SPA: SUSY Parameter Analysis at LHC/ILC

SPA Collaboration: J.A.Aguilar-Saavedra et al

1. SPA Project: Basis and Objectives

2. Extracting SUSY Parameters at LHC/ILC

3. Extrapolation to GUT/Planck Scale

SUPERSYMMETRY PARAMETER ANALYSIS

1. SPA PROJECT: BASIS AND OBJECTIVES

Physics scenario : Standard Model | $v \sim 100$ GeV

$\Downarrow$

Supersymmetry | $\tilde{M} \sim 100$ GeV ... 1 TeV

$\Downarrow$

GUT theory | $M_{gut} \sim 10^{16}$ GeV

Program :
- Measurement of exp SUSY parameters: masses, mixings, couplings
- Extraction of essential SUSY elements: gaugino/scalar $\mathcal{L}$ parameters
- b-up/t-down approaches to GUT/Planck physics scenario

Machines : LHC : $\sqrt{s}_{eff} \simeq 5$ TeV

ILC [CLIC] : $\sqrt{s} \simeq 1$ [3/5] TeV // *pol* $e^{\pm}{}_{90/60}$ | $e^- e^-$ | GigaZ

Technique : Definition of h.o. renormalization and l.e. parameter scheme [F.2A]

SPA Convention

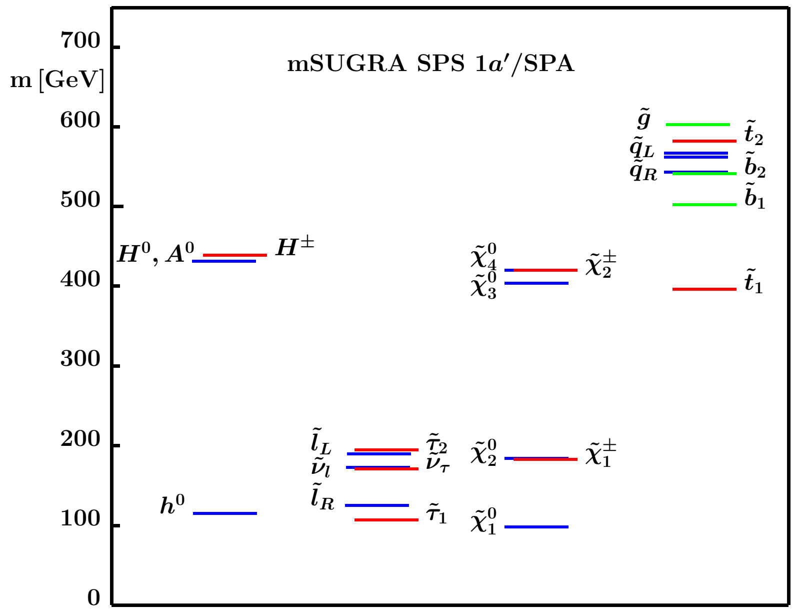
- The *masses* of the SUSY particles and Higgs bosons are defined as pole masses.
- All SUSY *Lagrangian parameters*, mass parameters and couplings, including $\tan\beta$, are given in the $\overline{DR}$ scheme and defined at the scale $\tilde{M} = 1$ TeV.
- Gaugino/higgsino and scalar *mass matrices, 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 momentum scale 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. [F.2A]

Specific SUSY Point

Allanach ea

SPS1a/a′ spectrum in mSUGRA :

favorable mass range
for ILC and LHC



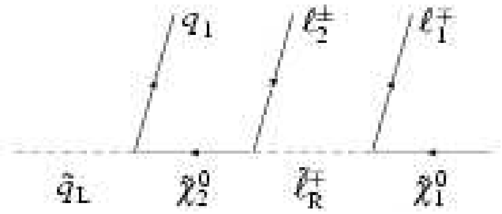
Low-energy data :

$b \to s\gamma$	$3.0 \cdot 10^{-4}$	3.70 ± 0.30
m_h	115.4 GeV	$\geq$ 114 GeV
Δa_μ [ee]	$34 \cdot 10^{-10}$	25.2 ± 9.2
$\Omega_{cdm} h^2$	0.10	$0.127^{+0.007}_{-0.013}$

LHC

cascade decays : $\tilde{q} \to q\,\tilde{\chi}_2^0 \to q\,(\tilde{\ell}\ell) \to q\,(\ell\ell)\,\tilde{\chi}_1^0$

