SUPERSYMMETRY IN COHERENT ILC/LHC ANALYSES

LHC/LC SUSY [WG]:

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1. INTRODUCTION

- Physics scenario
- LHC/ILC characteristics

2. EXTRACTING SUSY PARAMETERS

- LHC/ILC observables and Lagrangian parameters / elw scale

3. EXTRAPOLATION TO HIGH SCALES

- minimal SUGRA: gauge couplings and mass parameters
- Intermediate scales: LR extension
- Determining superstring effective parameters

4. CONCLUSIONS

1. INTRODUCTION

Scenario: Standard Model / $v \sim 100$ GeV

$\Downarrow$

Supersymmetry / $\tilde{M} \sim 1$ TeV

$\Downarrow$

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

Question:

- to what extent can theory / parameters be reconstructed in bottom-up approach?
  - – symmetries
  - – impact of high-scale parameters
- what precision can be reached in the alternative top-down approach?

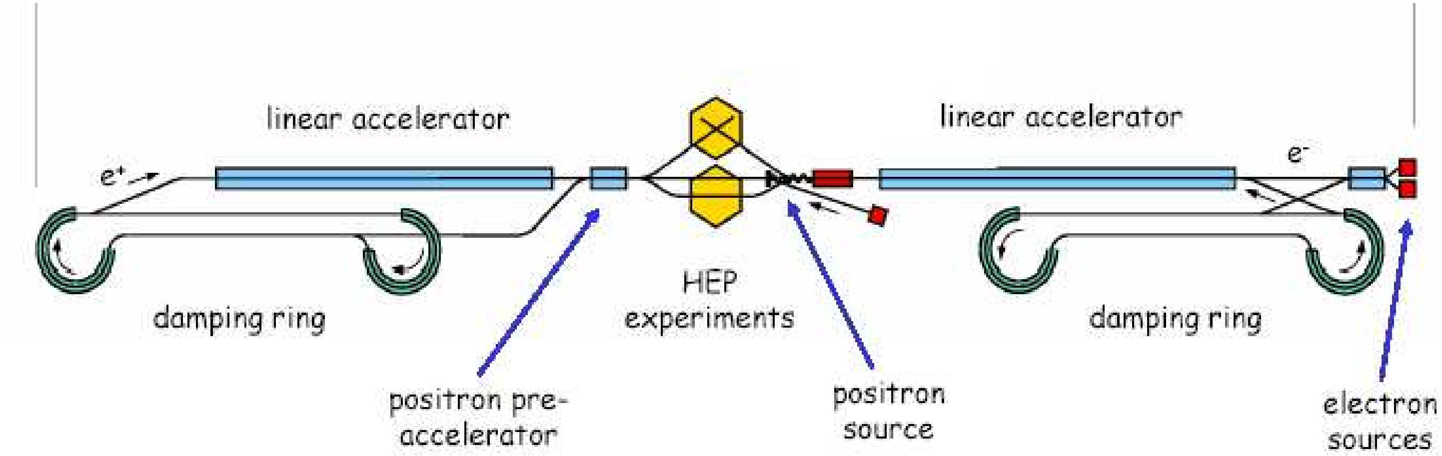
parallel: P decay
ν physics
cosmology

Experimental Approach

Machines : PP collider LHC : $\sqrt{s}_{eff} \sim 4$ to 5 TeV for SUSY sector

e^+e^- linear collider : $\star$ ILC : $\sqrt{s} = 1$ TeV polarized $e^\pm$ beams | e^-e^- | $e\gamma$ | $\gamma\gamma$ | GigaZ

$\star$ CLIC : $\sqrt{s} = 3$ to 5 TeV



ILC LAYOUT

Experimental Approach

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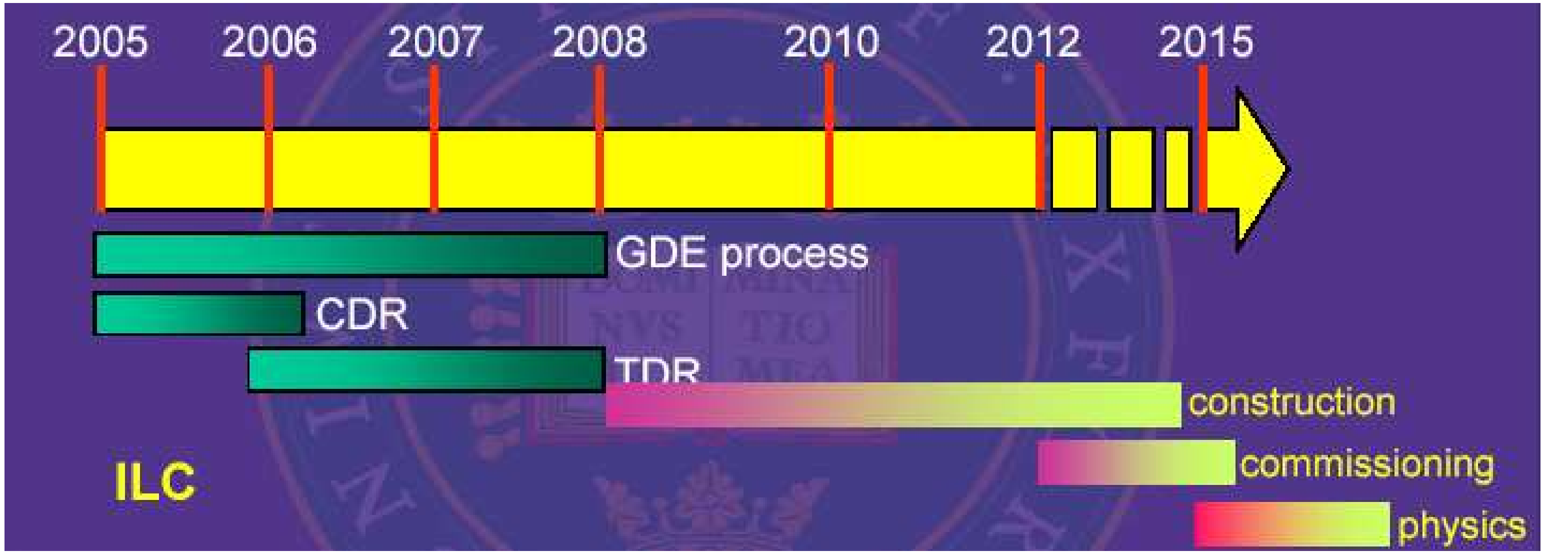
$e^-e^- \,|\, e\gamma \,|\, \gamma\gamma \,|$ GigaZ

technical road map:



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⋆ CLIC : $\sqrt{s} = 3$ to 5 TeV

