LINEAR COLLIDER PHYSICS WITH HIGH LUMINOSITY

1. INTRODUCTION

- target of LC physics
- set of machine parameters

2. HIGH-PRECISION PHYSICS : SM & BEYOND (I)

- top quark
- electroweak gauge theories
- ew symmetry breaking / Higgs mechanism

3. THEORIES BEYOND THE STANDARD MODEL (II)

- supersymmetry
- non-standard scenarios

4. CONCLUSIONS

E. Accomando et al, Phys. Rept. 299 (1998) 1

TESLA Tech. Design Rept / in preparation

1. INTRODUCTION

LC TARGET : first phase : high-precision coverage / ~ per mille level / of energy range above LEP2 up to TeV range

→ electroweak symmetry breaking :
Higgs mechanism / alternatives

→ supersymmetry
other new physics scenarios

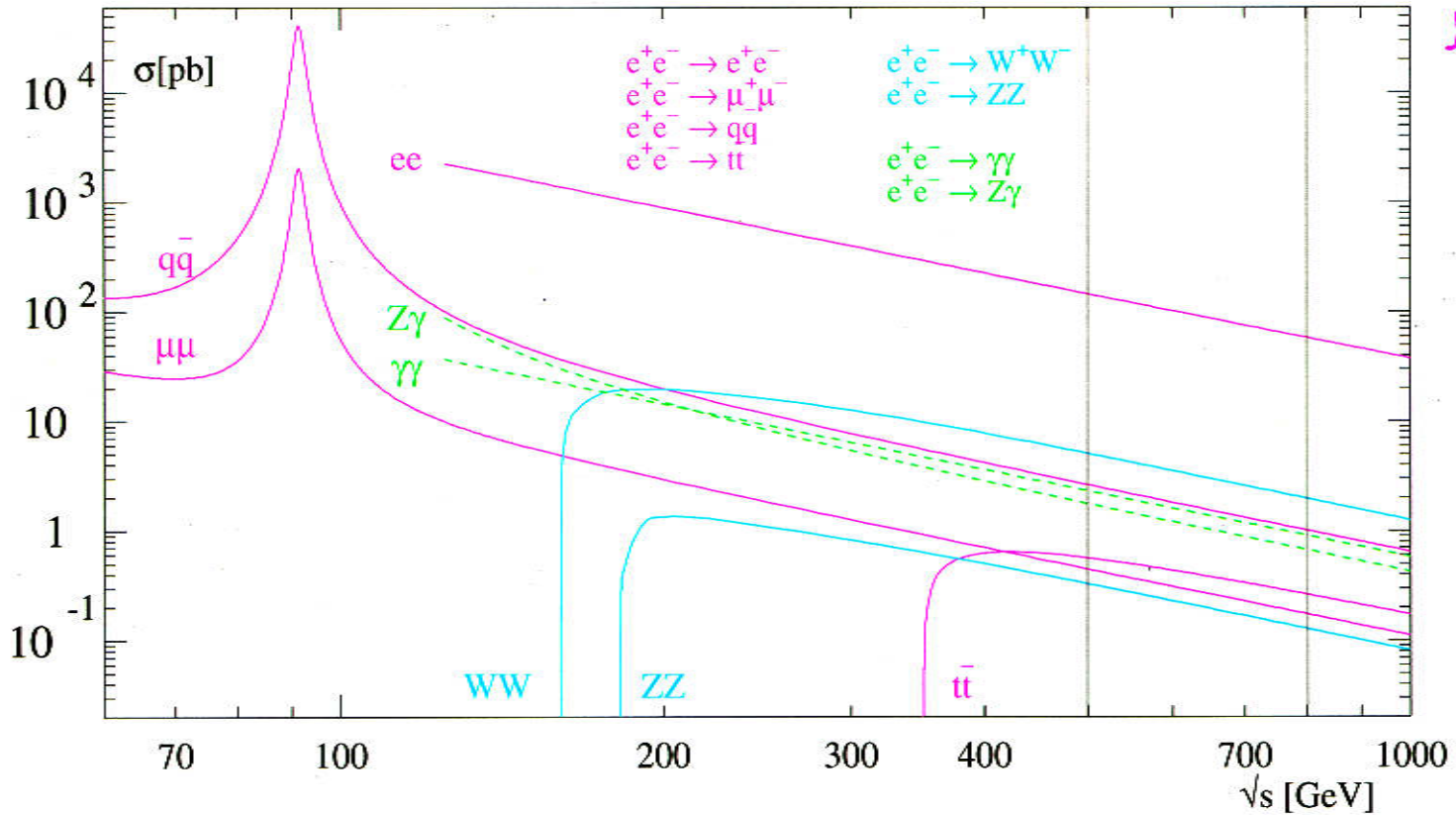
: extrapolation to scales far beyond the experimentally accessible energies [eventually GUT / PLANCK scale] :

~ crucial step to comprehensive theory of matter

PARAMETERS [TESLA] :

	energy $\sqrt{s}$	integ. lumi ~ per a
phase Ia	200 – 300 GeV	200 fb^{-1}
	300 – 500 GeV	300 fb^{-1}
Ib	500 – 0.8/1 TeV	500 fb^{-1}
	Z	1 giga Z

Plehn et al



$\int \mathcal{L} = 500\ fb^{-1}$

5×10^5 events

<u>luminosity</u> : high ← long bunch trains ~ 2,800
safe ← large separation ~ 200 – 300 μs

<u>beamstrahlung</u> : $\delta_E \simeq$ 2.8 %, 4.7 % } ~ ISR — spectrometer, Bhabha scattering

<u>polarization</u> : $\mathbb{P}[e^-] = 80\%$
$\mathbb{P}[e^+] = 60\%$

- suppring backgrd
  $e^-_R e^+ \not\to W^- W^+$
- particle diagnostics
  $\tilde{\chi}^\pm = \alpha \tilde{W}^\pm + \beta \tilde{H}^\pm$

<u>satellite modes</u> :

e^-e^-	: $E \sim 100\%$	$\mathcal{L} \sim 10\%$	
$e\gamma$	: $E \sim 90\%$	$\mathcal{L} \sim 30\%$	}
$\gamma\gamma$	: $E \sim 80\%$	$\mathcal{L} \sim 10\%$	}

↑ Compton - back scattering of laser light

<u>Physics with high luminosity</u> :

- problems can be solved in short time
- some specific problems can only be solved at high luminosity

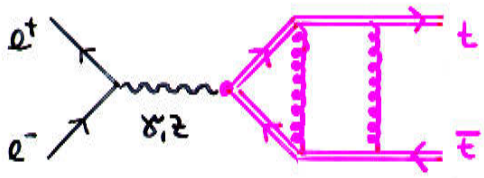
2. HIGH-PRECISION PHYSICS: SM & BEYOND (I)

a) TOP QUARK

high-precision measurements of t-quark properties:

- test of ew symmetry breaking at qm level:
  M_t, M_Z, $\sin^2\vartheta_W$ $\rightarrow$ M_H
- $M_t \sim v/\sqrt{2}$ maximal mass in SM fermion sector:
  key rôle in flavor dynamics / non-std Higgs physics ...

M_t max. precision: $e^+e^- \rightarrow t\bar{t}$ excitation curve near threshold



$\sigma_{t\bar{t}} \sim \beta_t \sim \sqrt{s-4M_t^2}$

⊖ width

⊕ 1S remnant

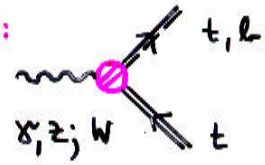
accuracy:

$\Delta M_t \lesssim 200\,\text{MeV}$

$\Delta M_t / M_t \lesssim 1‰$

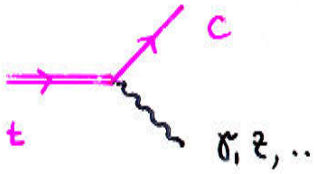
most precise mass in quark sector

ELW FF:

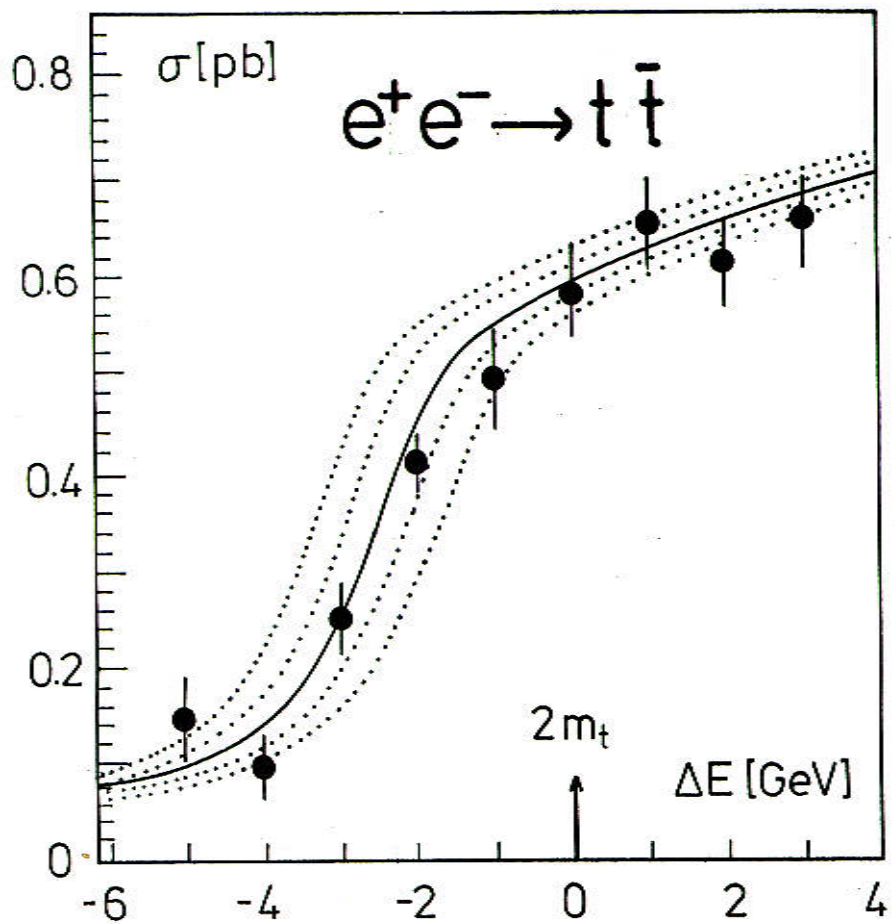


charges $\lesssim 1\%$

RARE DECAYS:



$\# 10^6\ t$: $BR \sim 10^{-4} - 10^{-5}$



Igo-Kemenes et al.
Martinez et al.

b) ELECTROWEAK GAUGE SYMMETRIES

→ establish <u>non-abelian gauge symmetry</u> of elw. interactions

→ open window to <u>new elw gauge bosons</u> / leptons: L/R ..

(i) ELECTROWEAK MIXING ANGLE $\sin^2\vartheta_W$:

left-right polarization asymmetry:

$$A_{LR} = \frac{2(1-4s_\ell^2)}{1+(1-4s_\ell^2)^2}$$

1 gigaZ : $\delta s_\ell^2 \approx 1\cdot 10^{-5}$

HIGGS TEST :

Higgs mass prediction based on $[G_F,\ \alpha(M_Z),\ \sin^2\vartheta_W]$:

compared with direct mass measurement

: field-theoretic consistency test ~ new scales in loops

$$\frac{G_F}{\sqrt{2}} = \frac{\pi\alpha(M_Z^2)}{M_Z^2 s_\ell^2 c_\ell^2}\ \frac{1}{1-\Delta r_\ell} \quad : \quad \Delta r^t = -\frac{3G_F M_t^2}{8\sqrt{2}\pi^2} + \dots$$

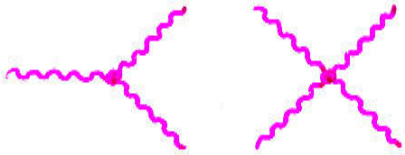
$$\Delta r_\ell^H = +\frac{G_F M_Z^2 c_\ell^2}{8\sqrt{2}\pi^2}\ \frac{1+9s_\ell^2}{3c_\ell^2}\left[\log\frac{M_H^2}{M_Z^2 c_\ell^2} - \frac{5}{6}\right]$$

	ΔM_t	$\Delta \sin^2\vartheta_\ell$	ΔM_W	$\Delta M_H / M_H$
LHC	1 GeV	2×10^{-4}	15 MeV	0.37 / 0.31
LC	200 MeV	1×10^{-5}	[6 MeV]	0.06

Hollik ..