Baer ea, Hinchliffe ea,...
Gjelsten ea, Polesello ea
Kawagoe, Nojiri, Polesello



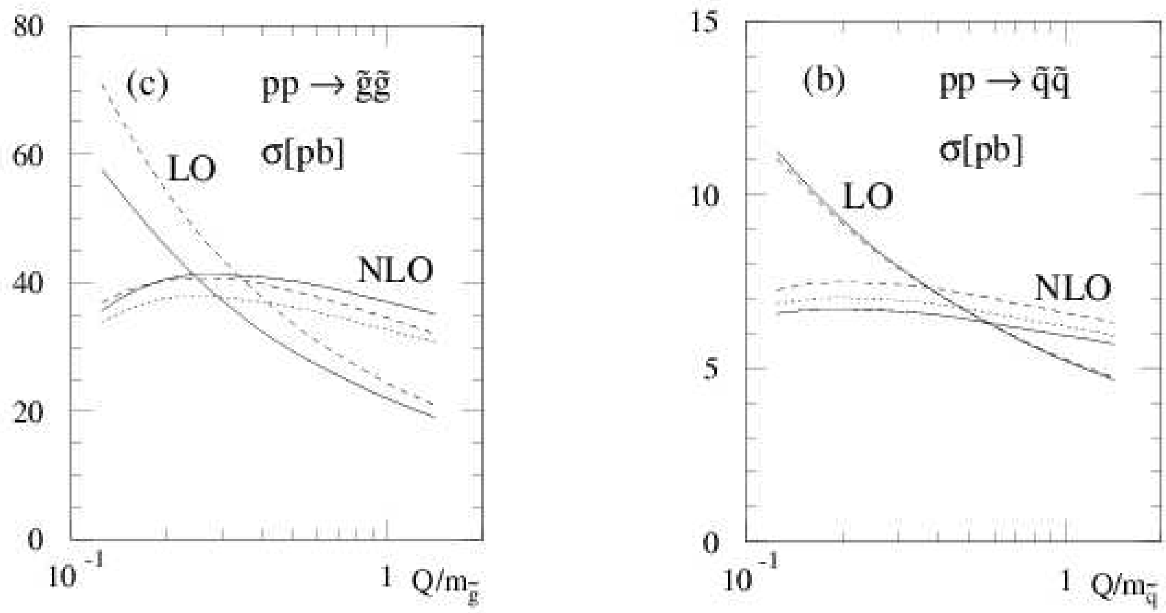
LHC direct production : $pp \to \tilde{q}\tilde{q}, \tilde{g}\tilde{g}, \tilde{q}\tilde{g}$

Beenakker, Höpker,
Spira, Z

cross sections in NLO : small residual scale dependence

DIS $\Rightarrow$ parton densities

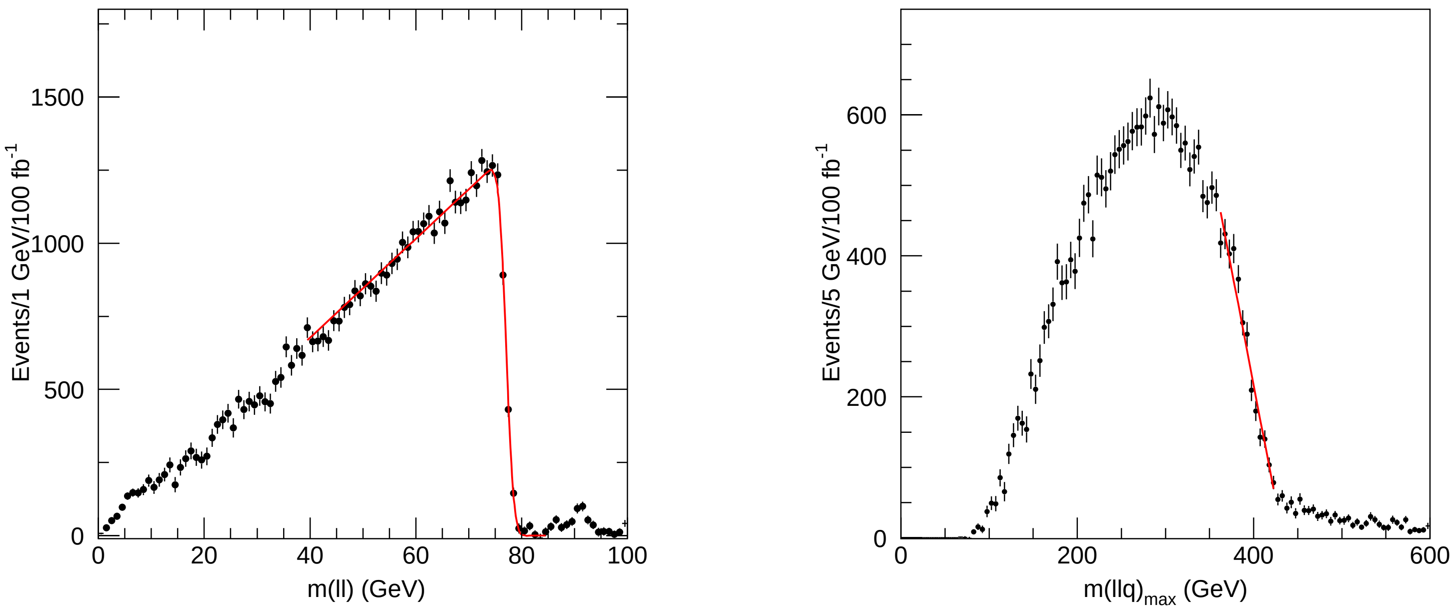
$m_{\tilde{q}/\tilde{g}} \sim 1$ TeV $\Rightarrow \sim 1$M particles