PROGRAM: comprehensive and high-precision picture at elw scale

platform for high-scale extrapolations ⇒

- fundamental SUSY theory
- SUSY breaking mechanism

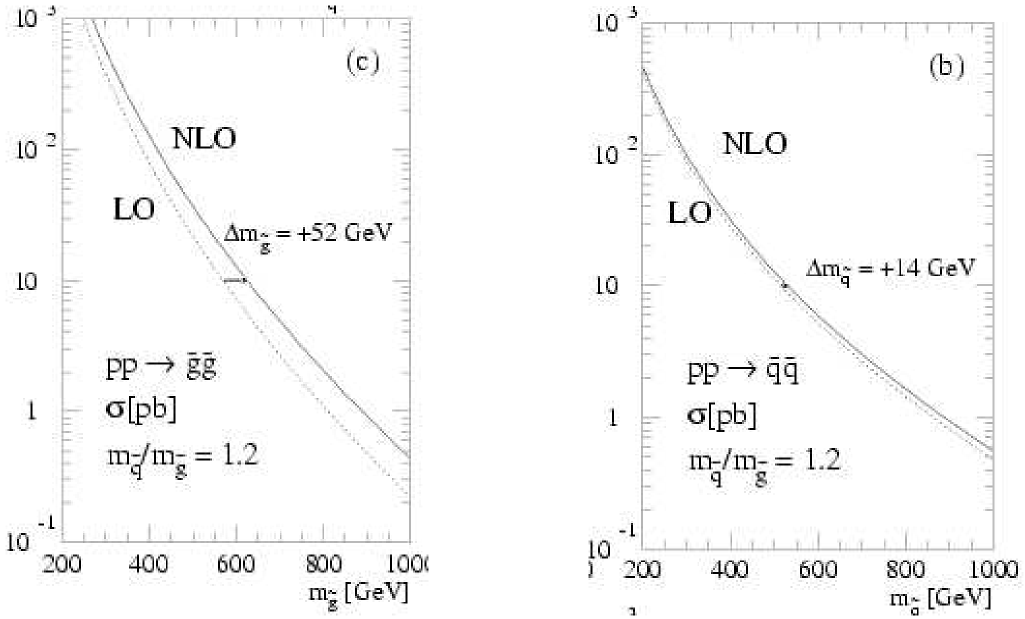
2. EXPERIMENTAL PARAMETER ANALYSIS

LHC : direct production : $pp \to Higgs$ Spira ea

$\to \tilde{q}\tilde{q}, \tilde{g}\tilde{g}, \tilde{q}\tilde{g}$ Beenakker ea

cross sections theoretically under good control

$m_{\tilde{q}/\tilde{g}} \sim 1$ TeV $\Rightarrow \sim 10^6$ particles



2. EXPERIMENTAL PARAMETER ANALYSIS

LHC : direct production : $pp \longrightarrow Higgs$ Spira ea

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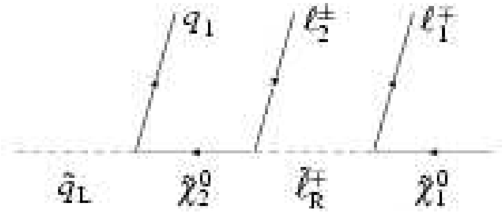
cascade decays : $\tilde{q} \longrightarrow q\,\tilde{\chi}_2^0 \longrightarrow q\,(\tilde{\ell}\ell) \longrightarrow q\,(\ell\ell)\,\tilde{\chi}_1^0$ Hinchliffe ea



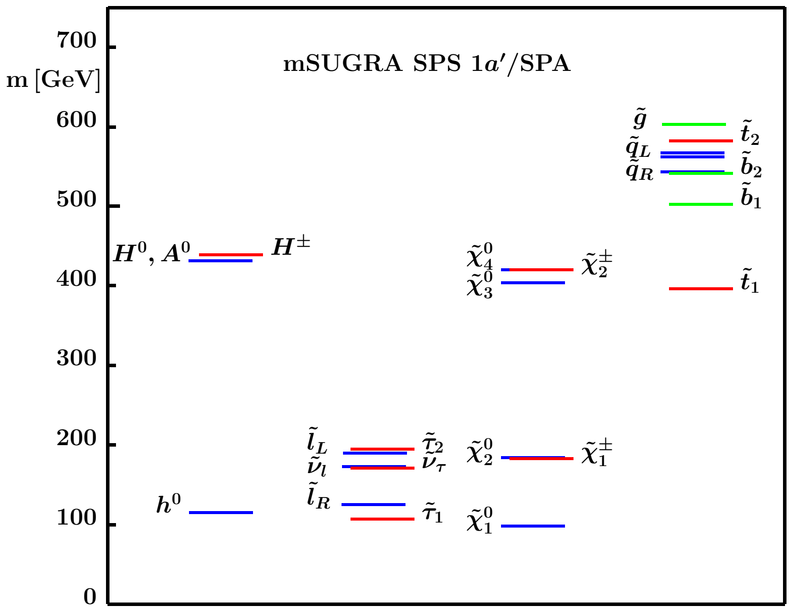
primary source of non-colored SUSY particles

SPECIFIC SUSY POINT

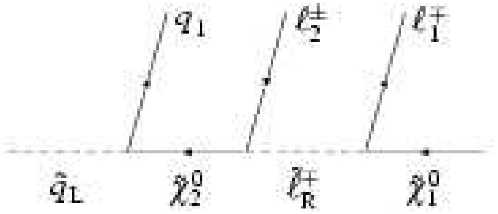
Spectrum SPS1a/a′ :

compatible with all LE and cosmology data **

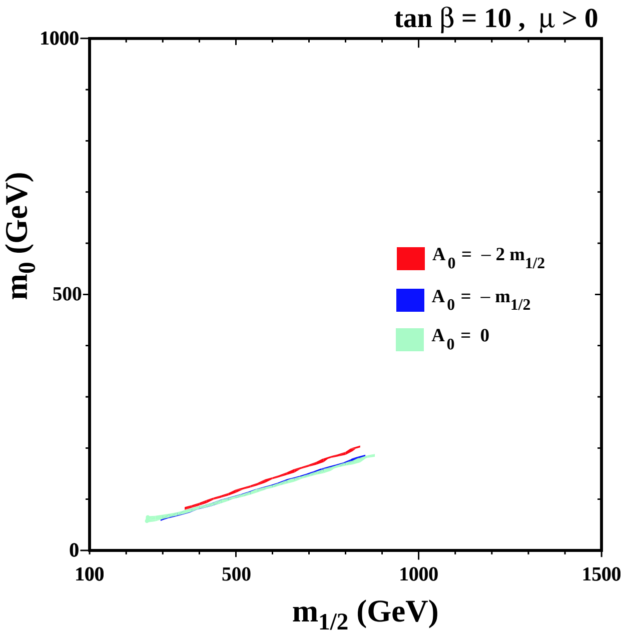
favorable mass range for ILC and LHC

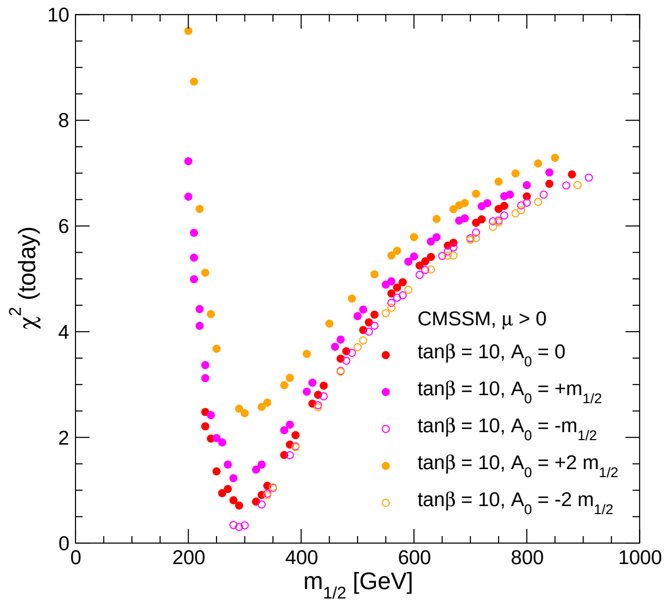


SPS1a/a′ cascade : $\tilde q \to q\,\tilde\chi_2^0 \to q\,(\tilde\ell\ell) \to q\,(\ell\ell)\,\tilde\chi_1^0$