(ii) NON-ABELIAN GAUGE SYMMETRY / $SU_2 \times U_1$

self-interactions :

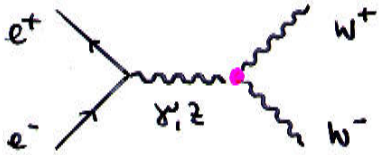


deviations :
$\delta \sim (M_W / \Lambda)^2$

elw static param. γ / Z :

monopole charge	:	e
magn. dipole mom.	:	$2 \times e / 2 M_W$
el. quadrup. mom.	:	$- e / M_W^2$

measurement :



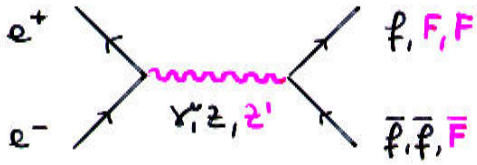
LC 500 : first
$\delta \lesssim 10^{-3}$

(iii) EXTENDED GAUGE SYMMETRIES

LR insp.
S-string

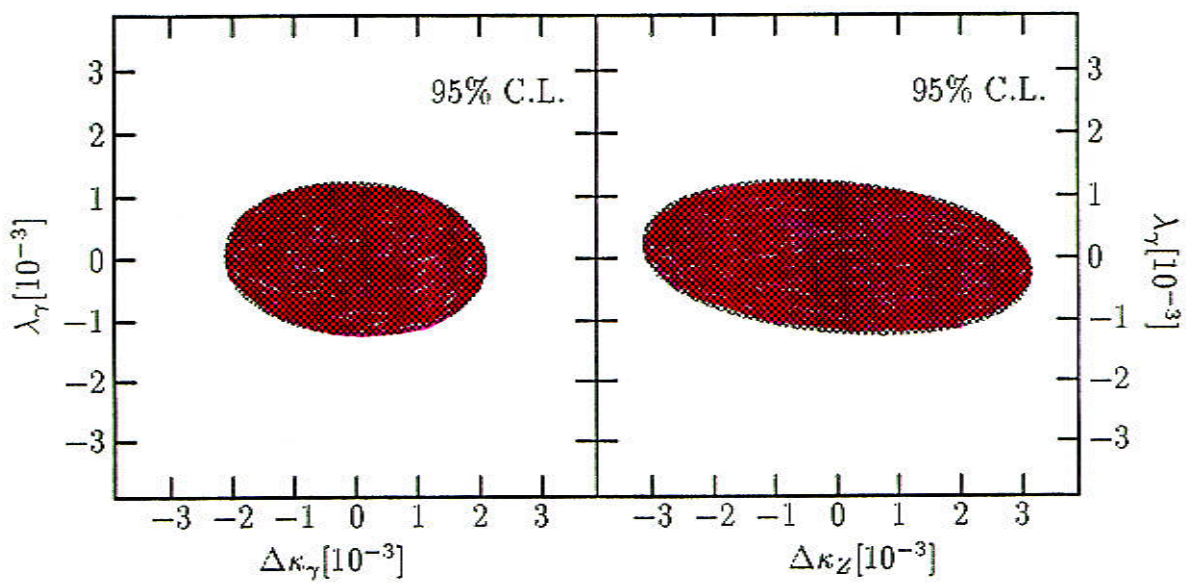
SO (10) : W_R, Z_R : ν_R

E (6) : Z' : ν_R $\begin{bmatrix} N \\ E \end{bmatrix}_L$ $\begin{bmatrix} N \\ E \end{bmatrix}_R$ n_R D_L D_R



$\sqrt{s}$	SO (10)	E(6)
500 GeV	7 TeV	4 - 6 TeV
800 GeV	11 TeV	6 - 10 TeV

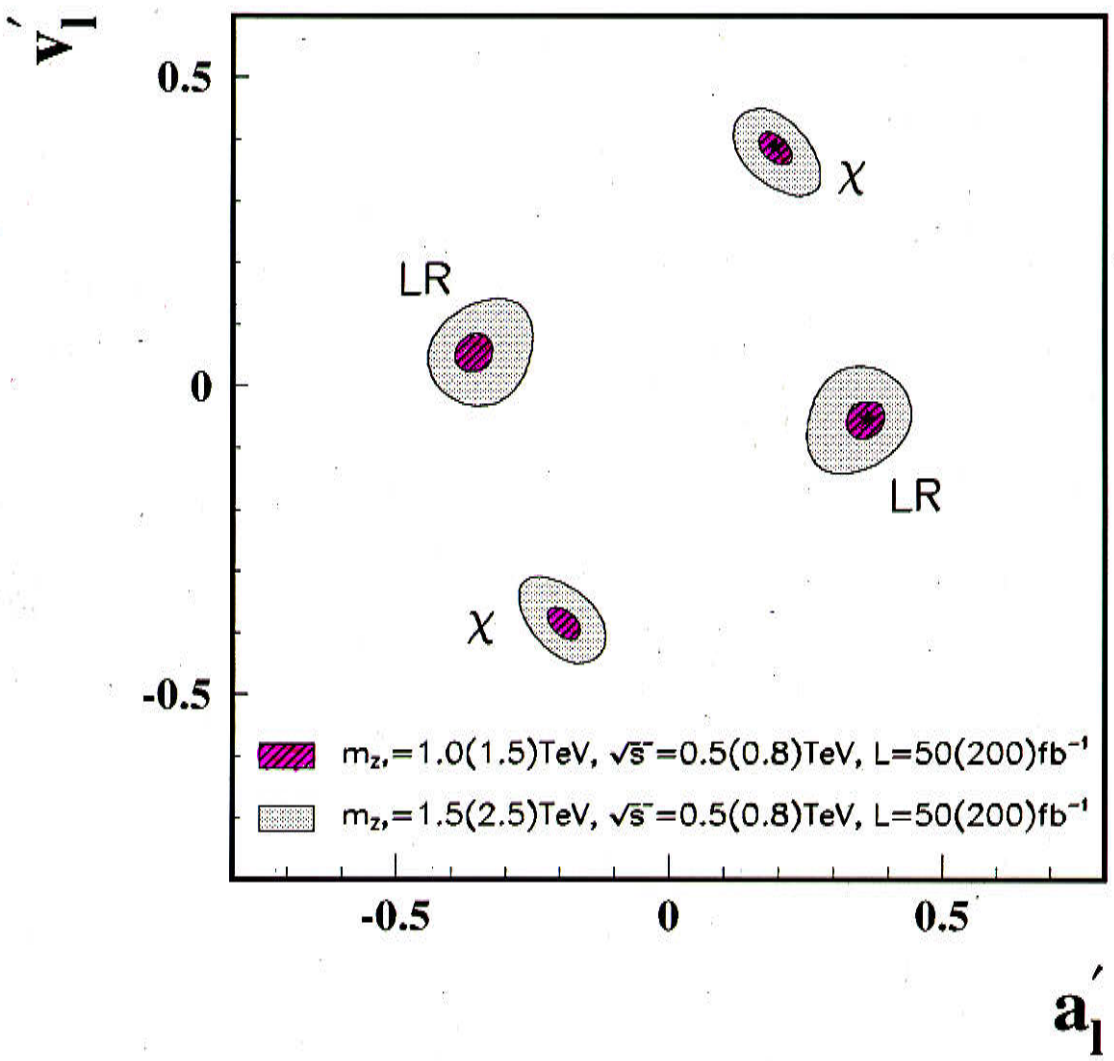
- new gauge bosons : beyond LHC $\sim$ 5 TeV // couplings .
- new leptons $m_L \lesssim \sqrt{s}$



Gounaris et al.
Dashalakis et al.

Figure 0.15: *Measurement of the anomalous couplings $\Delta\kappa_\gamma$, $\Delta\kappa_Z$, and λ of the electroweak gauge bosons. The deviations from the Standard Model are taken as singlets under the SM symmetry group; $\int \mathcal{L} = 50\ fb^{-1}$ at $\sqrt{s} = 500$ GeV. Ref.[72].*

Leike
Riemann



c) SM HIGGS MECHANISM

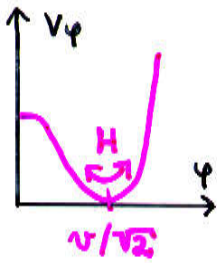
elw symmetry breaking : central problem of physics / after non-abel. gauge symmetry

↳ qualitative support for Higgs mechanism :
RAD. CORR. : $M_H \lesssim 250$ GeV

↳ high-luminosity e^+e^- collider excellent tool :

TASK : establish Higgs mechanism sui generis for generating masses of fundamental SM particles :

3 STEPS :



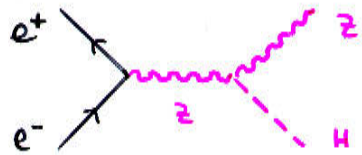
(1) Higgs excitation ≡ Higgs boson must be discovered — LEP 2, Tevatron, LHC

(2) generating masses by interaction with Higgs field : cplg ~ mass — [LHC], LC

(3) Higgs field $\langle\varphi\rangle_0$ generated through Spon. Sym. Brkg :
reconstruction of Higgs potential ← H self-cplgs — TESLA

LC HIGGS PRODUCTION :

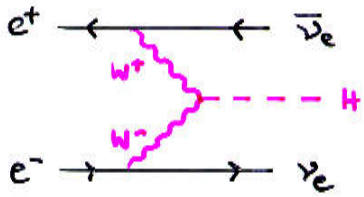
Higgs-strahlung :



$$\sigma \simeq \frac{G_F^2 M_Z^4}{96\pi s}$$

$\sqrt{s}$ mod. / M_H mod.

WW fusion :



$$\sigma \simeq \frac{G_F^3 M_W^4}{4\sqrt{2}\pi^3} \log \frac{s}{M_H^2}$$

$\sqrt{s}$ large / M_H small (ℓ)

$\sqrt{s} \sim 300$ GeV / $\int \mathcal{L} \sim 500$ fb^{-1}
$M_H \sim$ intermediate mass range

10^5 Higgs bosons nearly degd pee

COUPLINGS :

HZZ, HWW :

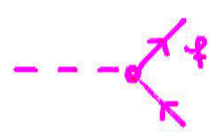
Higgs-strahlg, fusion, decay width.

