultaka [computes (g-2)_μ, b->sγ ...]

   (D) Cosmological and astrophysical aspects
   - MICROMEGAS by G. Belanger, F. Boudjema, A. Pukhov, and A. Semenov
4. **Event generators**
   - ISAJET/ISASUSY by H. Baer, F.E. Paige, S.D. Protopescu, and X. Tata (SLHA interface)
   - PYTHIA by T. Sjöstrand, L. Lönnblad, P. Skands, and S. Mrenna (SLHA interface)
   - WHIZARD by W. Kilian (uses O’Mega by T. Ohl and J. Reuter)
5. **Analysis programs**
   - FITTINO by P. Bechtle, K. Desch, and P. Wienemann
   - SFITTER by T. Plehn, R. Lafaye, and D. Zerwas
6. **RGE programs**
   - ISAJET/ISASUSY by H. Baer, F.E. Paige, S.D. Protopescu, and X. Tata (SLHA interface)
   - SOFTSUSY by B. Allanach
   - SPHENO by W. Porod
7. **Auxiliary programs and libraries**

Project Tasks

(i) SUSY calculations including higher orders
$\rightarrow$ match experimental precision

shift $M = 1$ TeV to 100 GeV $\rightarrow$ δ_{scale}

Particle	Mass [GeV]	δ_{scale} [GeV]
h^0	115.4	1.3
H^0	431.1	0.7
$\tilde{\chi}_1^0$	97.75	0.4
$\tilde{\chi}_2^0$	184.4	1.2
$\tilde{\chi}_4^0$	419.6	1.2
$\tilde{\chi}_1^+$	183.1	1.3
$\tilde{e}_R$	125.2	1.2
$\tilde{e}_L$	190.1	0.4
$\tilde{\tau}_1$	107.4	0.5
$\tilde{q}_R$	547.7	9.4
$\tilde{q}_L$	565.7	10.2
$\tilde{t}_1$	368.9	5.4
$\tilde{b}_1$	506.3	8.0
$\tilde{g}$	607.6	1.4

(ii) including new channels, new observables

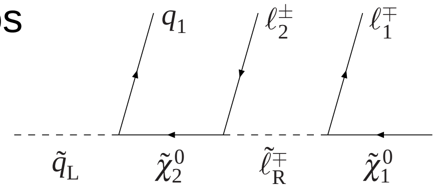
(iii) combining LHC+ILC [$\rightarrow$ G. Weiglein]

(iv) extensions: CP-MSSM, NMSSM, ...

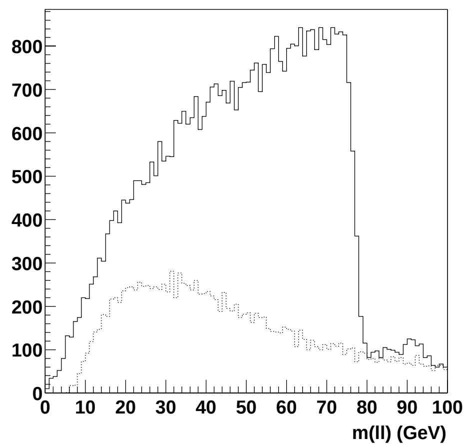
Example: Determination of SUSY parameters at LHC / LC

[*M. Chiorboli, B.K. Gjelsten, J. Hisano, K. Kawagoe, E. Lytken, U. Martyn, D. Miller, M. Nojiri, P. Osland, G. Polesello, A. Tricomi '03*]

Cascade decays: complicated decay chains for squarks and gluinos



Main tool: dilepton "edge" from $\tilde{\chi}_2^0 \to \ell^+\ell^-\tilde{\chi}_1^0$



REFERENCE POINT SPS1a′

SPS1a′ deriv. of Snowmass Point SPS1a: conform with Ω_{cdm}, LE data

mSUGRA values:

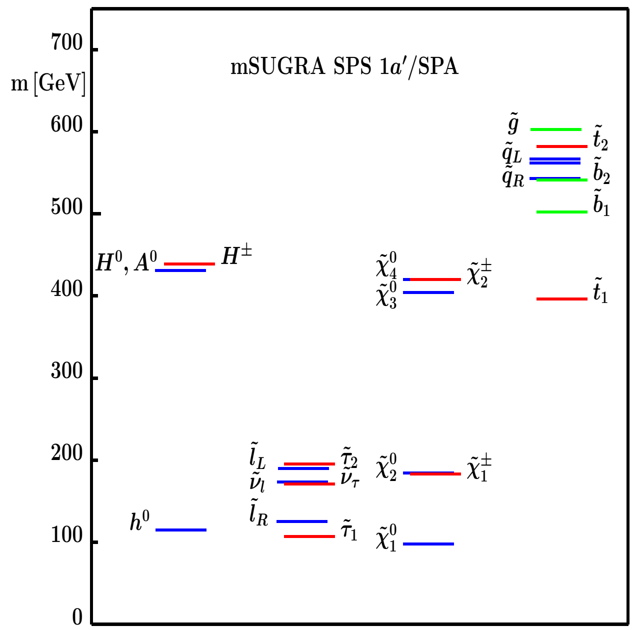
$M_{1/2}$	=	250 GeV	sign(μ)	=	+1
M_0	=	70 GeV	$\tan\beta$	=	10
A_0	=	−300 GeV			

LE/cosmic parameters:

$BR(b \to s\gamma) = 3.0 \times 10^{-4}$		micrOMEGAs
$\Delta[g_\mu - 2]/2 = 34 \times 10^{-10}$		FeynHiggs
$\Omega_{cdm} h^2 = 0.10$		micrOMEGAs

POLE MASSES:

	m [GeV]		m [GeV]
h^0	115.4	$\tilde{e}_R$	125.2
H^0	431.1	$\tilde{e}_L$	190.1
A^0	431.0	$\tilde{\nu}_e$	172.8
H^+	438.6	$\tilde{\tau}_1$	107.4
$\tilde{\chi}_1^0$	97.75	$\tilde{\tau}_2$	195.3
$\tilde{\chi}_2^0$	184.4	$\tilde{\nu}_\tau$	170.7
$\tilde{\chi}_3^0$	406.8	$\tilde{u}_R$	547.7
$\tilde{\chi}_4^0$	419.6	$\tilde{u}_L$	565.7
$\tilde{\chi}_1^+$	184.2	$\tilde{t}_1$	368.9
$\tilde{\chi}_2^+$	421.1	$\tilde{t}_2$	584.9
$\tilde{g}$	607.6	$\tilde{b}_1$	506.3



$BR(\tilde{\nu} \to \nu\chi_1^0) = 100\%$ $\Rightarrow$ $\tilde{\nu}$ invis.

Measurements

– edge effects at LHC

– decay spectra at ILC

– cross sections/asymmetries at ILC

	Mass	"LHC"	"LC"	"LHC+LC"
h^0	115.4	0.25	0.05	0.05
H^0	431.1		1.5	1.5
$\tilde{\chi}_1^0$	97.75	4.8	0.05	0.05
$\tilde{\chi}_2^0$	184.4	4.7	1.2	0.08
$\tilde{\chi}_4^0$	419.6	5.1	$3-5$	2.5
$\tilde{\chi}_1^\pm$	184.2		0.55	0.55
$\tilde{e}_R$	125.2	4.8	0.05	0.05
$\tilde{e}_L$	190.1	5.0	0.18	0.18
$\tilde{\tau}_1$	107.4	$5-8$	0.24	0.24
$\tilde{q}_R$	547.7	$7-12$	–	$5-11$
$\tilde{q}_L$	565.7	8.7	–	4.9
$\tilde{t}_1$	368.9		1.9	1.9
$\tilde{b}_1$	506.3	7.5	–	5.7
$\tilde{g}$	607.6	8.0	–	6.5

Reconstructing Lagrange param.