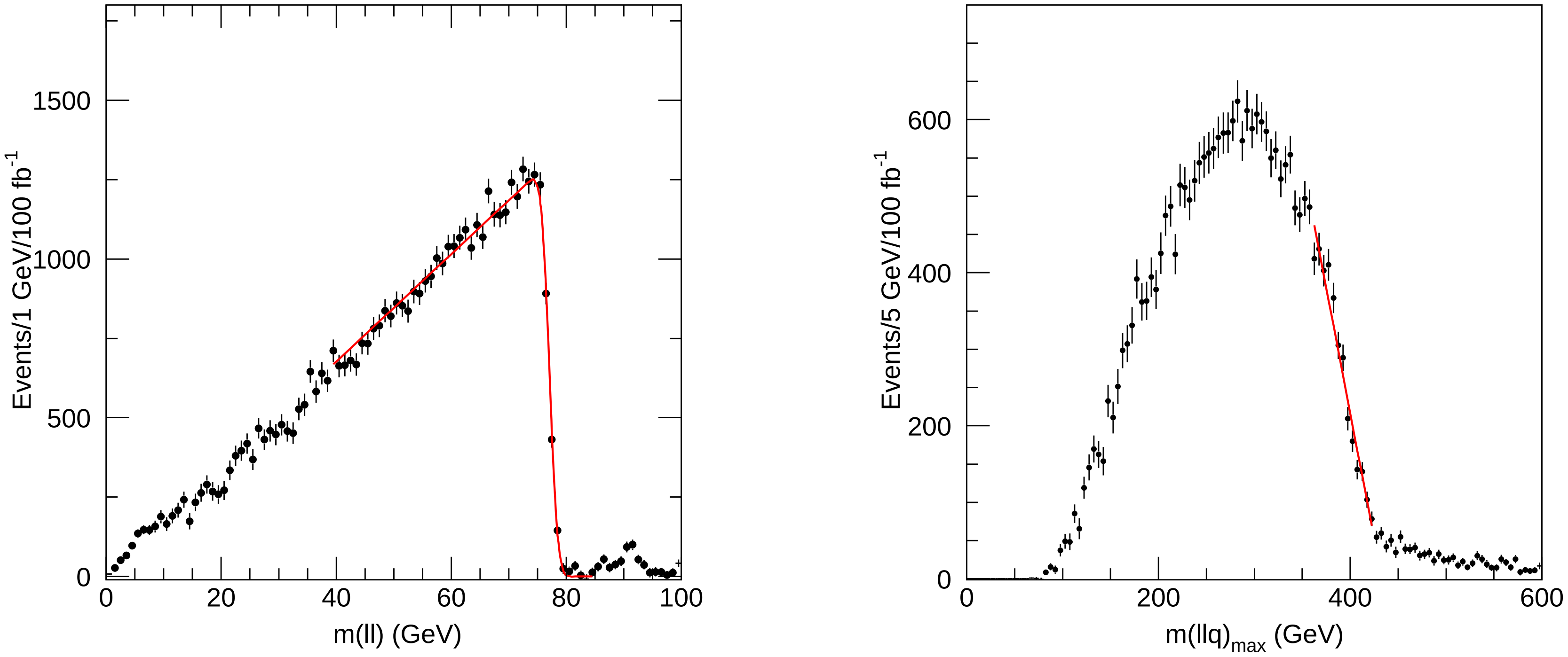
mSUGRA in WMAP and electroweak precision data:





Ellis, Heinemeyer, Olive, Weiglein

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



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

$$
\begin{aligned}
\left(m_{ll}^2\right)^{\mathrm{edge}} &= \frac{\left(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}_R}^2\right)\left(m_{\tilde{l}_R}^2 - m_{\tilde{\chi}_1^0}^2\right)}{m_{\tilde{l}_R}^2} \\
\left(m_{qll}^2\right)^{\mathrm{edge}} &= \frac{\left(m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2\right)\left(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\chi}_1^0}^2\right)}{m_{\tilde{\chi}_2^0}^2} \\
\left(m_{ql}^2\right)_{\mathrm{min}}^{\mathrm{edge}} &= \frac{\left(m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2\right)\left(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}_R}^2\right)}{m_{\tilde{\chi}_2^0}^2} \\
\left(m_{ql}^2\right)_{\mathrm{max}}^{\mathrm{edge}} &= \frac{\left(m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2\right)\left(m_{\tilde{l}_R}^2 - m_{\tilde{\chi}_1^0}^2\right)}{m_{\tilde{l}_R}^2} \\
\left(m_{qll}^2\right)^{\mathrm{thres}} &= \Big[\left(m_{\tilde{q}_L}^2 + m_{\tilde{\chi}_2^0}^2\right)\left(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{l}_R}^2\right)\left(m_{\tilde{l}_R}^2 - m_{\tilde{\chi}_1^0}^2\right) \\
&\quad -\left(m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2\right)\sqrt{\left(m_{\tilde{\chi}_2^0}^2 + m_{\tilde{l}_R}^2\right)^2\left(m_{\tilde{l}_R}^2 + m_{\tilde{\chi}_1^0}^2\right)^2 - 16 m_{\tilde{\chi}_2^0}^2 m_{\tilde{l}_R}^4 m_{\tilde{\chi}_1^0}^2} \\
&\quad +2 m_{\tilde{l}_R}^2\left(m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2\right)\left(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\chi}_1^0}^2\right)\Big] \Big/ \left(4 m_{\tilde{l}_R}^2 m_{\tilde{\chi}_2^0}^2\right)
\end{aligned}
$$

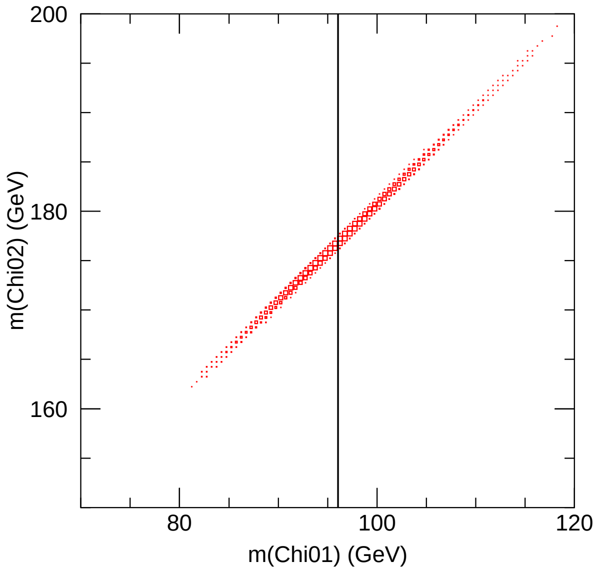
⇒ mass differences with high precision

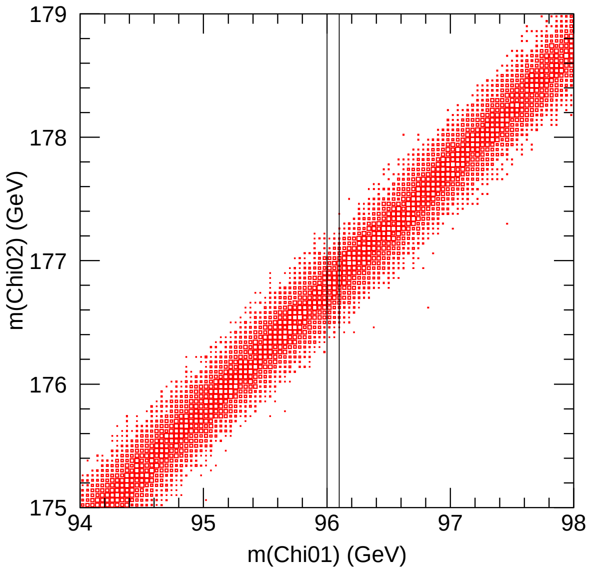
⇒ absolute values less: escaping light $\tilde{\chi}_1^0$ ⇒

LHC

	Mass, ideal	"LHC"	"LC"	"LHC+LC"
$\tilde{\chi}_1^\pm$	179.7			
$\tilde{\chi}_2^\pm$	382.3	–		
$\tilde{\chi}_1^0$	97.2	4.8		
$\tilde{\chi}_2^0$	180.7	4.7		
$\tilde{e}_R$	143.9	4.8		
$\tilde{e}_L$	207.1	5.0		
$\tilde{\nu}_e$	191.3	–		
$\tilde{\mu}_R$	143.9	4.8		
$\tilde{\tau}_1$	134.8	5-8		
$\tilde{\tau}_2$	210.7	–		
$\tilde{q}_L$	570.6	8.7		
$\tilde{t}_1$	399.5			
$\tilde{t}_2$	586.3			
$\tilde{g}$	604.0	8.0		
h^0	110.8	0.25		
A^0	399.4			