SPS1a/a′ cascade at LHC

$$\tilde{q} \to q\,\tilde{\chi}^0_2 \to q\,(\tilde{\ell}\ell) \to q\,(\ell\ell)\,\tilde{\chi}^0_1$$

invar masses $\Rightarrow$ edges / thresholds / distributions

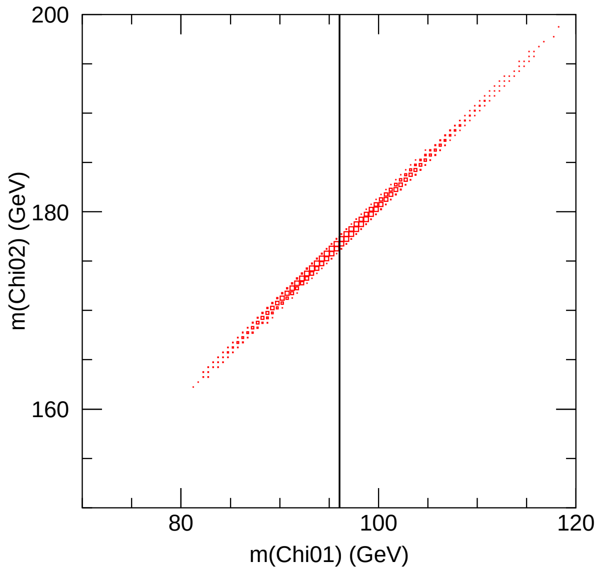


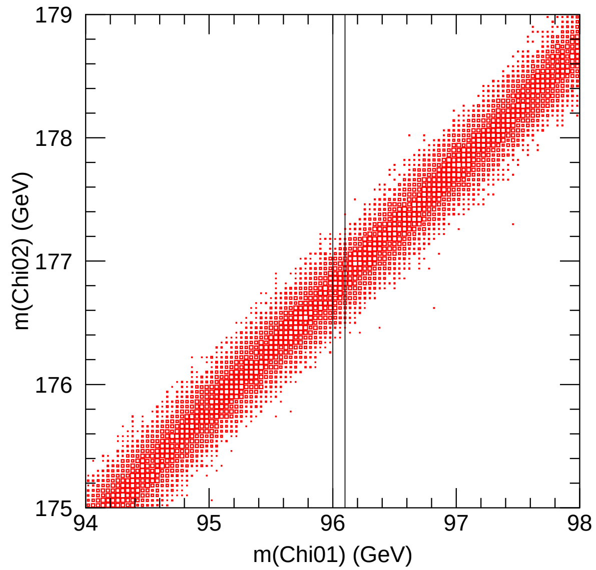
1.) mass accuracies : *col* $\simeq$ 8 GeV | *non-col* $\simeq$ 5 GeV

2.) voids in *non-color* spectrum

3.) strong correlations with χ^0_1

SPS1a/a′ cascade at LHC $\quad \tilde{q} \to q\,\tilde{\chi}_2^0 \to q\,(\tilde{\ell}\ell) \to q\,(\ell\ell)\,\tilde{\chi}_1^0$





1.) mass accuracies : *col* $\simeq$ 8 GeV | *non-col* $\simeq$ 5 GeV

2.) voids in *non-color* spectrum

3.) strong correlations with χ_1^0

$\Rightarrow$ three problems resolved by LC

LC

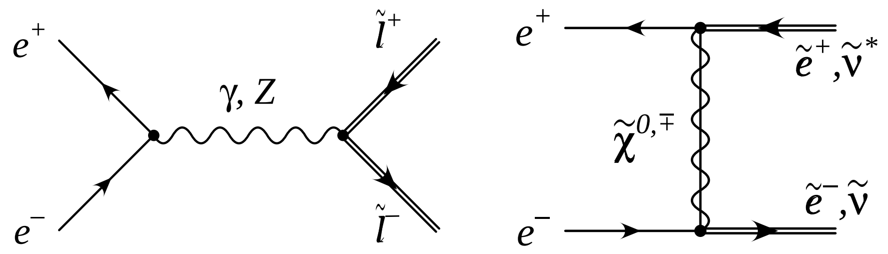
charginos, neutralinos : $e^+e^- \to \tilde{\chi}\tilde{\chi}$