$\sigma \sim g^2(ZZH)$

0.8 %

Hff for f = b, c, τ :

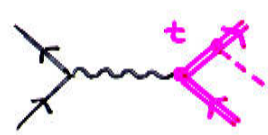
decay BR for ≲ 150 GeV



BR $\sim g_Y^2(ffH)$

Htt :

H bremsstrahlung off t

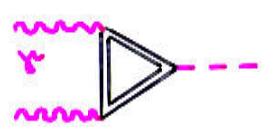


$\sigma \sim g_Y^2(ttH)$

5%

Hγγ :

γγ production of Higgs

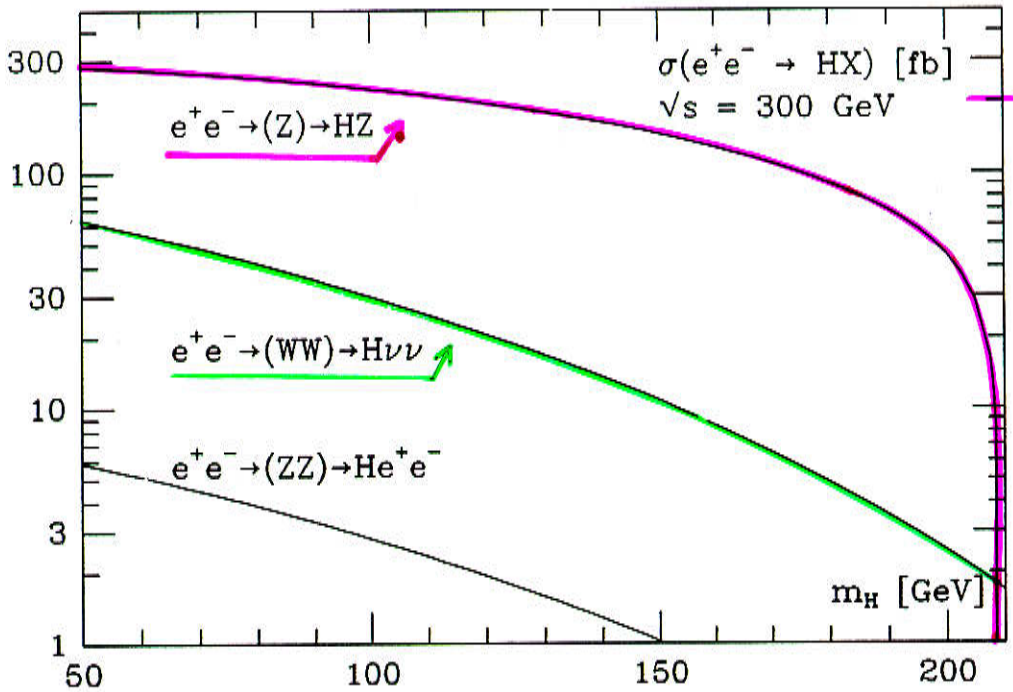


$\sigma \sim g^2(H\gamma\gamma)$

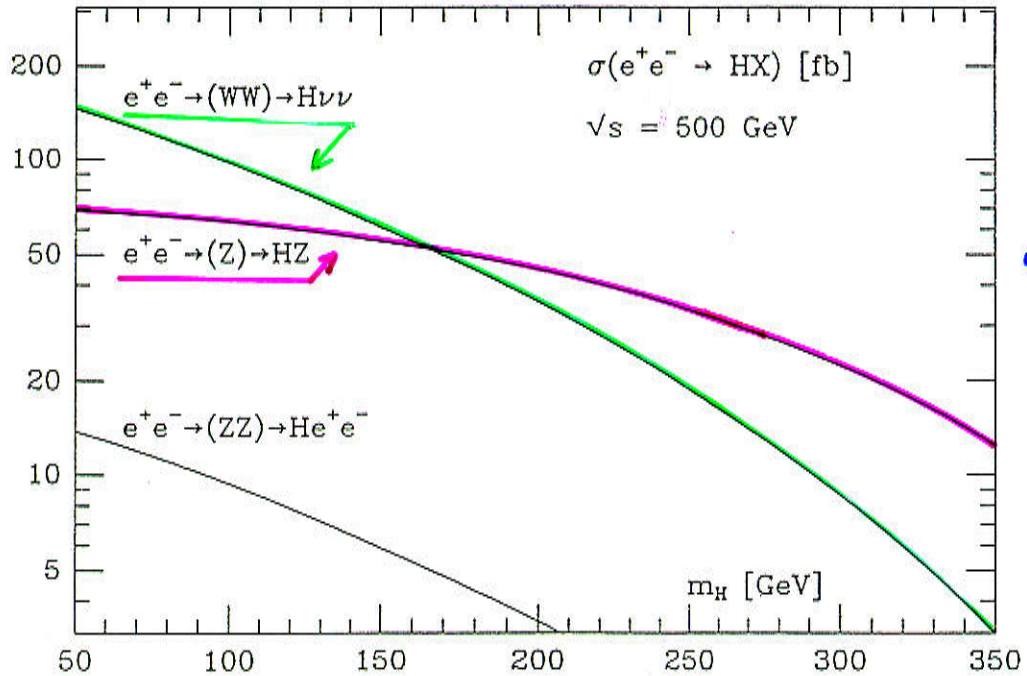
1%

$\int \mathcal{L} = 500\ fb^{-1}$

Djouadi et al



10^5 events



25,000

5,000

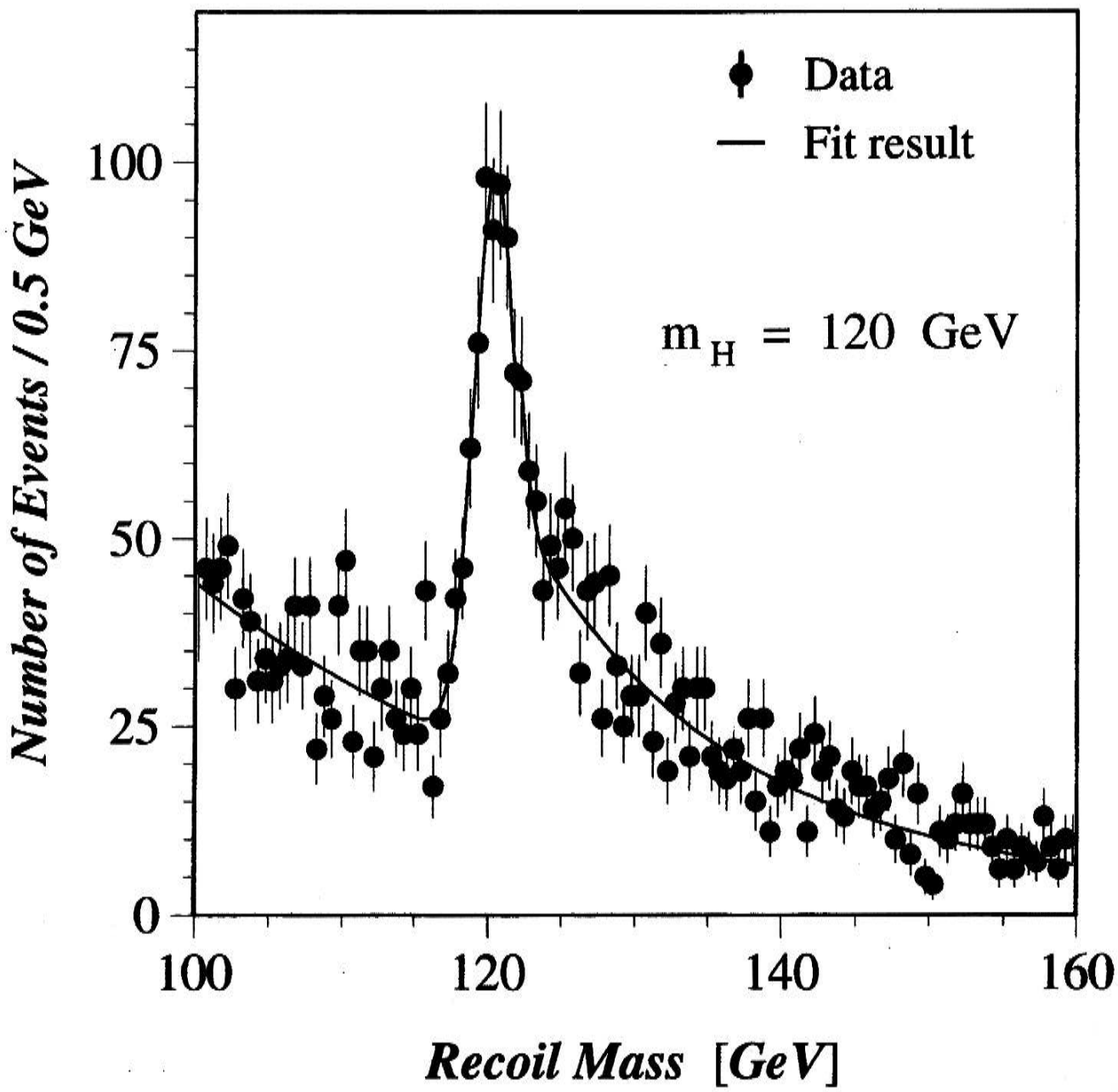
Garcia
Rohmann

Recoil Mass Fit, e^+e^-

$$M_H = 120.48 \pm 0.14 \text{ GeV}$$

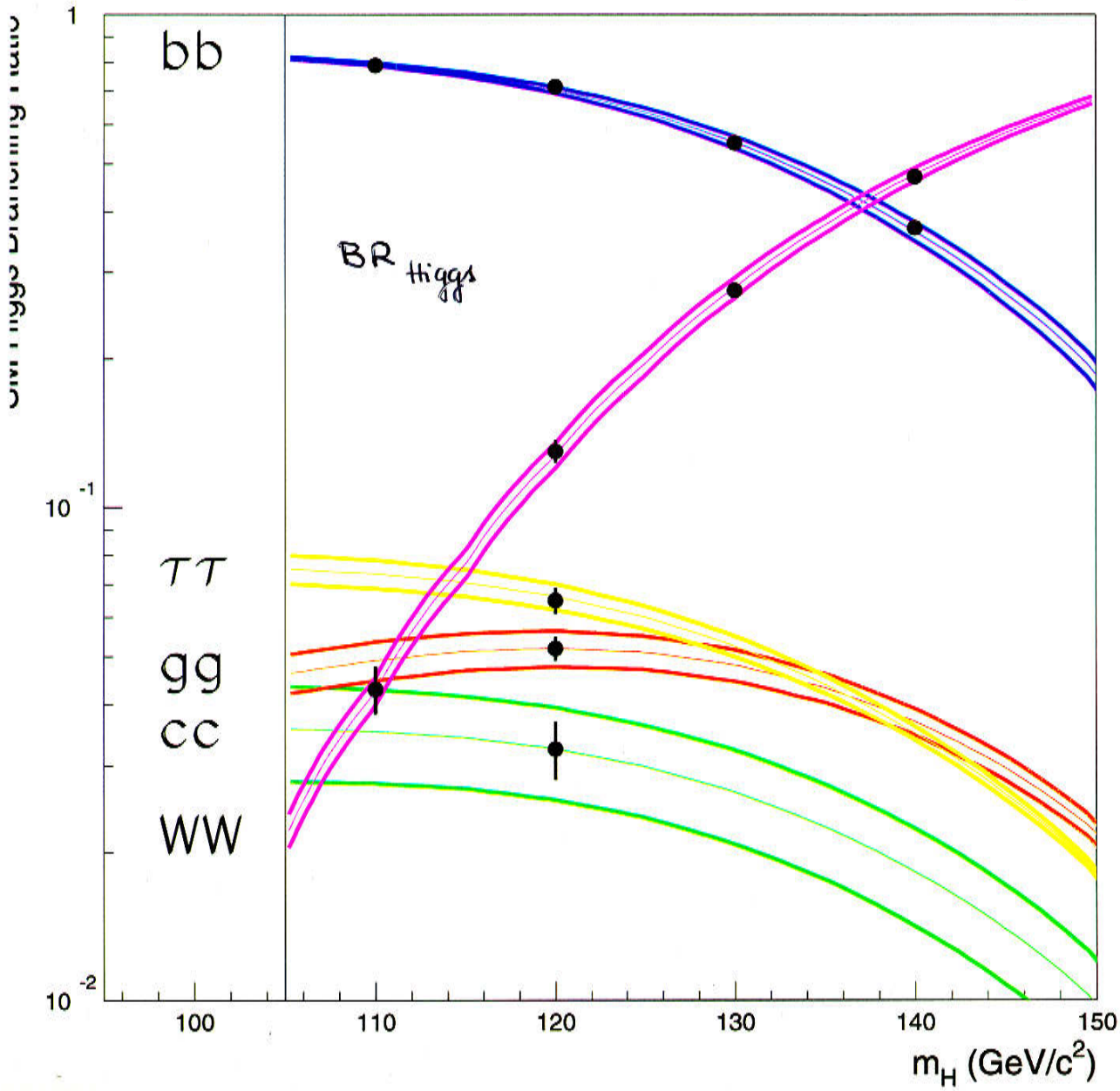
$$\sigma_H = 1.48 \pm 0.11 \text{ GeV}$$