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





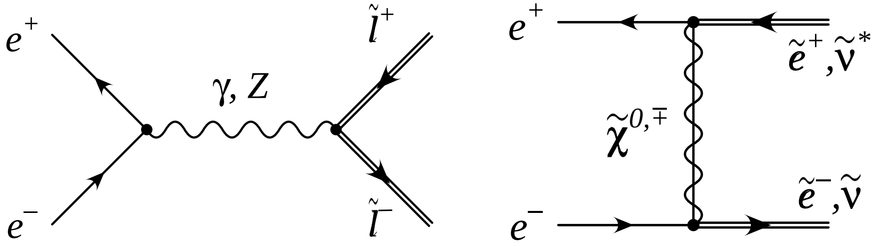
LHC : residual ambiguities

strong correlations with χ^0_1 : both problems resolved by LC

LC charginos, neutralinos : $e^+e^- \to \tilde\chi\tilde\chi$ Fritzsche ea

sleptons, sneutrinos : $e^\pm e^- \to \tilde\ell\tilde\ell$ Freitas ea

Production :



wonderful th laboratory : non-zero width and gauge invariance
Sommerfeld rescattering
analyticity : anomalous thresholds

LC

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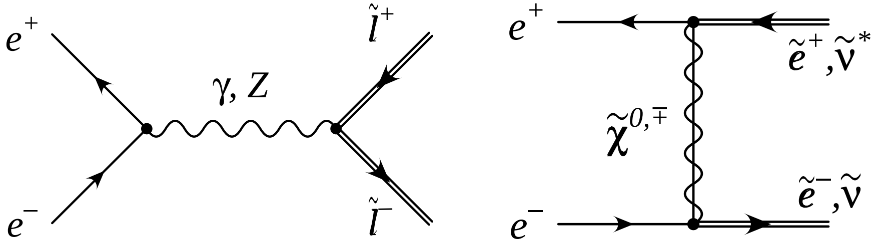

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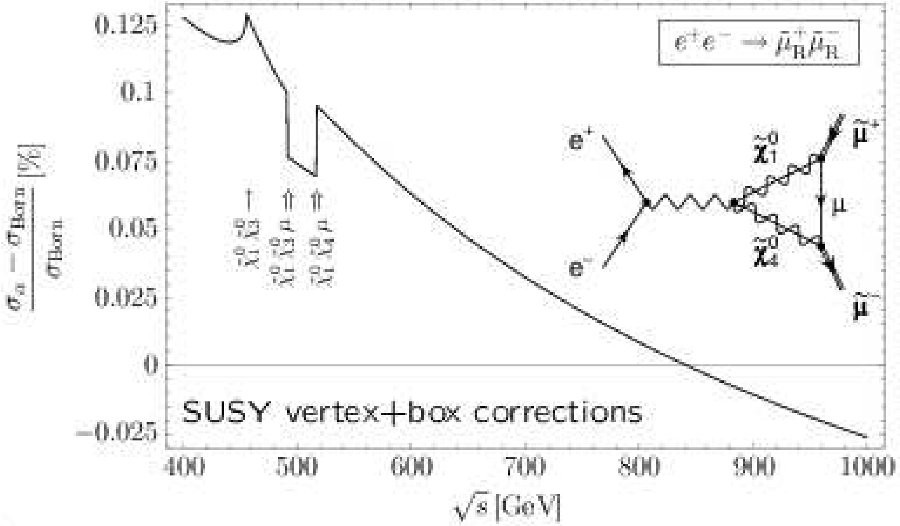

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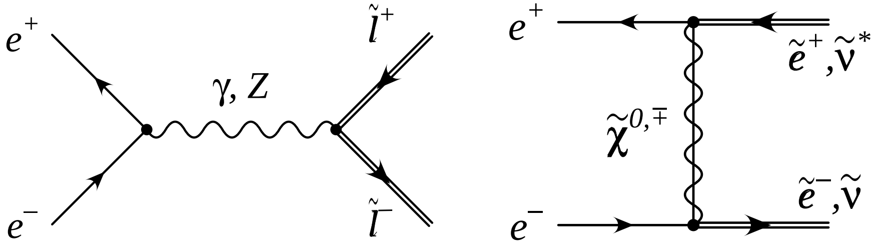

wonderful th laboratory : non-zero width and gauge invariance

Sommerfeld rescattering

analyticity : anomalous thresholds

complete to 1-loop: exp relevant at 1% level

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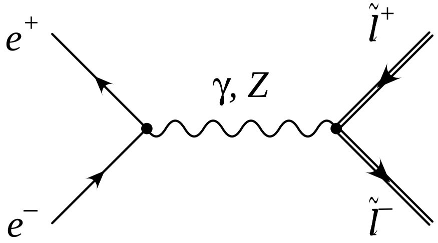

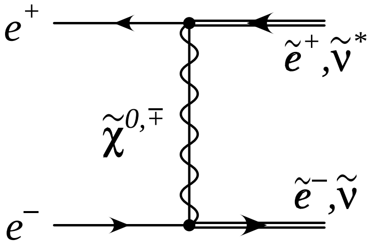

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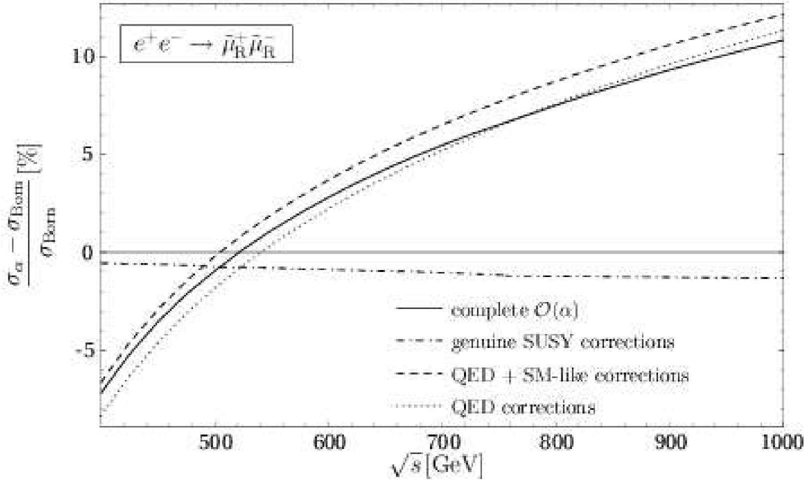
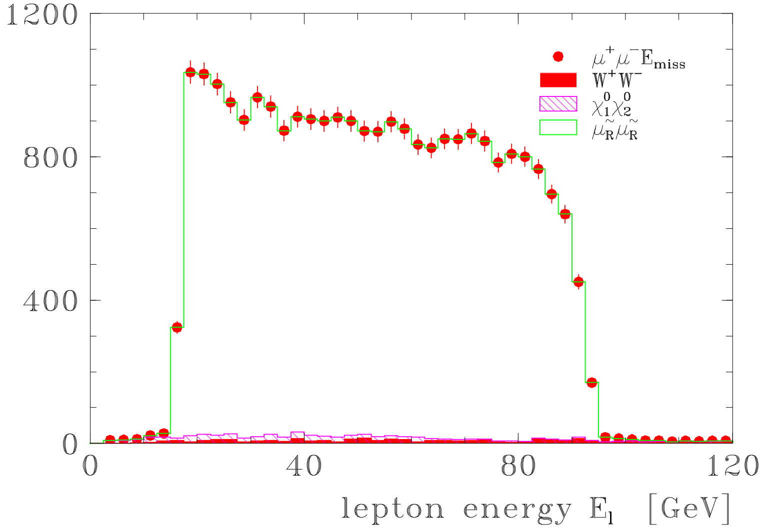