Fritzsche ea, Hollik ea
Majerotto ea, ..

sleptons, sneutrinos : $e^\pm e^- \to \tilde{\ell}\tilde{\ell}$

Feng, Peskin, ...
Freitas, Manteuffel, Z

Production :

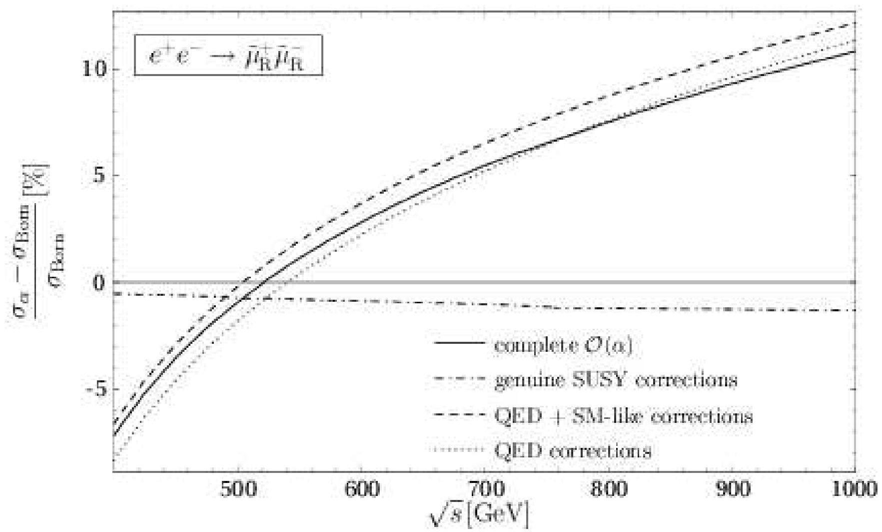


1-loop Analysis :

dominating QED but $\Rightarrow$

genuine SUSY $\sim$ few per-cent

[experimentally relevant]

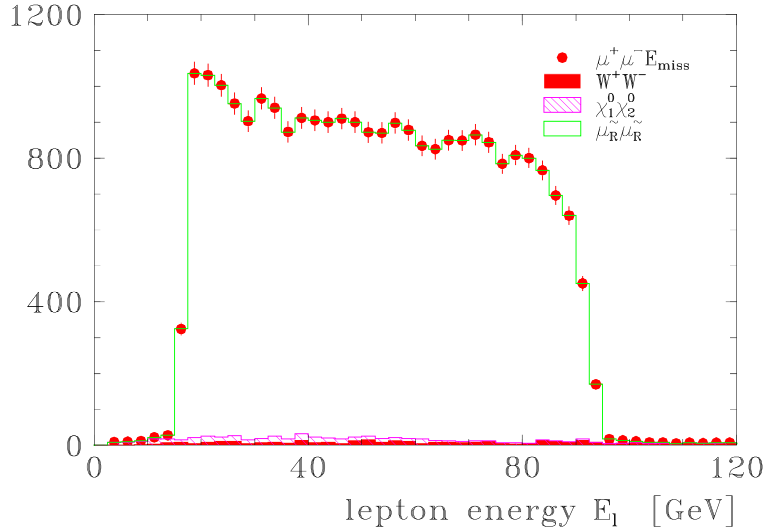


MASSES at LC

- edge effects: $\tilde{\mu}_R \to \mu + \tilde{\chi}_1^0$

$$m_{\tilde{\ell}} = \sqrt{s}\sqrt{E_+E_-}/(E_+ + E_-)$$
$$m_{\tilde{\chi}_1^0} = m_{\tilde{\ell}}\sqrt{1 - 2(E_+ + E_-)/\sqrt{s}}$$

precision on χ_1^0 increased by $\sim 10^2$



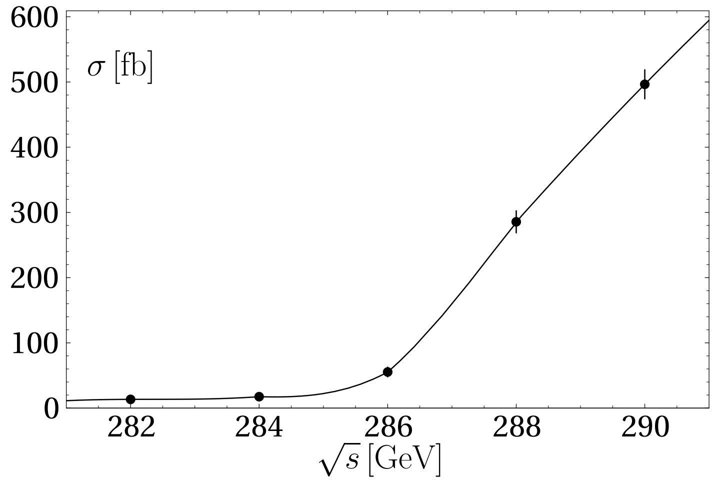
- threshold excitations:

$$e^+e^- \to \tilde{\mu}_R^+ + \tilde{\mu}_R^- \to \mu^+\mu^- + E_{miss}$$

P-wave: slow β^3 rise

$$e^-e^- \to \tilde{e}_R^- + \tilde{e}_R^- \to e^-e^- + E_{miss}$$

S-wave: fast β rise



SUMMARY:

LHC+LC

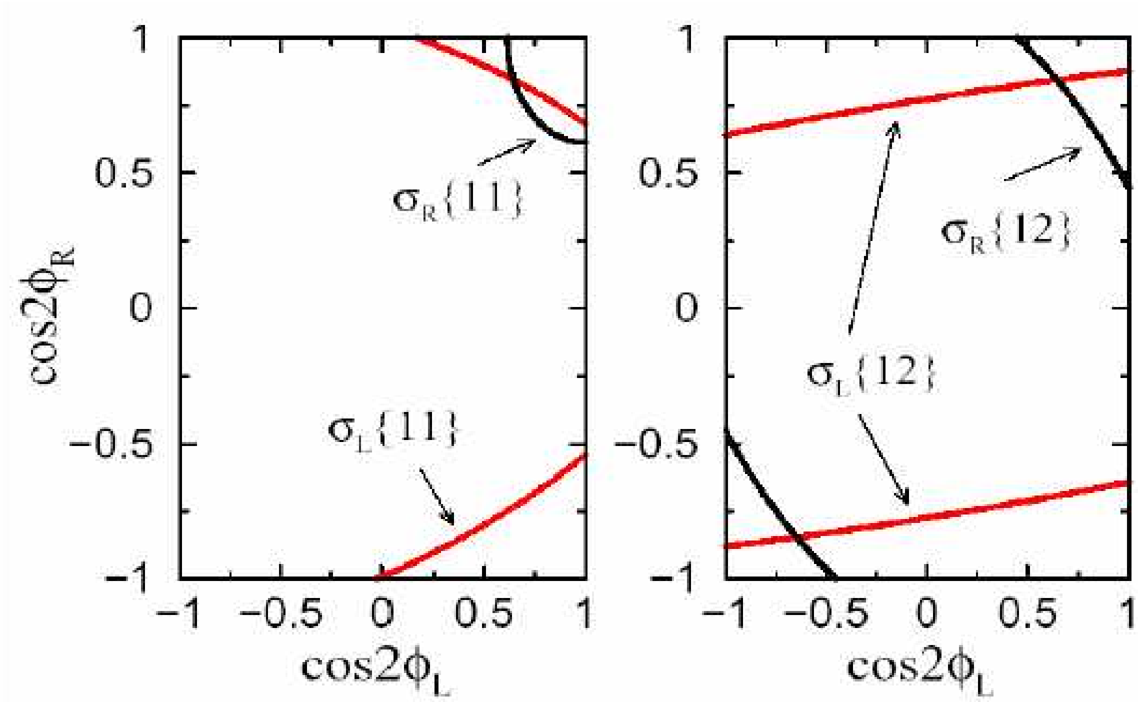
Coherent LHC+LC analyses complete and increase resolution of SUSY picture significantly

	Mass, ideal	"LHC"	"LC"	"LHC+LC"
$\tilde{\chi}_1^\pm$	179.7		0.55	0.55
$\tilde{\chi}_2^\pm$	382.3	–	3.0	3.0
$\tilde{\chi}_1^0$	97.2	4.8	0.05	0.05
$\tilde{\chi}_2^0$	180.7	4.7	1.2	0.08
$\tilde{e}_R$	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
$\tilde{\tau}_1$	134.8	5-8	0.3	0.3
$\tilde{\tau}_2$	210.7	–	1.1	1.1
$\tilde{q}_L$	570.6	8.7	–	4.9
$\tilde{t}_1$	399.5		2.0	2.0
$\tilde{t}_2$	586.3		–	
$\tilde{g}$	604.0	8.0	–	6.5
h^0	110.8	0.25	0.05	0.05
A^0	399.4		1.5	1.5