$$\sigma\,(ZH \to e^+e^-X) = 5.26 \pm 0.18 \pm 0.13 \text{ fb}$$



L = 500 fb^{-1}

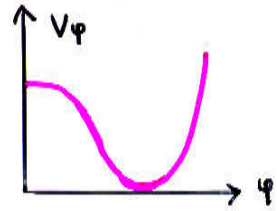
Battaglia



HIGGS SELF-COUPLINGS

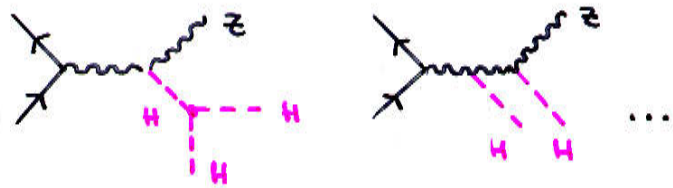
$$V = \lambda \left[|\varphi|^2 - \tfrac{1}{2} v^2 \right]^2$$

$$= \frac{M_H^2}{2} H^2 + \frac{M_H^2}{2v} H^3 + \frac{M_H^2}{8v^2} H^4$$



HHH

double Higgs-strahlung :



$\sigma \sim \alpha^2 g^2 (HHH)$

$\lesssim 1$ fb : sensitivity $\Delta g/g \lesssim 20\%$.

↳ essential elements of the Higgs mechanism can experimentally be established at high-luminosity e^+e^- linear colliders

c') STRONGLY INTERACTING W BOSONS

no fund. light Higgs : WW strongly interacts at $\sim$ 1TeV :

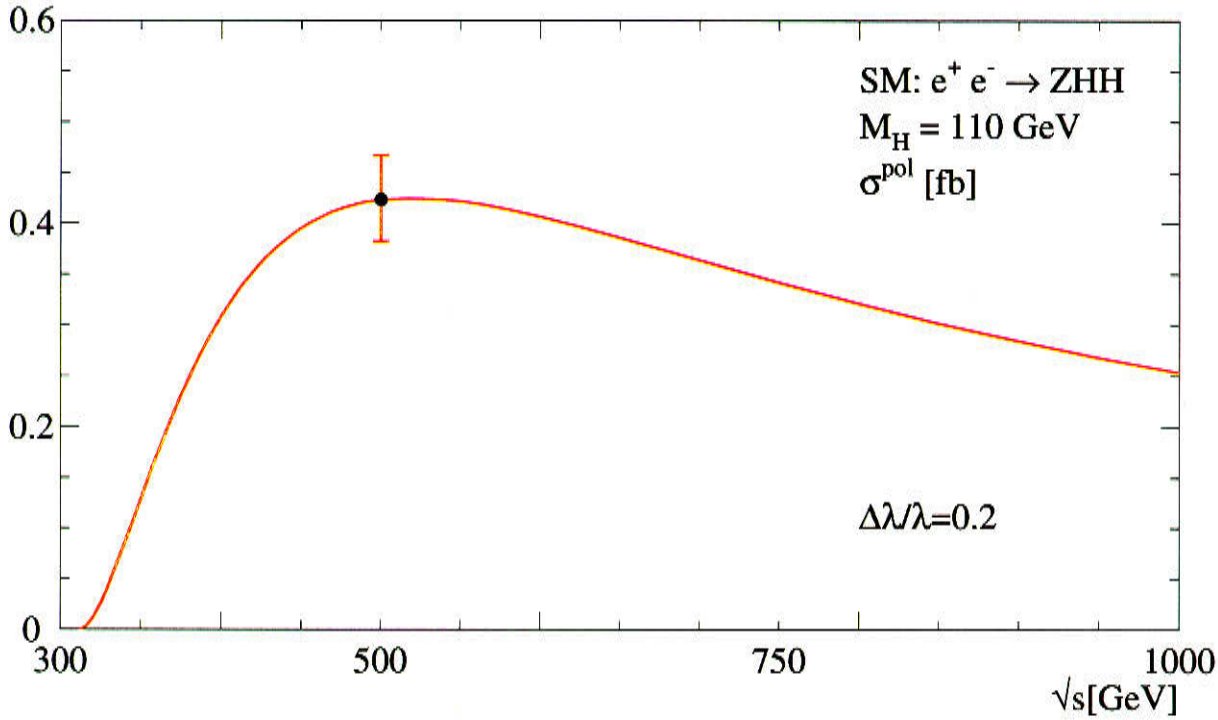
elw symmetry breaks dynamical : new strong interactions spont. broken χ FT : goldstones $\sim W_L$ states

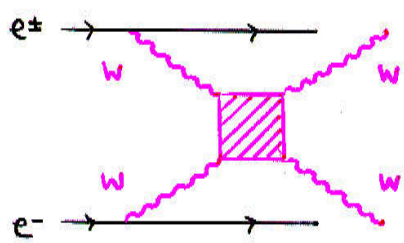
$W_L W_L \to W_L W_L$:

$$a_{00} = + \frac{6s}{96\pi v^2} \qquad a_{20} = - \frac{2s}{96\pi v^2}$$

$$a_{11} = + \frac{s}{96\pi v^2} \qquad \text{corr}_s = \mathcal{O}(s/\Lambda^2)$$

Djouadi et al
Lutz et al





threshold measurement of chiral expansion in energy:

$$\boxed{\begin{array}{lll} \delta a/a \lesssim 15\% & \Big\} & 1\,\text{TeV} \\ \Lambda \gtrsim 3\,\text{TeV} & \Big\} & 1\,\text{ab}^{-1} \end{array}}$$

LC : $W \to jj$ reconstruction

3a) SUPERSYMMETRY

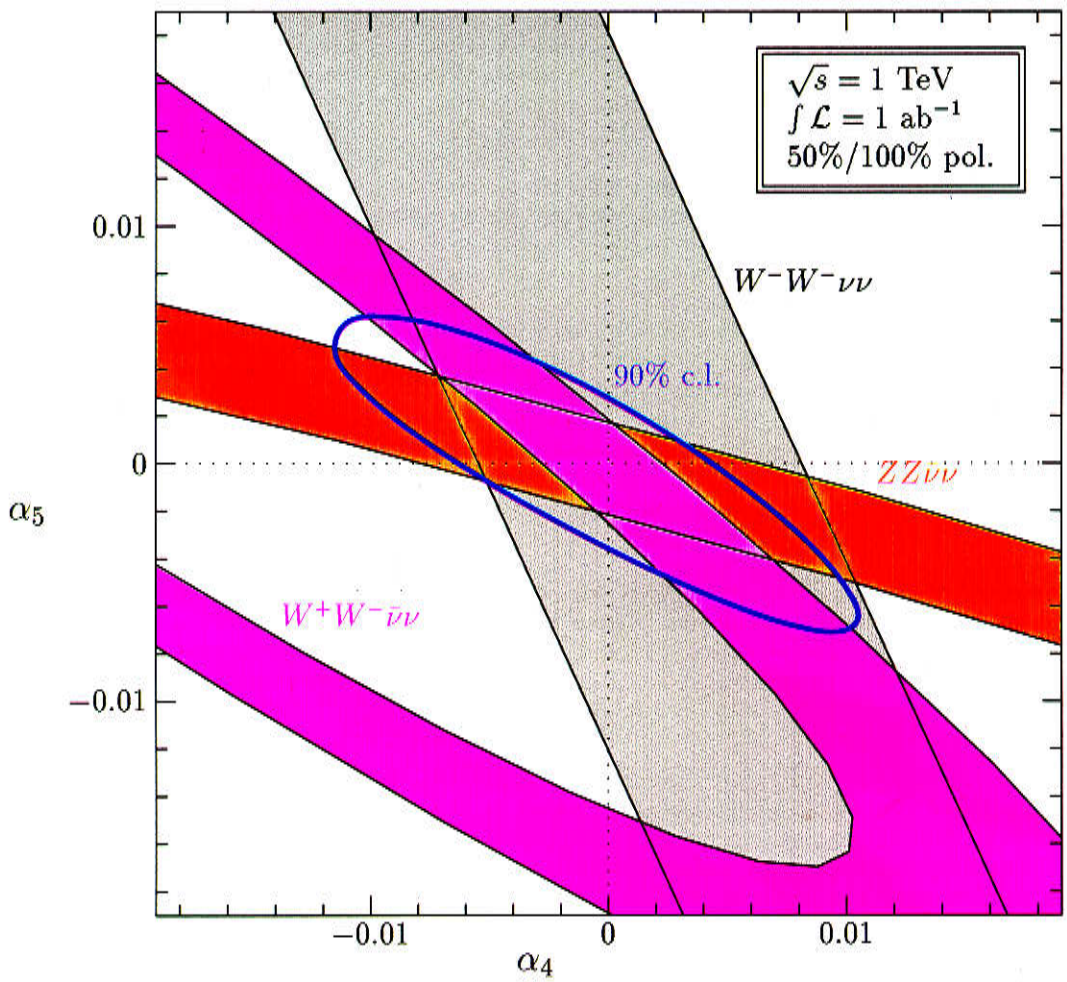
- reconstruction of entire SUSY spectrum
- high-precision measurements of masses, couplings, ...
  - → fundamental parameters
  - → SUSY breaking $\Rightarrow$ $\boxed{\text{extrapolation to scales} \sim M_{PLANCK} \sim \text{gravity}}$

HIGGS - SECTOR

MSSM : $h^0 \lesssim 140$ GeV
$H^0, A^0, H^\pm \sim \mathcal{O}(v)$ to $\mathcal{O}(1\,\text{TeV})$

LHC : covering MSSM parameter range may not find [some of the] heavy Higgs

Boos et al


$\sqrt{s} = 1$ TeV
$\int \mathcal{L} = 1$ ab^{-1}
50%/100% pol.
$W^-W^-\nu\nu$
90% c.l.
$ZZ\bar{\nu}\nu$
$W^+W^-\bar{\nu}\nu$
0.01
0
−0.01
α_5
−0.01
0
0.01
α_4

$\boxed{h^0}$: <u>guaranteed to be discovered</u>

Higgs-strahlung : $e^+e^- \to Zh$: mutually complementary
pair production : $e^+e^- \to Ah$ reactions

[no-lose theorem in (M+n) SSM]

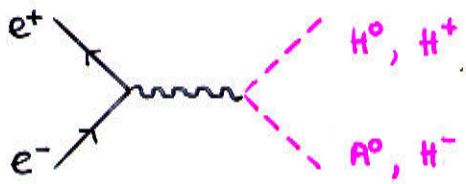
$\boxed{H^0, A^0, H^\pm}$: <u>heavy Higgs bosons</u>

← indirectly :

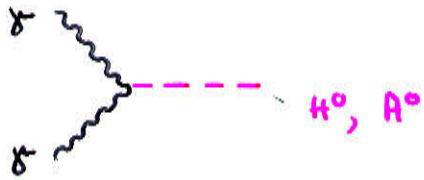
$$\frac{BR(h \to c\bar{c})}{BR(h \to b\bar{b})} \propto \frac{(M_A^2 - M_h^2)^2}{(M_A^2 + M_Z^2)^2}$$

visibility up to : $M_A \sim 600$ GeV

← directly :