MASSES at LC

a) 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 $\sim 10^2$

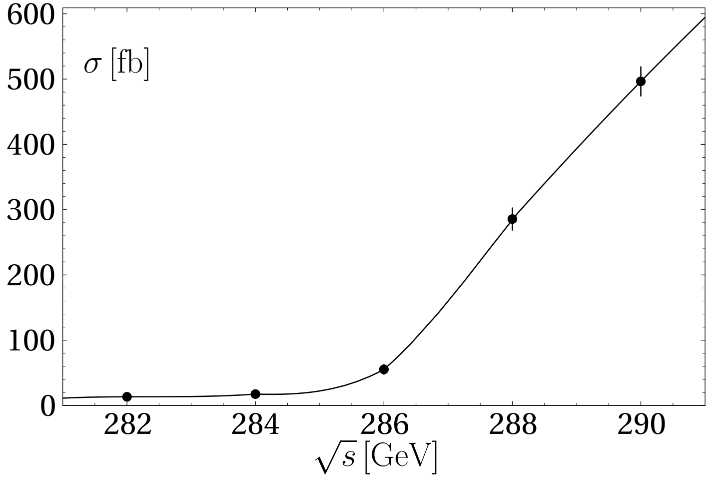
b) threshold excitations:

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

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
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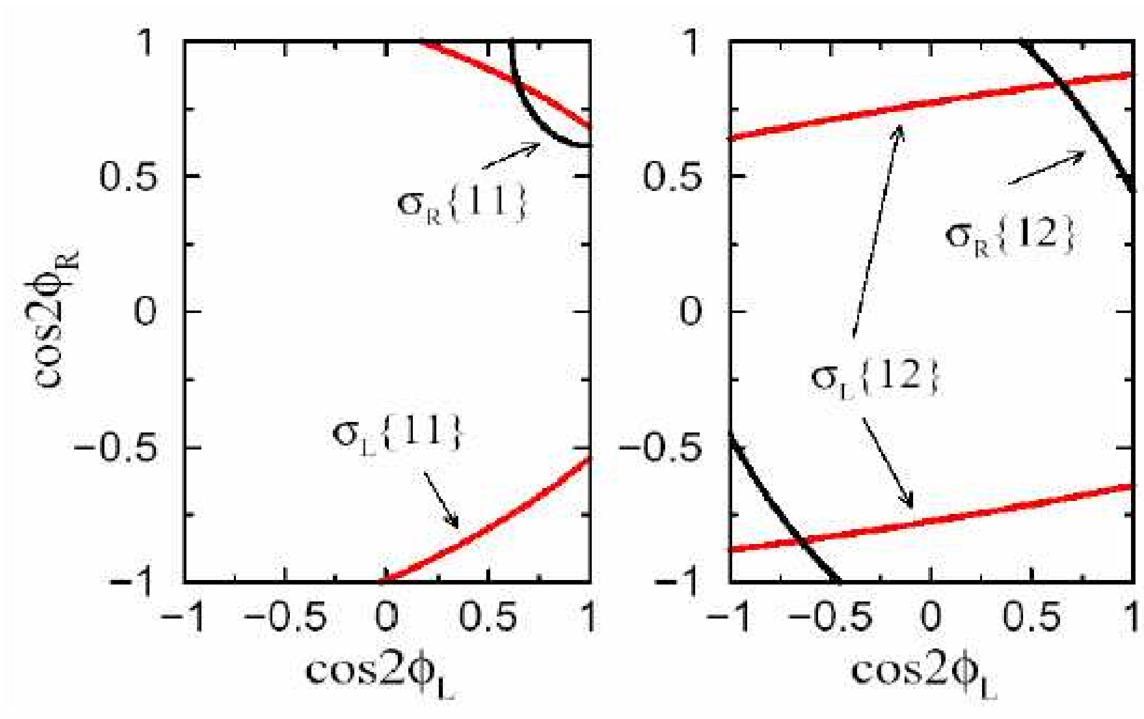
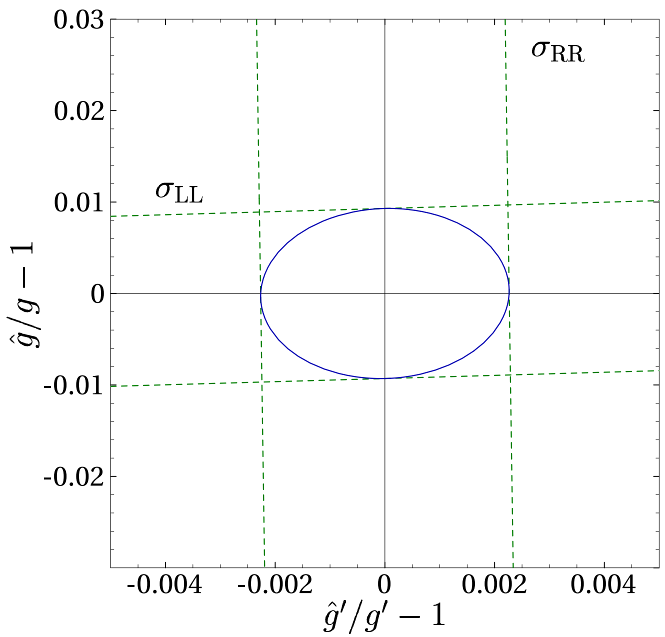
$\tilde{\tau}_2$	210.7	–	1.1	1.1
$\tilde{q}_L$	570.6	8.7	–	4.9
$\tilde{t}_1$	399.5		2.0	2.0
$\tilde{t}_2$	586.3		–	
$\tilde{g}$	604.0	8.0	–	6.5
h^0	110.8	0.25	0.05	0.05
A^0	399.4		1.5	1.5

Mixings and Couplings

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



Yukawa = gauge identity*:



⇐ Crucial elements of basic Lagrangian at electroweak scale can be reconstructed

* Choi ea

EXTRACTING LAGRANGIAN PARAMS [ELW]

input : particle masses $\tilde{\chi}^{\pm,0}, \tilde{g}, \tilde{\ell}, \tilde{q}, Higgs$

polarized cross-sections $e^+e^- \to \tilde{\chi}\tilde{\chi}, \tilde{\ell}\tilde{\ell}$

Born analysis: analytical

Choi ea

$$\begin{aligned}
|\mu| &= M_W \left[M_\chi^+ + M_\chi^- (\cos 2\phi_R + \cos 2\phi_L)\right]^{1/2} \\
M_2 &= M_W \left[M_\chi^+ - M_\chi^- (\cos 2\phi_R + \cos 2\phi_L)\right]^{1/2} \\
|M_1| &= \left[\sum_i m^2_{\tilde{\chi}^0_i} - M_2^2 - \mu^2 - 2M_Z^2\right]^{1/2} \\
|M_3| &= m_{\tilde{g}} \\
\tan\beta &= \left[\frac{1 + M_\chi^- (\cos 2\phi_R - \cos 2\phi_L)}{1 - M_\chi^- (\cos 2\phi_R - \cos 2\phi_L)}\right]^{1/2}
\end{aligned}$$

$\Rightarrow$ LHC not sufficient for complete parameter set: $[\tilde{\chi}^0_{1,2,4}] :/ \ [M_{1,2}, \mu, \tan\beta]$

$\Rightarrow$ ILC not sufficient: $/ \ [\tilde{g}] \sim [M_3]$

Extracting Lagrangian Parameters

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

integral LHC/LC analysis $\oplus$ loops: $\mathcal{O} = \mathcal{O}[\mathcal{MSSM}]$
[$\Leftarrow$ light Higgs h]

Martin[1+2], Vaughn, Pierce ea
Carena, Haber; Heinemeyer 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

3. EXTRAPOLATION TO GUT SCALE

high-precision measurements of LE Lagrangian parameters

⇒ extrapolate to high scale: – symmetries/universal behavior?