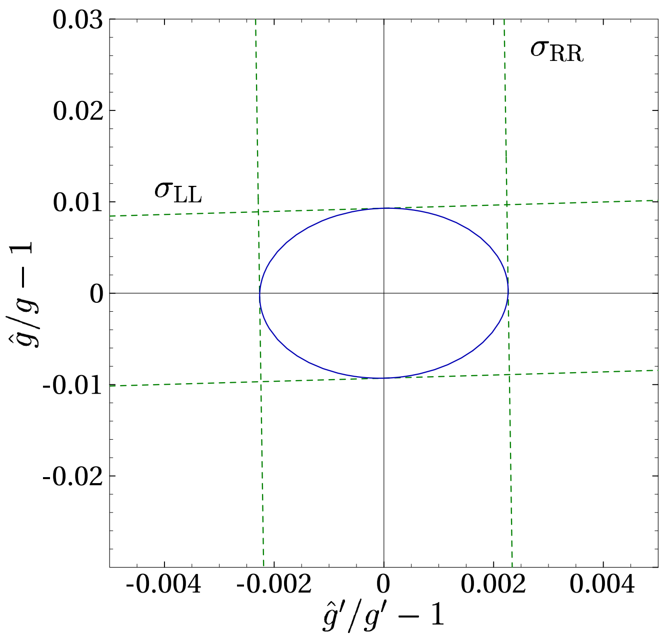
Mixings and Couplings

Choi ea, Freitas ea

Mixing in $\tilde{\chi}^{\pm,0}$ sector:



Yukawa = gauge identity:



Essential SUSY elements at electroweak scale reconstructed at LHC/LC $\Rightarrow$

2. EXTRACTING LAGRANGIAN PARAMETERS

Gaugino, higgsino, scalar mass parameters, trilinear coupling, etc:

– basic Born analysis   Choi ea, Freitas ea

– integral LHC/LC analysis ⊕ $MSSM$ loops   Martin[1+2], Vaughn, Pierce ea

EXC	LHC	LC	LHC+LC	SPS1a
M_1	102.5±5.3	102.3±0.1	102.2±0.1	102.2
M_2	191.8±7.3	192.5±0.7	191.8±0.2	191.8
M_3	578.±15.	→	588.±11.	589.4
$M_{\tilde{e}_L}$	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
$M_{\tilde{q}_L}$	550.±13.	→	553.3±6.5	553.7
$M_{\tilde{u}_R}$	529.±20.	→	532.±15.	532.1
$M_{\tilde{d}_R}$	526.±20.	→	529.±15.	529.3
A_t	-507.±91.	-501.9±2.7	-505.2±3.3	-504.9
μ	345.2±7.3	344.3±2.3	344.4±1.0	344.3
$\tan\beta$	10.2±9.1	10.3±0.3	10.06±0.2	10

SFitter: Lafaye, Plehn, Zerwas.D

[*idem* Fittino: Bechtle ea]

3. EXTRAPOLATION TO GUT SCALE

high-precision measurements of LE Lagrangian parameters

$\Rightarrow$ extrapolate to high scale: – symmetries/universal behavior?

– impact of high-scale physics?

evolution: RG Equations [3 loops $\sim$ 2 loops] (Jack ea; Martin)

minimal SUGRA

universal GUT scale parameters SPS1a/a′:

gaugino mass	$M_{1/2}$	250 GeV
scalar mass	M_0	100/70 GeV
trilin cplg	A_0	-100/-300 GeV
signum μ	$sgn[\mu]$	+
higgs mix	$\tan\beta$	10

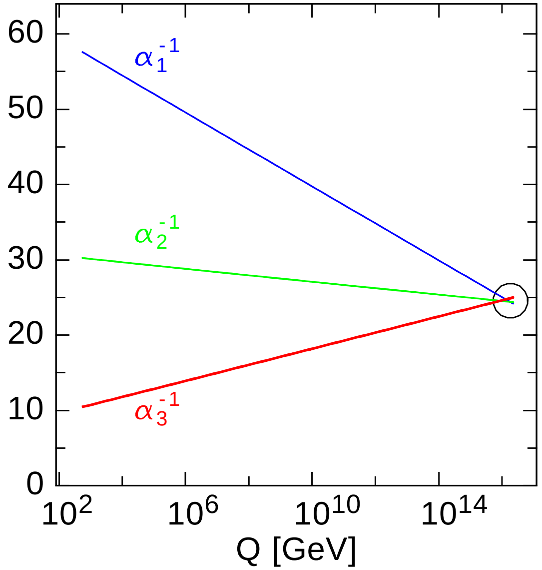
GAUGE COUPLINGS

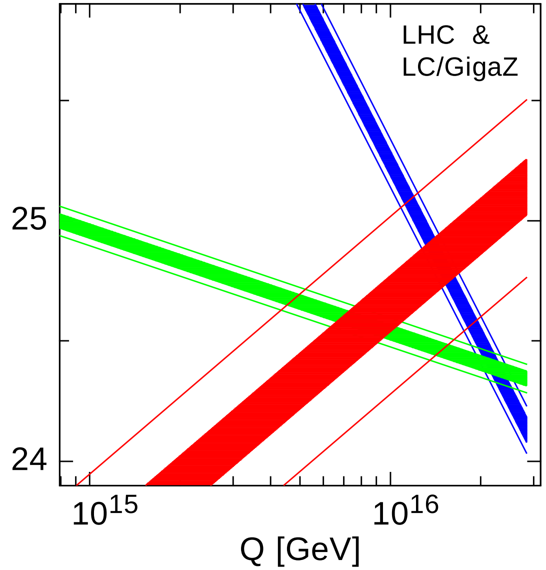
Evolution: present elw/strong gauge couplings $\oplus$ SUSY threshold corr. $\sim$ LHC