$M_H \lesssim \sqrt{s}/2$
~ 500 GeV



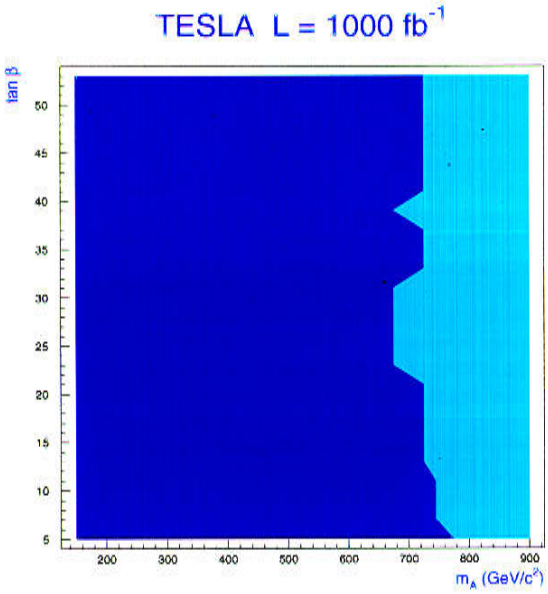
$M_H \lesssim [\sqrt{s}/2 + 100]$
$\sim [600]$ GeV

<u>heavy Higgs masses up to $M(H^0, A^0, H^\pm) \lesssim \sqrt{s}/2\ [+100]$ GeV</u>

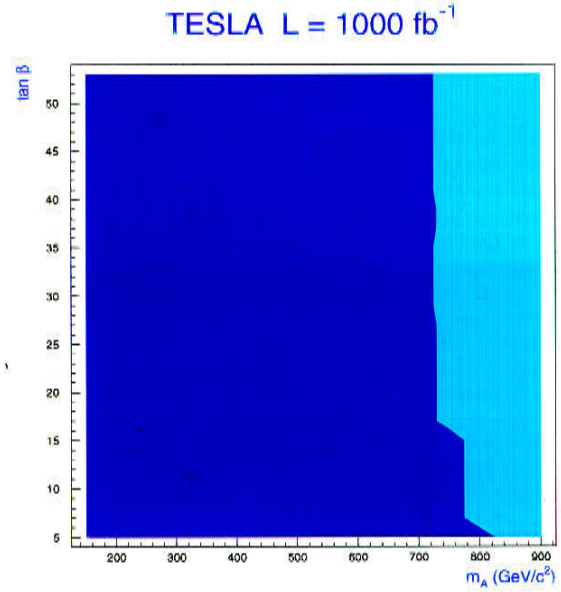
BATTAGLIA

SM / MSSM Separation in M_A - $\tan\beta$ plane
$\int L = 1000$ fb^{-1}, Theory Syst. / 2.0

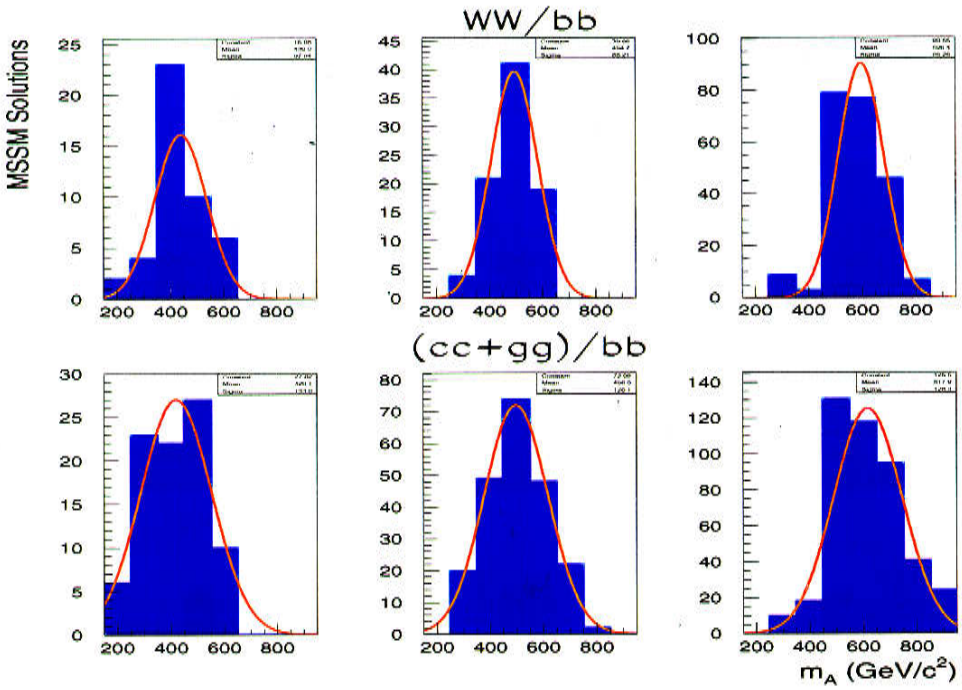
CDR Vertex Tracker

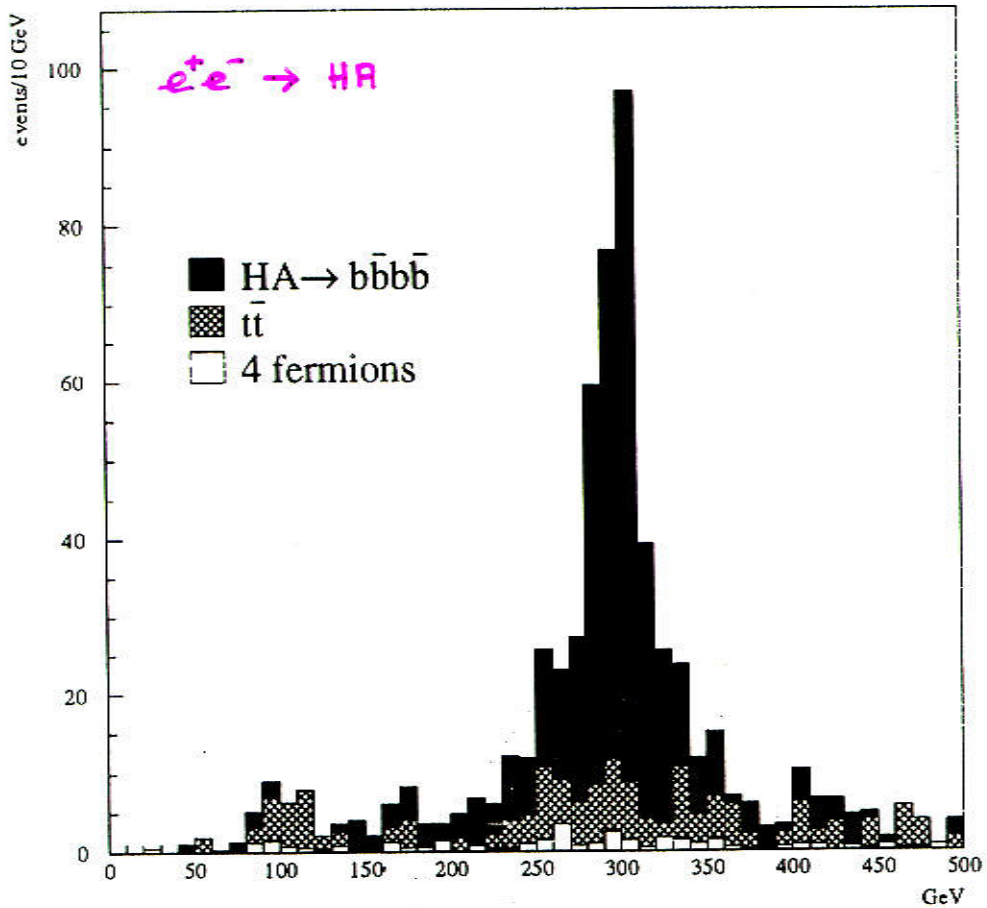


Improved Vertex Tracker



Sensitivity to M_A





Andreazza
Troncon

SUPERSYMMETRIC PARTICLES

- squarks, gluinos : LHC $\sim$ 2 TeV

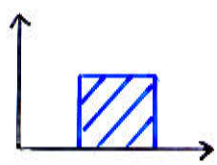
  LC : $e^+e^- \to \tilde{t}_i \bar{\tilde{t}}_j$ stop mixing / A

- charginos, neutralinos : $e^+e^- \to \tilde{\chi}_i^+ \tilde{\chi}_j^-$, $\tilde{\chi}_i^0 \tilde{\chi}_j^0$

- sleptons : $e^+e^- \to \tilde{\ell}^+ \tilde{\ell}^-$, $\tilde{\nu}_\ell \bar{\tilde{\nu}}_\ell$

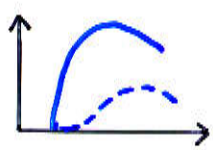
Mass Measurement :

final state :



threshold :

$\frac{1}{2}/0 : \beta/\beta^3$



Martyn

.	final state	threshold
$\tilde{\chi}$	200 - 300 MeV	40 $\to$ 500 MeV
$\tilde{\ell}$	200 - 300 MeV	70 $\to$ 600 MeV

experimental analysis of more than $\sim$ 10 channels : $\int \mathcal{L} \gtrsim 1 ab^{-1}$.

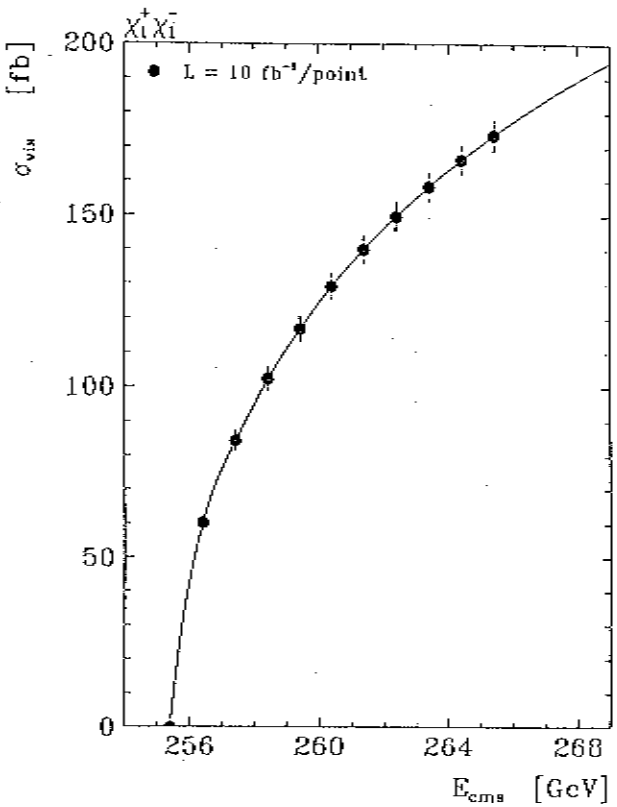
Mixing Effects :

$$\tilde{\chi}_{1L}^- = \cos\phi_L \tilde{W}_L^- + \sin\phi_L \tilde{H}_L^-$$

$$\tilde{\chi}_{2L}^- = -\sin\phi_L \tilde{W}^- + \cos\phi_L \tilde{H}_L^- \quad \text{and} \quad L \to R$$

: $\sigma_{L,R}$ binomial in $\cos 2\phi_{L,R}$.