based on 82 simulated measurements at LHC and ILC

Parameter	SPS1a$'$value	Fit error [exp]
M_1	103.3	0.1
M_2	193.4	0.1
M_3	568.9	7.8
μ	400.4	1.1
$M_{\tilde{e}_L}$	181.3	0.2
$M_{\tilde{e}_R}$	115.6	0.4
$M_{\tilde{\tau}_L}$	179.5	1.2
$M_{\tilde{u}_L}$	523.2	5.2
$M_{\tilde{u}_R}$	503.9	17.3
$M_{\tilde{t}_L}$	467.7	4.9
$m_{\rm A}$	374.9	0.8
$A_{\rm t}$	-525.6	24.6
$\tan\beta$	10.0	0.3

High Scale Extrapolations

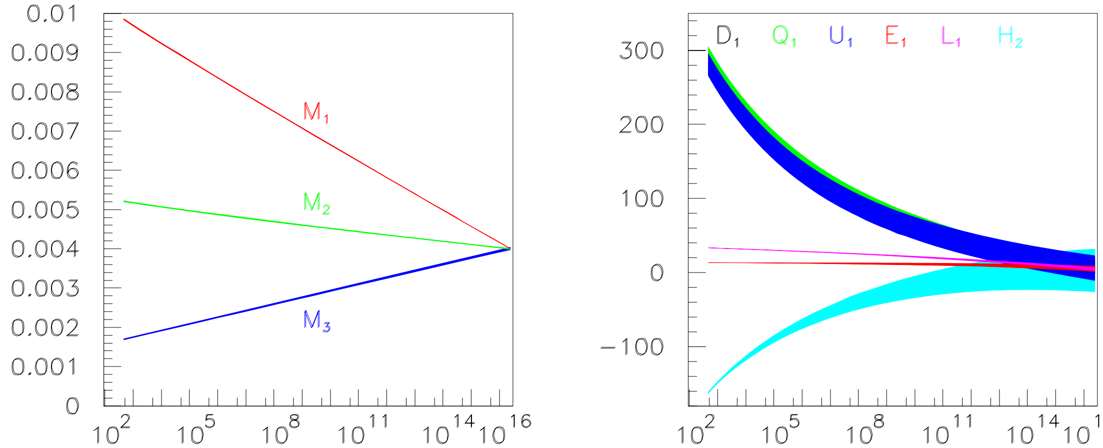


Fig. 1. *Running of the gaugino and scalar mass parameters in SPS1a′ [*`SPheno 2.2.2`*]. Only experimental errors are taken into account; theoretical errors are assumed to be reduced to the same size in the future.*

ERRORS `SPS1a′`:

mSUGRA	Parameter, ideal	"LHC+LC" errors
M_1	250. GeV	0.18 GeV
M_2	*ditto*	0.26 GeV
M_3		2.8 GeV
M_{L_1}	70. GeV	4.1 GeV
M_{E_1}	*ditto*	7.9 GeV
M_{Q_1}		11. GeV
M_{U_1}		31. GeV
M_{H_1}	*ditto*	7.5 GeV
M_{H_2}		72. GeV
A_t	−300. GeV	44. GeV

CONCLUSION:
– gauginos in excellent $\mathcal{O}$[per-mille] condition
– scalar leptons in good $\mathcal{O}$[per-cent] condition
– squarks in $\mathcal{O}$[1] condition

mSUGRA Fit:

	Param,ideal	Experimental error
M_U	$2.47 \cdot 10^{16}$ GeV	$0.02\ 10^{16}$ GeV
α_U^{-1}	24.17	0.06
$M_{\frac{1}{2}}$	250. GeV	0.2 GeV
M_0	70. GeV	0.2 GeV
A_0	-300. GeV	13. GeV
μ	402.9 GeV	0.3 GeV
$\tan\beta$	10.	0.3

General conclusion:

- universality can be tested in bottom-up approach in non-colored sector very well;
- colored sector needs improvement

- mSUGRA fit of high quality

Summary & Outlook

- SPA: a joint interregional theoretical and experimental effort
- it provides
  - well defined framework for SUSY analyses
  - necessary theoretical and computational tools
  - well defined testground SPS1a$'$
  - platform for future developments/extensions
- many things to work on both theoretical and experimental side
- Report: SUSY Parameter Analysis
  SPA Convention and Project

visit `http://spa.desy.de/spa`