GigaZ: $\Delta s_W^2/\alpha_s \leq 10^{-5/-3}$
[DIS] / ILC completed

Grand Unification : $\sim 2\sigma$ / g_i^U : 2%

$\sim \epsilon_3$ at 8σ level



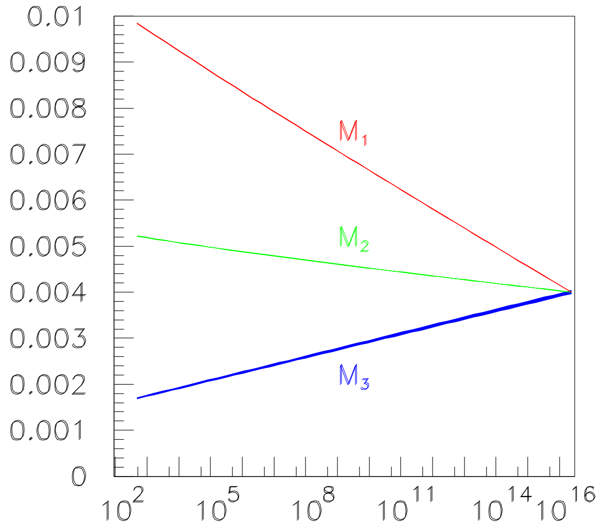


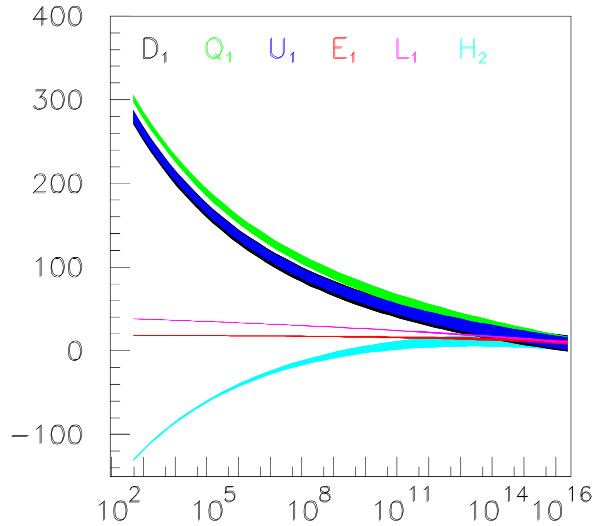
	Present/"LHC"	GigaZ/"LHC+LC"
M_U	$(2.36 \pm 0.06) \cdot 10^{16}$ GeV	$(2.360 \pm 0.016) \cdot 10^{16}$ GeV
α_U^{-1}	24.19 ± 0.10	24.19 ± 0.05
$\alpha_3^{-1} - \alpha_U^{-1}$	0.97 ± 0.45	0.95 ± 0.12

UNIVERSALITY OF MASS PARAMETERS

Evolution : Gaugino and scalar mass parameters

b-up





t-down

	Parameter, ideal	Experimental error
$M_{1/2}$	250. GeV	0.2 GeV
M_0	100. GeV	0.2 GeV
A_0	-100. GeV	14 GeV
μ	357.4 GeV	0.4 GeV