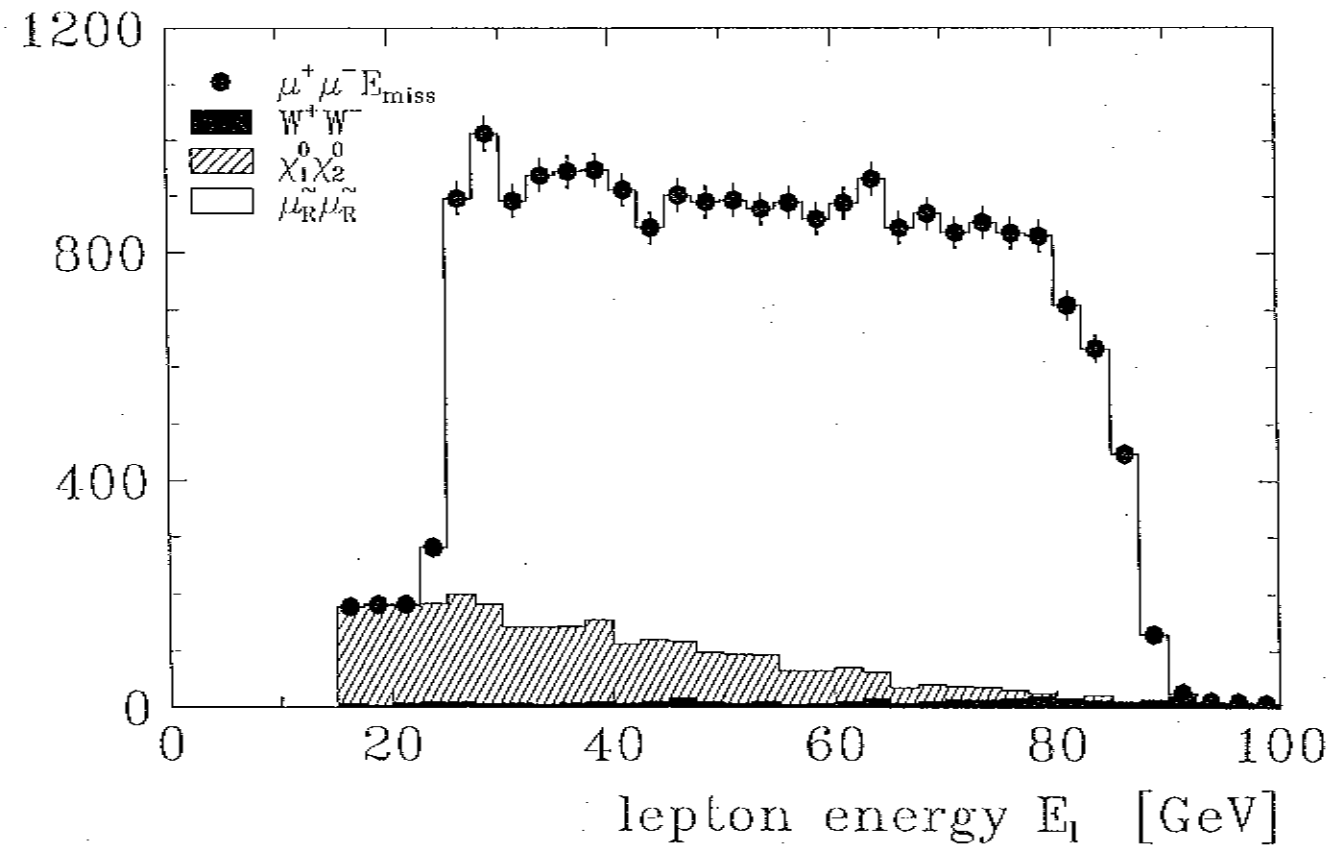
$e_L^- e_R^+ \to \chi_1^- \chi_1^+$



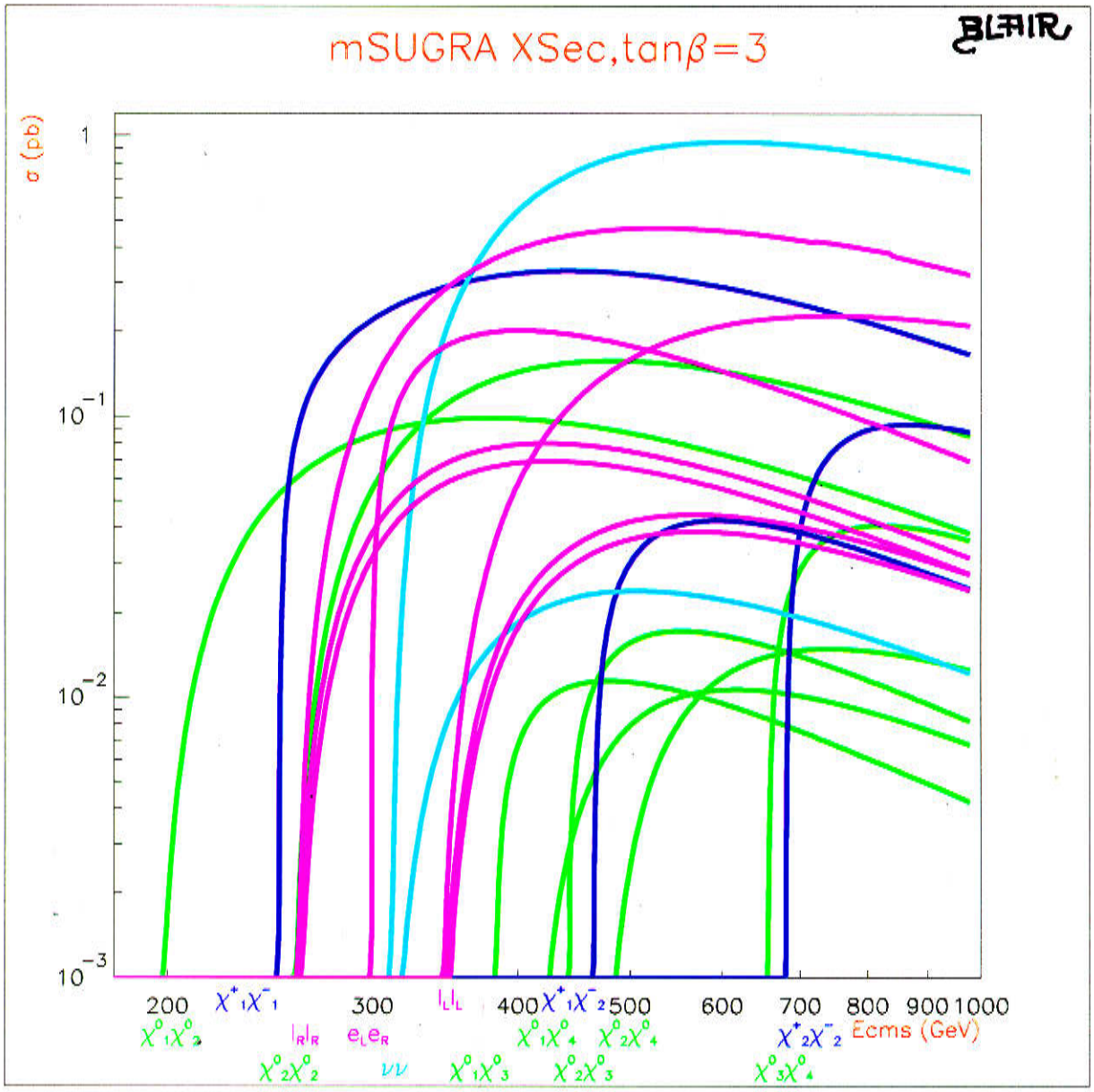
$m_{\chi_1^\pm} = 127.7 \pm 0.04$ GeV

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

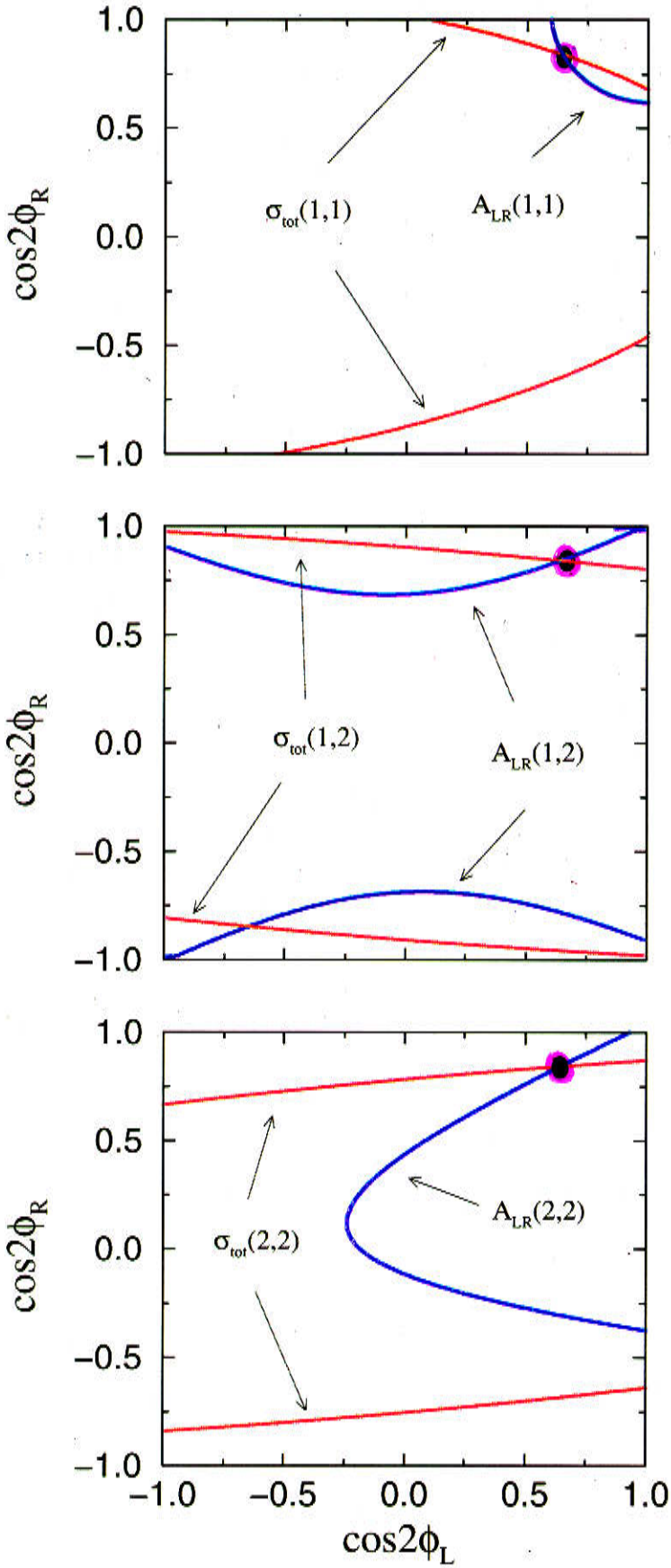
Martyn



$m_{\tilde{\mu}_R} = 132.0 \pm 0.3$ GeV $\quad m_{\chi_1^0} = 71.9 \pm 0.2$ GeV


mSUGRA XSec,tanβ=3
BLAIR
σ (pb)
1
10^-1
10^-2
10^-3
200
300
400
500
600
700
800
900
1000
Ecms (GeV)
χ+1χ-1
χ0 1χ0 2
lRlR
χ0 2χ0 2
eLeR
νν
lLlL
χ0 1χ0 3
χ+1χ-2
χ0 1χ0 4
χ0 2χ0 3
χ0 2χ0 4
χ+2χ-2
χ0 3χ0 4

Choi, Song, Djouadi, Z.