– impact of high-scale physics?

transport: RG Equations [← up to 3 loops : Jack ea]

minimal SUGRA

universal GUT scale parameters
SPS1a/a′:

$b \to s\gamma$	$3.0 \cdot 10^{-4}$	3.70 ± 0.30
m_h	115.4 GeV	≥ 114 GeV
Δa_μ	$34 \cdot 10^{-10}$	25.2 ± 9.2
$\Omega_{cdm} h^2$	0.10	0.112 ± 0.017
LE data	EHOW	*max.prob.*

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

RGE's:

gauge couplings : $\alpha_i = Z_i \, \alpha_U$

gaugino mass parameters : $M_i = Z_i \, M_{1/2}$

scalar mass parameters : $M^2_{\tilde{j}} = M^2_0 + c_j M^2_{1/2} + \sum_{\beta=1}^{2} c'_{j\beta} \Delta M^2_\beta$

trilinear couplings : $A_k = d_k A_0 + d'_k M_{1/2}$

Z transporters : $Z_i^{-1} = 1 + b_i \frac{\alpha_U}{4\pi} \log \left(\frac{M_U}{M_Z} \right)^2$

for i = U(1), SU(2), SU(3)

\# couplings, M_i: explicit linear connections

\# $M^2_{\tilde{j},H}$ implicit connections :

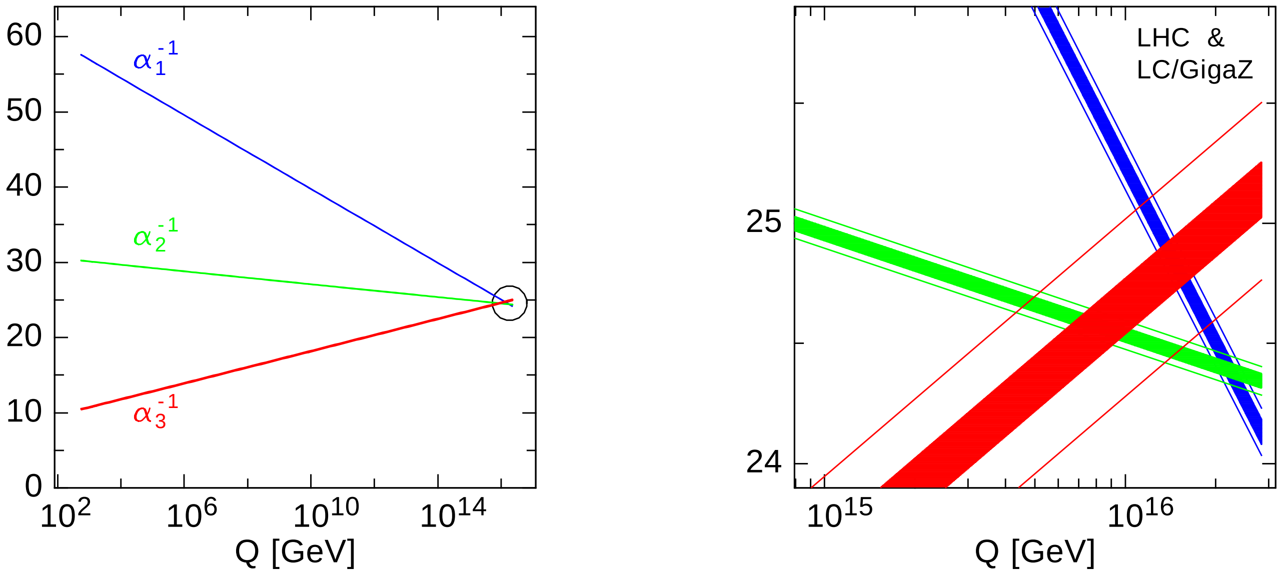
$$
\begin{aligned}
M^2_{\tilde{L}_1} &= M^2_0 + 0.5 M^2_{1/2} \\
M^2_{\tilde{Q}_1} &= M^2_0 + 5.0 M^2_{1/2} \\
M^2_{H_2} &= -0.03 M^2_0 - 1.3 M^2_{1/2} + .. \\
A_t &= A_0 \ \textit{insensitive} \ [IR - fp]
\end{aligned}
$$

GAUGE COUPLINGS

Evolution: **1.** present electroweak/strong gauge couplings

$\oplus$ SUSY threshold corrections $\sim$ LHC

$\Rightarrow$ Grand Unification at $\sim 2\sigma$ / g : 2%



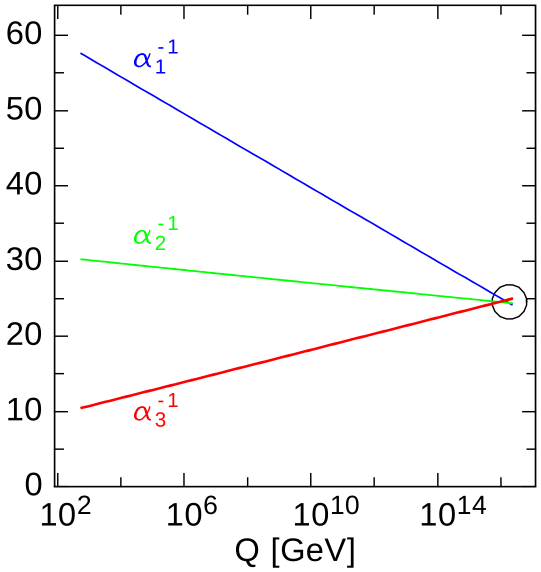
	Present/"LHC"	GigaZ/"LHC+LC"
M_U	$(2.36 \pm 0.06) \cdot 10^{16}$ GeV	$(2.360 \pm 0.016) \cdot 10^{16}$ GeV
α_U^{-1}	24.19 ± 0.10	24.19 ± 0.05
$\alpha_3^{-1} - \alpha_U^{-1}$	0.97 ± 0.45	0.95 ± 0.12

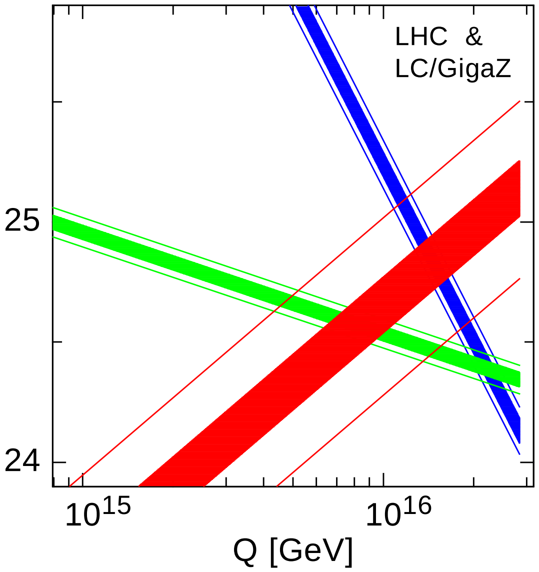
GAUGE COUPLINGS

Evolution: **2.** GigaZ improved gauge couplings $\Delta \sin^2 \theta_{\mathrm{W}} \simeq 10^{-5}$, $\Delta\alpha_{\mathrm{s}} \simeq 10^{-3}$