- sensit. SUSY breaking
- reconstrg [PL] scenario

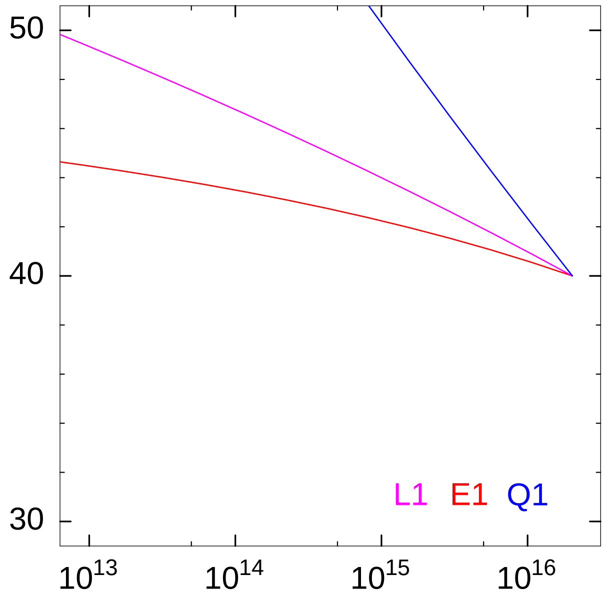
INTERMEDIATE SCALE

$m_\nu \neq 0$: neutrino mass generated by seesaw mechnism $\Rightarrow$

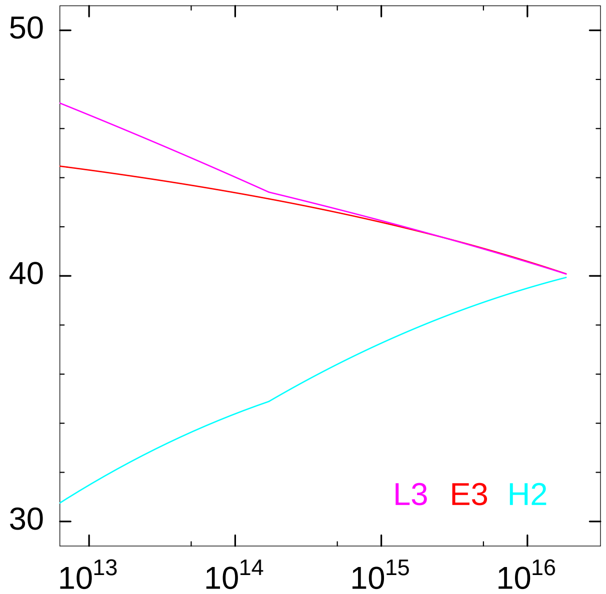
intermediate seesaw scale $M[\nu_R] \sim 10^{10}/10^{14}$ GeV in SO(10)

affecting evolution in 3rd generation $\Rightarrow$ kink

1.) Scalar masses 1 and 2 generation



2.) Scalar masses 3 generation



INTERMEDIATE SCALE

$m_\nu \neq 0$: neutrino mass generated by seesaw mechnism $\Rightarrow$

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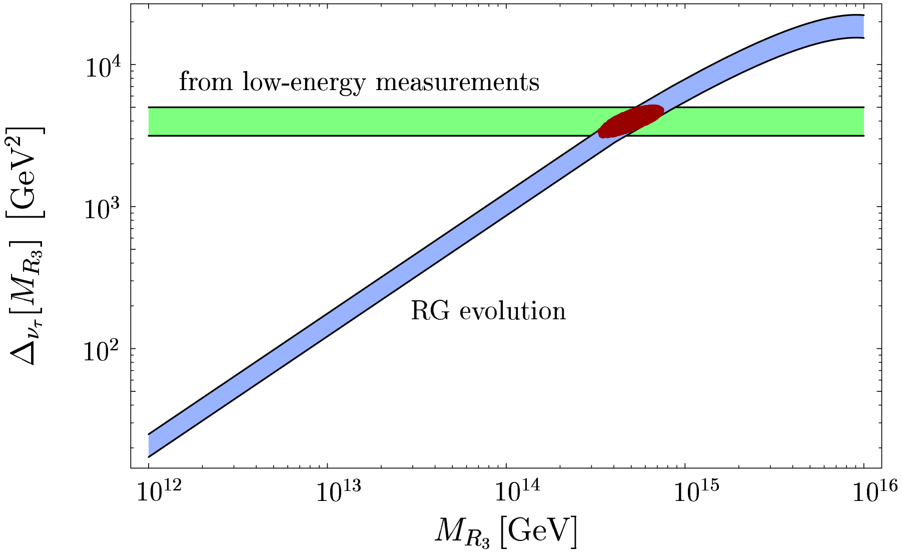

shift 3rd *vs.* 1/2nd generation $\tilde{\ell}, \tilde{\nu}_\ell$: $\Delta_{\nu_3} \sim M[\nu_{R3}] m_{\nu_3} \log M[\nu_{R3}]$ $\Rightarrow$

$M[\nu_{R3}] \sim 10^{14}$ GeV [30%]

4. SUMMARY

1. Coherent SPA "LHC+LC" analyses establish SUSY scenario
   at electroweak scale comprehensively and with high precision:
   non-colored $\Leftarrow$ per-mille level
   colored $\Leftarrow$ per-cent level $\Leftarrow$ QCD and parton distributions

2. Fundamental SUSY theory at GUT/Planck scale can be reconstructed /
   high and intermediate scale parameters :
   universal mSUGRA, LR-extended, ...

   P decay / ν physics / cosmology / $\oplus$
   high-precision high-energy experiments $\Rightarrow$

LHC$\otimes$LC $\Rightarrow$ GUT/Planck-scale physics
– if supersymmetry realized and mass domain favorable –