BASIC PARAMETERS :

M_2, M_1	gaugino mass parameters
μ	higgsino mass parameter
$tg\,\beta$	

RR1

$M_2 = 152 \pm 1.8$ GeV
$M_1 = 72 \pm 3.2$ GeV
$\mu = 316 \pm 0.9$ GeV
$tg\,\beta = 3.0 \pm 0.7$

$$M_2/|\mu| = \frac{1}{2}\left[2(x_2 + x_1 - 2W) \mp (x_2 - x_1)(\cos 2\phi_R + \cos 2\phi_L)\right]^{1/2}$$

$$M_1^2 = \Sigma x_i^{02} - M_2^2 - \mu^2 - 2M_Z^2$$

$$tg\,\beta = \left[4W + (x_2 - x_1)(\cos 2\phi_R - \cos 2\phi_L)\right]^{1/2} / \left[-\right]^{1/2}$$

basic parameters can be determined in model independent way at an accuracy of ~ percent to permille

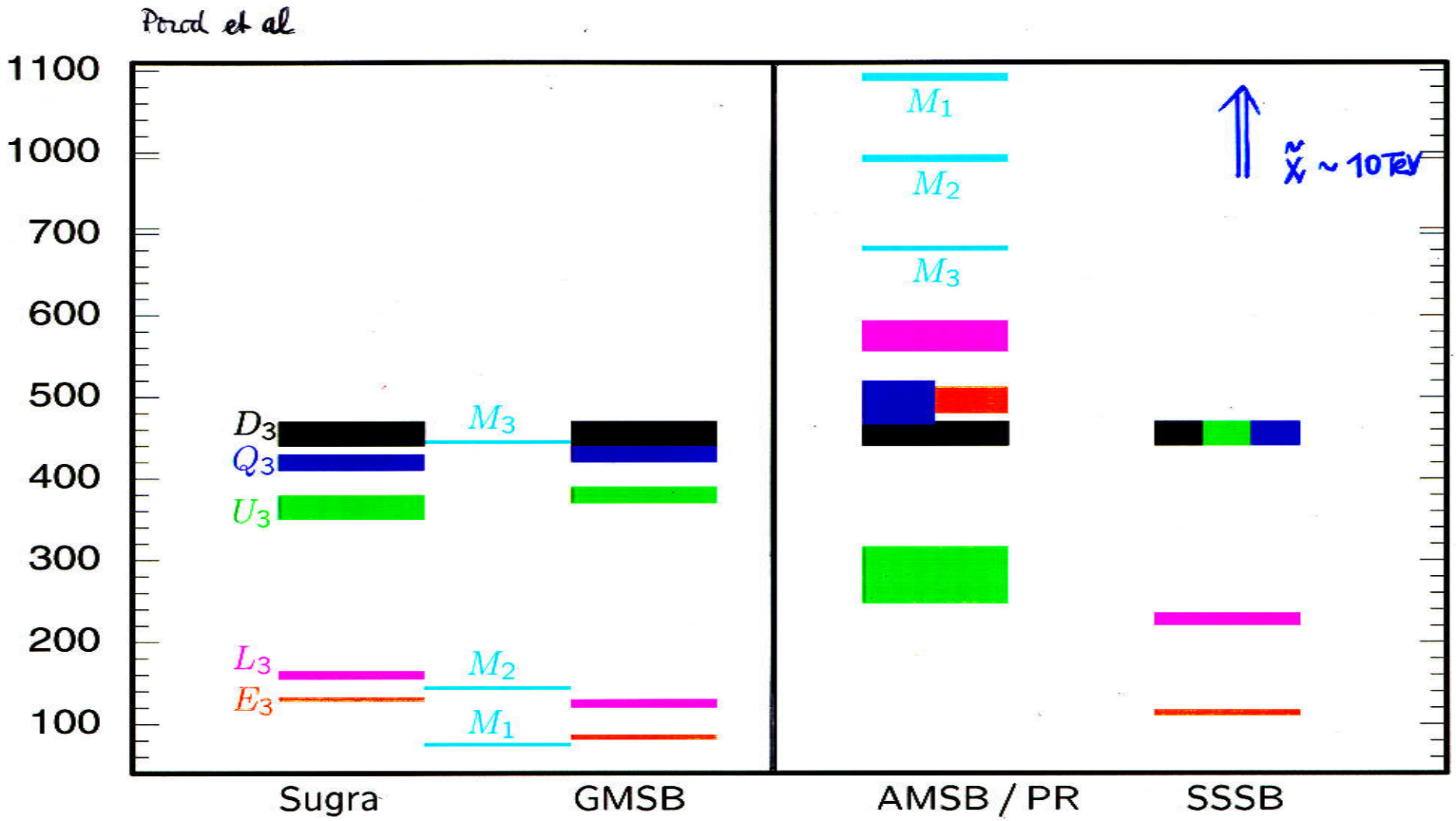
SUSY BREAKING MECHANISMS :

physics potential : fundamental problem
may provide clues on : gravity at small dist.
extra space dim ...

realizations : mSUGRA min. supergravity
AMSB
GMSB gauge mediated
:

signature : mass specra : * $M_i \sim x_i$ $\tilde{m}_i \sim M_2$
* $\tilde{m}_i \sim x_i$

Gaugino and Sfermion Masses



mSUGRA : ~~SUSY~~ transmitted from hidden world by gravity : $M_{PL} \sim 10^{19}$ GeV

fl. univ. bkg. : masses, decay modes, production processes } 4.5 parameters : m_0, $M_{1/2}$, A_0, $tg\beta$, $sgn\,\mu$

- mSUGRA extrapolation to GUT scale :

$sgn\,\mu = +$		theor. values	exp. error
scalar mass	m_0	100 GeV	0.085 GeV
gaugino mass	$M_{1/2}$	200 GeV	0.095 GeV
trilin. cplg	A_0	0 GeV	6 GeV
	$tg\beta$	3	0.019

Blair

- robust, model-independent approach from low → hi scale : non-universal GUT parameters

GMSB ~~SUSY~~ transmitted through messenger sector [~ 10 to 10^5 TeV] by gauge fields

- different mass pattern : low → hi scales.
- LSP = gravitino : $\tilde{\chi}_1^0 \to \gamma + \tilde{G} = \gamma + \not{E}$: displaced γ

  $\tilde{\tau}_1 \to \tau + \tilde{G} = \tau + \not{E}$: heavy c hadr

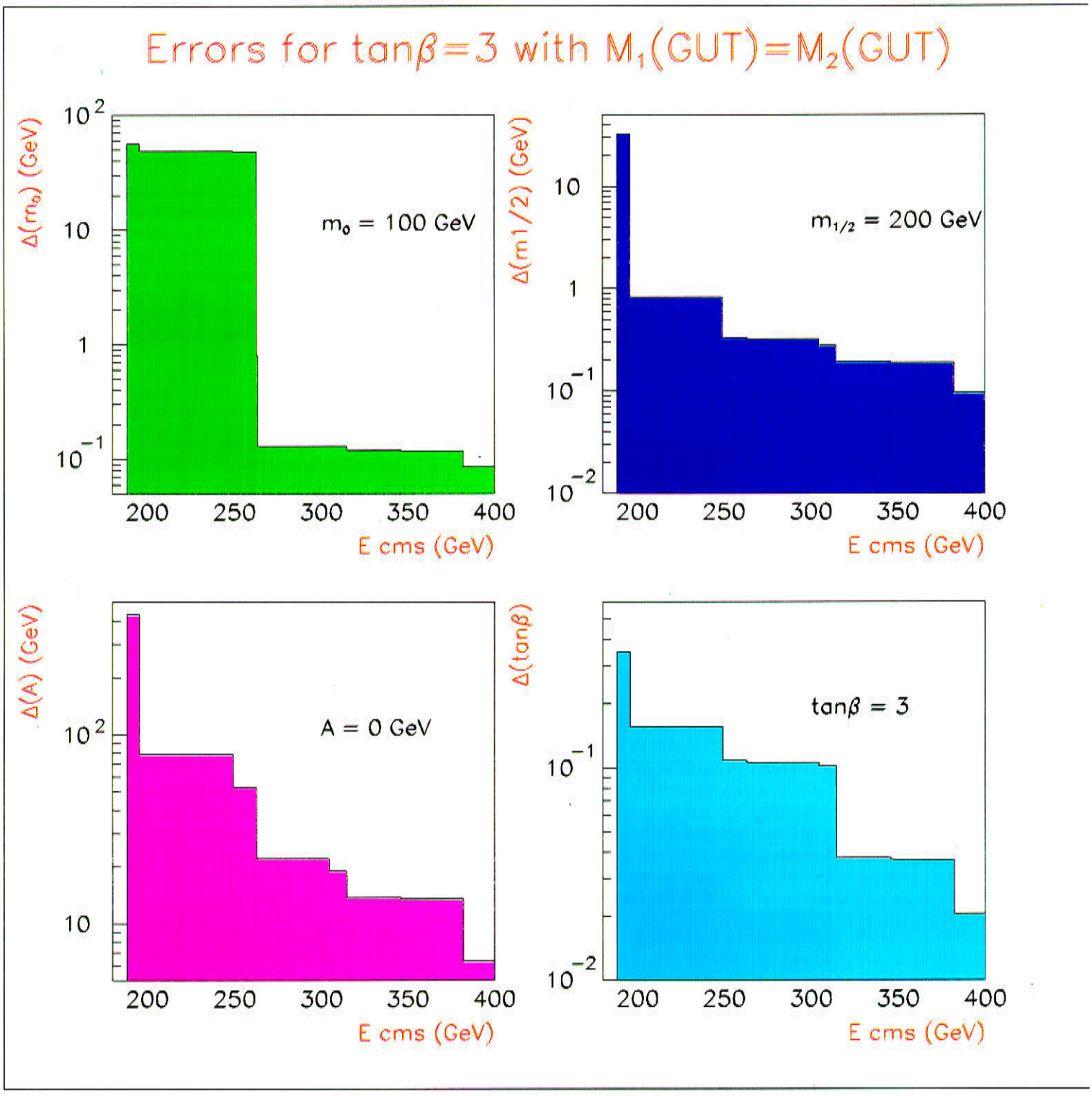
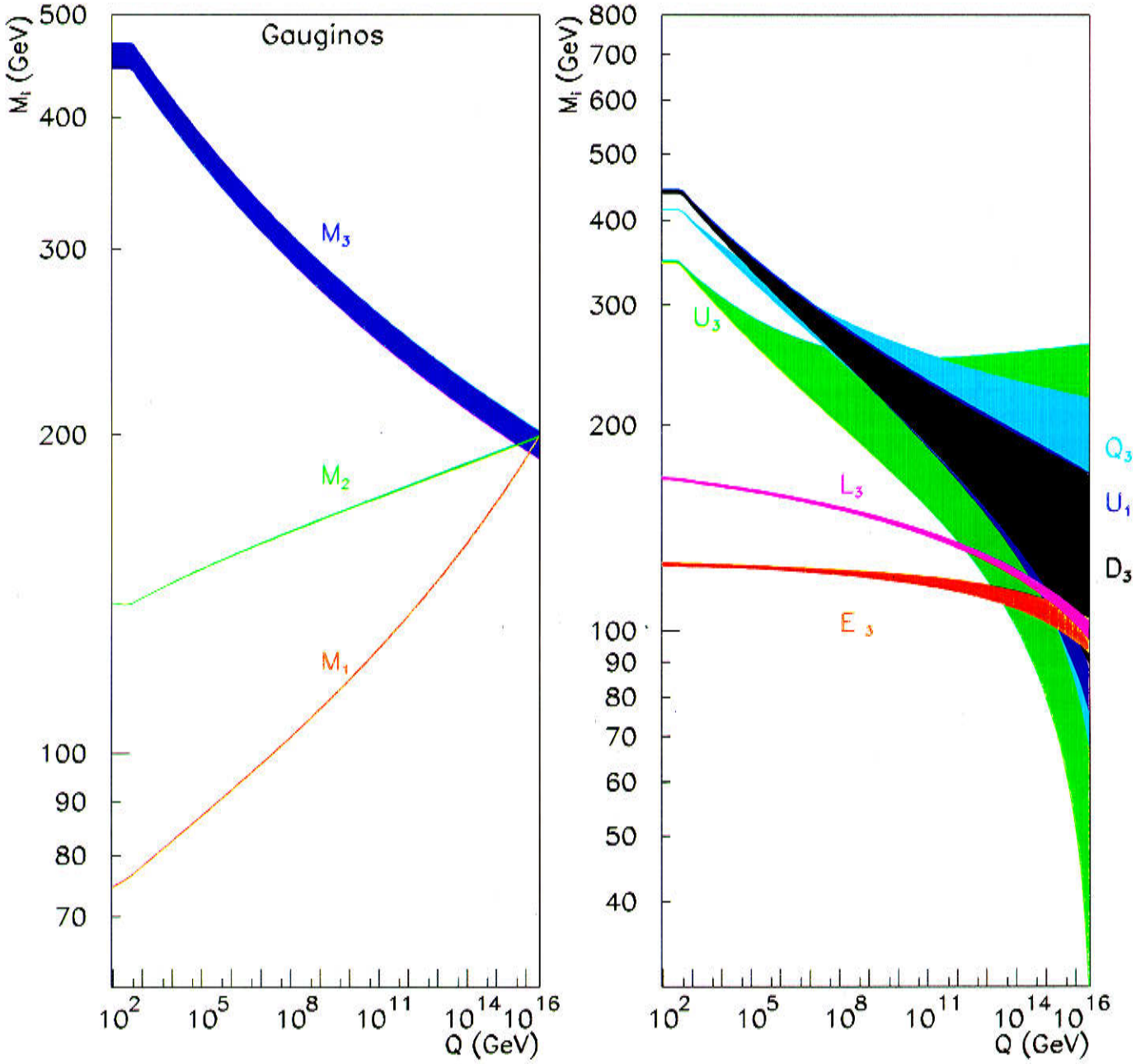