$\oplus$ "LHC+LC" completed SUSY threshold corrections

$\Rightarrow$ GUT scale parameters at $\sim 8\sigma$ level





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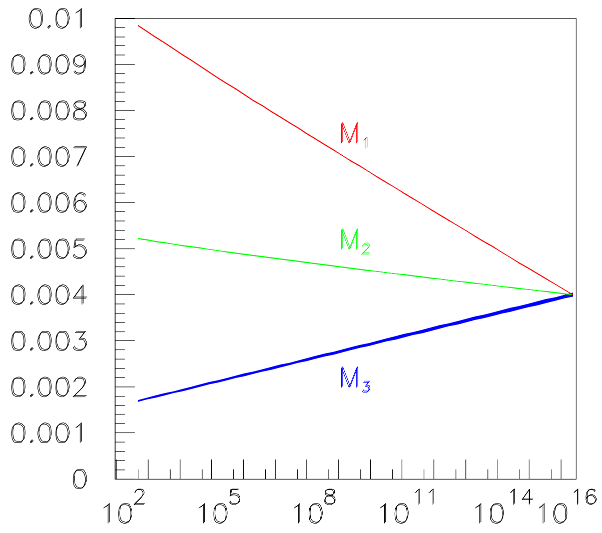
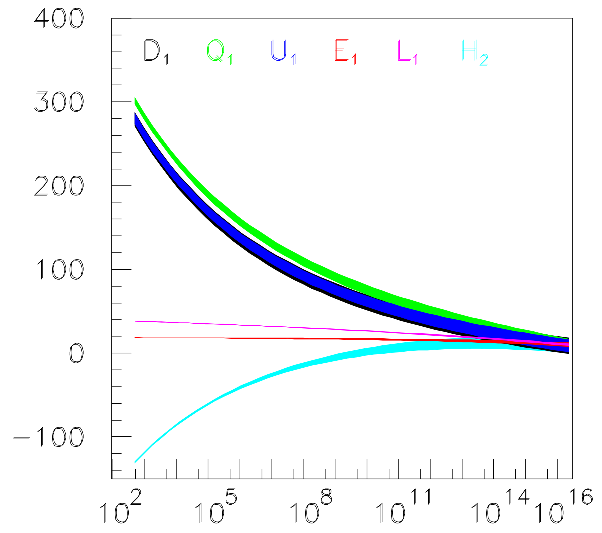
UNIVERSALITY OF MASS PARAMETERS

Evolution : Gaugino and scalar mass parameters



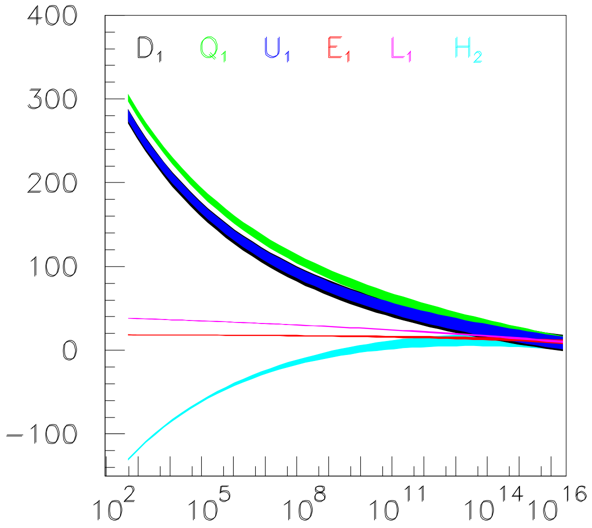


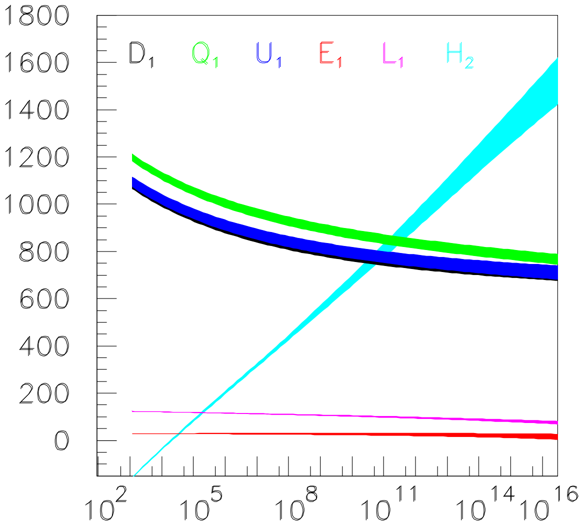
$M_i \to M_{1/2}$	excellent	$\sim 10^{-3}/10^{-2}$
$M^2_{\tilde{\ell}} \to M^2_0$	very good	$a\ few\ 10^{-2}$
$M^2_{\tilde{Q}} \to M^2_0$	abs:good / rel:improve	$a\ few\ 10^{-1}$

UNIVERSALITY OF MASS PARAMETERS

Evolution : Scalar mass parameters

mSUGRA *vs.* GMSB





⇒ evolution distictly different for mSUGRA *vs.* GMSB

⇒ testing microscopic parameters of SUSY breaking schemes

UNIVERSALITY OF MASS PARAMETERS

Evolution : Gaugino and scalar mass parameters $\Rightarrow$ top-down evaluation

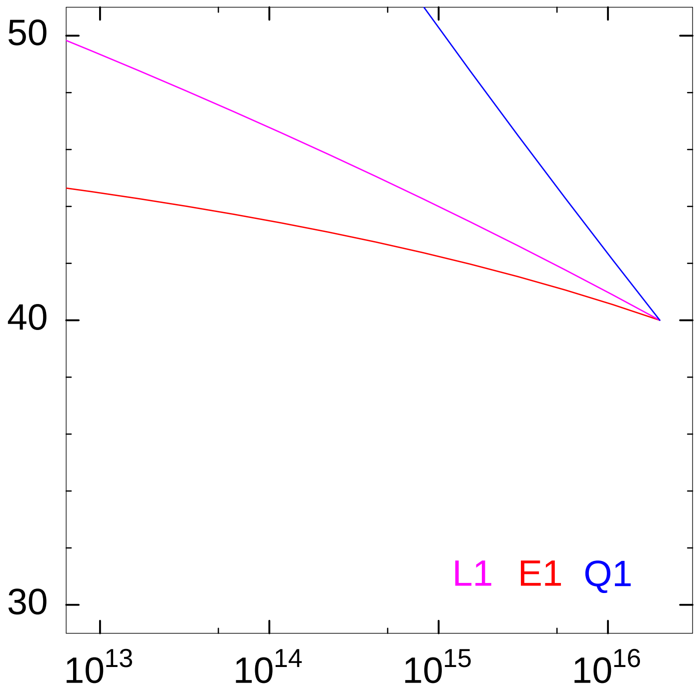
	Parameter, ideal	Experimental error
M_U	$2.36 \cdot 10^{16}$ GeV	$2.2 \cdot 10^{14}$ GeV
α_U^{-1}	24.19	0.05
$M_{1/2}$	250. GeV	0.2 GeV
M_0	100. GeV	0.2 GeV
A_0	-100. GeV	14 GeV
μ	357.4 GeV	0.4 GeV
$\tan\beta$	10.	0.4

$\Rightarrow$ excellent parametric analysis: physics scenario near GUT scale can be reconstructed at LHC+LC

INTERMEDIATE SCALE

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

intermediate seesaw scale $M[\nu_R]$ measurable [in-directly] ?



ν_R fields affect running through Yukawa couplings $\Rightarrow$

only 3rd generation + Higgs

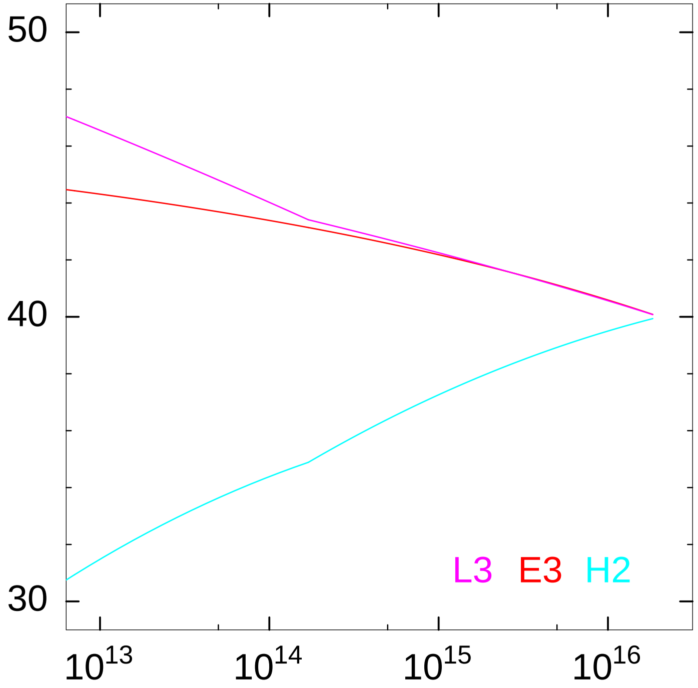
if parameters of GUT theory universal

$\Rightarrow$ universality in 1st/2nd generation directly observable: M_U, M_0

INTERMEDIATE SCALE

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

intermediate seesaw scale $M[\nu_R]$ measurable ? ⇒ "qualified yes"



ν_R fields affect running through Yukawa couplings ⇒ only 3rd generation + Higgs

if parameters of GUT theory universal

⇒ universality in 1st/2nd generation directly observable: M_U, M_0

⇒ in 3rd generation realized only if kink due to seesaw ν_R mass built in

STRING EFFECTIVE THEORY

Ibanez ea; Brignole ea

Binétruy ea

scenario : heterotic string theory with orbifold compactification

LE limit: dilaton field S

moduli fields T

vev's of scalar fields determine soft SUSY breaking parameters

M_i and $M_{\tilde{j}}^2$ etc

Goldstino $\tilde{G}$ ▷ SUSY breaking | S/T mixture :

$\tilde{G} = \sin\theta\,\tilde{S} + \cos\theta\,\tilde{T}$: $\sin\theta$ leading → dilaton-type/universal

$\cos\theta$ leading → moduli-type/non-universal

gaugino masses : $M_i = \frac{\alpha_i}{4\pi}\, m_{3/2}\,\langle S\rangle\,\sqrt{3}\sin\theta + \mathcal{O}\{\langle T\rangle, \delta_{GS}, \ldots\}$

scalar masses : $M_{\tilde{j}}^2 = m_{3/2}^2[1 + n_j\cos^2\theta] + \mathcal{O}\{\langle T\rangle \ldots\}$

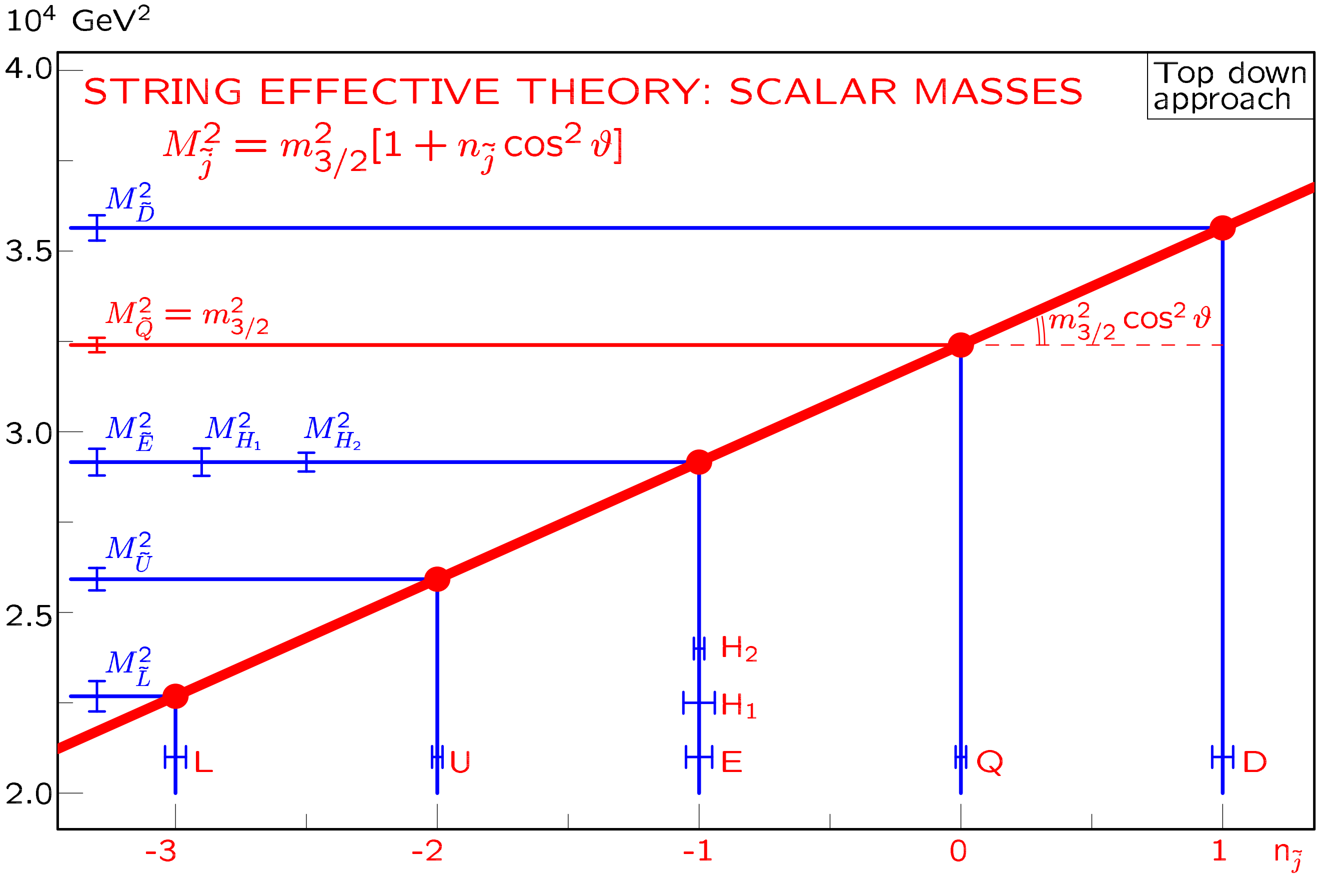
↑ integer modular weights

Model analysis :

Parameter	Ideal	Reconstructed		
$m_{3/2}$	180	179.9	±	0.4
$\langle S \rangle$	2	1.998	±	0.006
$\langle T \rangle$	14	14.6	±	0.2
$\sin^2\theta$	0.9	0.899	±	0.002
g_s^2	0.5	0.501	±	0.002
δ_{GS}	0	0.1	±	0.4
n_L	-3	-2.94	±	0.04
n_E	-1	-1.00	±	0.05
n_Q	0	0.02	±	0.02
n_U	-2	-2.01	±	0.02
n_D	+1	0.80	±	0.04
n_{H_1}	-1	-0.96	±	0.06
n_{H_2}	-1	-1.00	±	0.02

⇐ precision at per-cent level for integer modular weights testing stringently string-theoretical approach

“SUSY Chew-Frautschi Plot”



4. CONCLUSIONS

1. Coherent "LHC+LC" analyses establish SUSY scenario, if accessible, at electroweak scale comprehensively and with high precision:
   non-colored ⇐ per-mille level
   colored ⇐ per-cent level
2. Fundamental SUSY theory at GUT/Planck scale can be reconstructed / intermediate scales detected: universal mSUGRA, LR-extended, ...
3. String-effective parameters can be measured through gauge couplings and gaugino/scalar SUSY breaking parameters

   [P decay / ν physics / cosmology / $\oplus$]
   high-precision high-energy experiments ⇒

LHC+ILC may be interpreted as "Telescope to Planck-scale physics"
– if supersymmetry realized in Nature and mass domain favorable