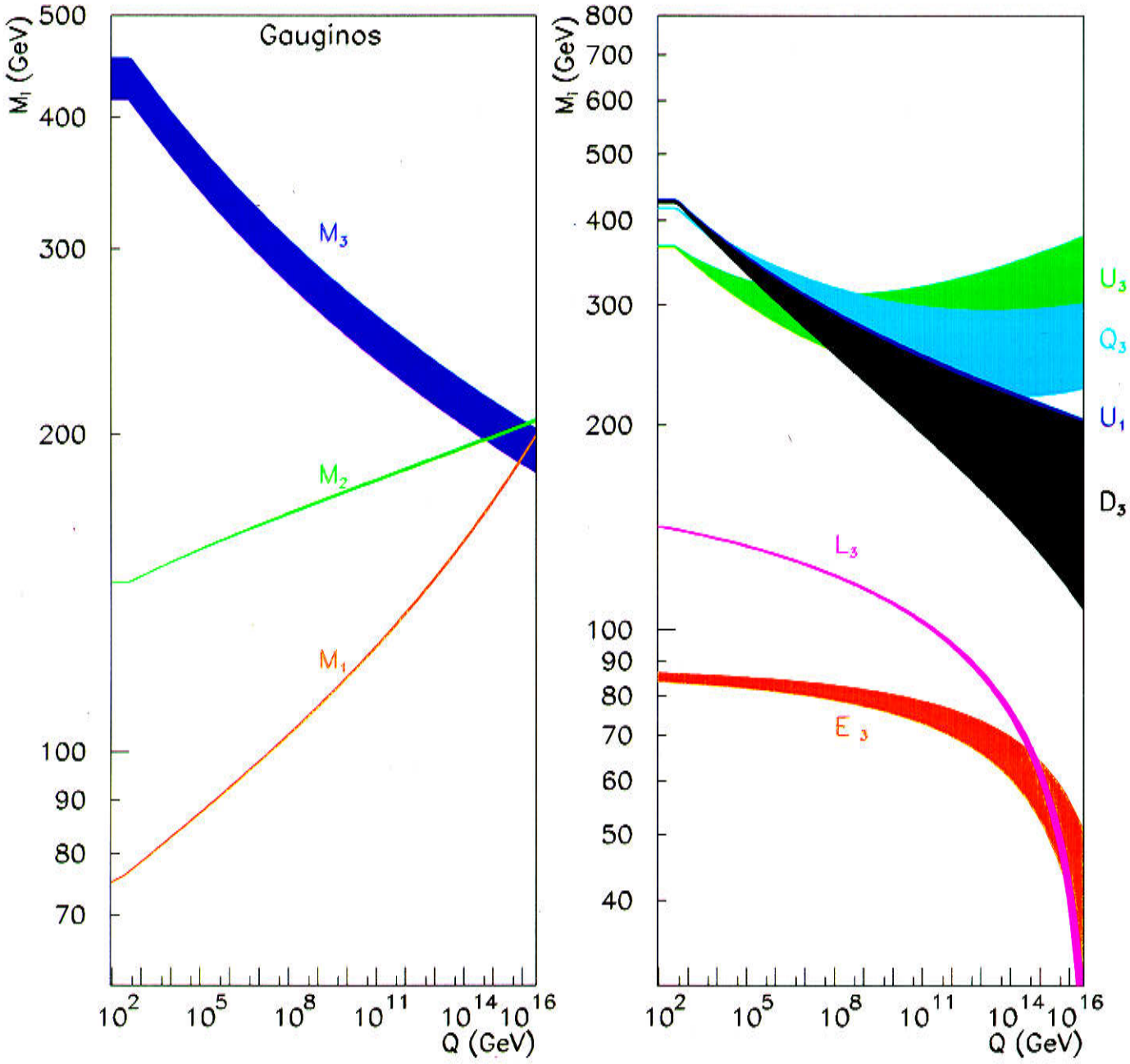
Figure 2: Possible precision on GUT scale parameters as a function of c.o.m. energy. Fits were performed to the mass precisons of H-U Martyn using separate theoretical algorthms supplied by S.Ambrosanio and W.Porod, which use 2-loop RGEs for gauge couplings, gaugino masses and 3rd generation Yukawa couplings and one loop for the other soft masses and couplings. The theoretical algorithms were interfaced to SUSYGEN and PYTHIA to obtain physical masses (and cross sections) which were then fit using MINUIT.

Blair et al

Sugra (with LC), Tanβ=3 PREL.



GMSB (with LC), Tanβ=3

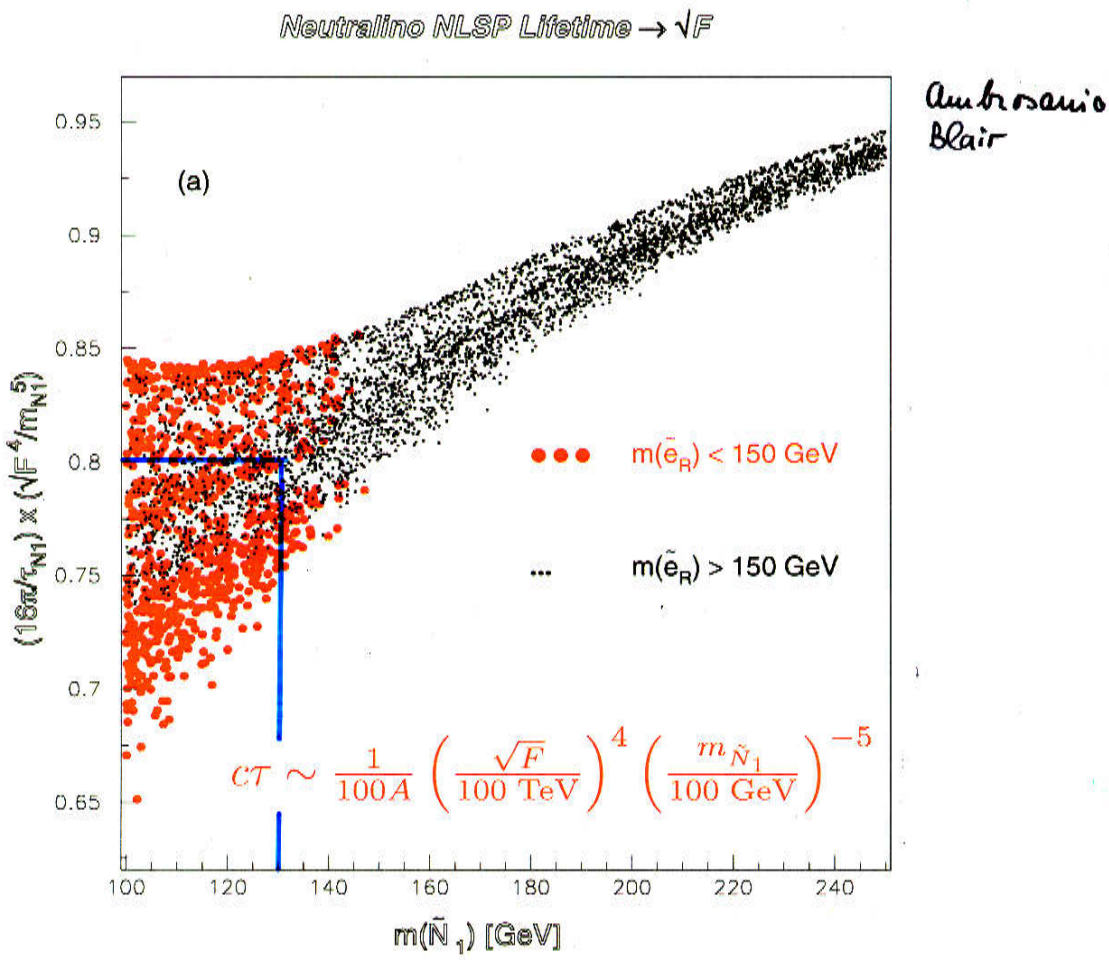


Determining the fundametal SUSY breaking scale $\sqrt{F}$

A new feature of GMSB models (not possible in SUGRA):

Measure of neutralino mass and proper lifetime only

$\Longrightarrow$ Determine narrow range for $\sqrt{F}$



Ambrosanio
Blair

$A =$

- ⋆ Before any extra information is supplied, the theoretical uncertainty on $\sqrt{F}$ is of order 10% or less for all $m_{\tilde{N}_1}$ of interest here.
- ⋆ Detailed knowledge of the $\tilde{N}_1$ composition is required for higher accuracy [from $\sigma(\tilde{N}_1\tilde{N}_1)$, $\tilde{N}_1$ BR's, distributions etc.]

A good measure of the $\tilde{N}_1$ lifetime in the whole allowed range is the key to access SUSY-breaking physics!

for $m_{\tilde{G}} \lesssim 1$ keV ~ complete coverage [$\mu m \to 10 m$..] :

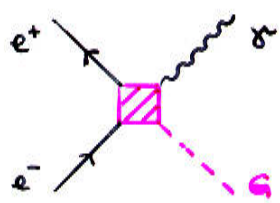
FUNDAMENTAL PARAMETERS :

		theor.	exp. error
mass scale	Λ	76.0 TeV	76.01 ± 0.08 TeV
mess. multiplicity	N_5	1	0.9994 ± 0.0009
messenger scale	M_m	160 TeV	161 ± 2 TeV
SUSY breg parameter	$\sqrt{F}$	60 to 5×10^3 TeV	± 5%
mix	tgβ	3.50	3.50 ± 0.03

Ambrosanio
Blair

3.b) EXTRA SPACE DIMENSIONS

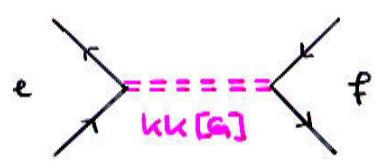
signatures : (i) missing $\not{E}$: $e^+e^- \to \gamma + G(m) = \gamma + \not{E}$



n	M / TeV
2	6.0
3	4.0
4	3.0

Giudice..
Mirabelli
..

(ii) Kaluza-Klein towers : $e^+e^- \to f\bar{f}$

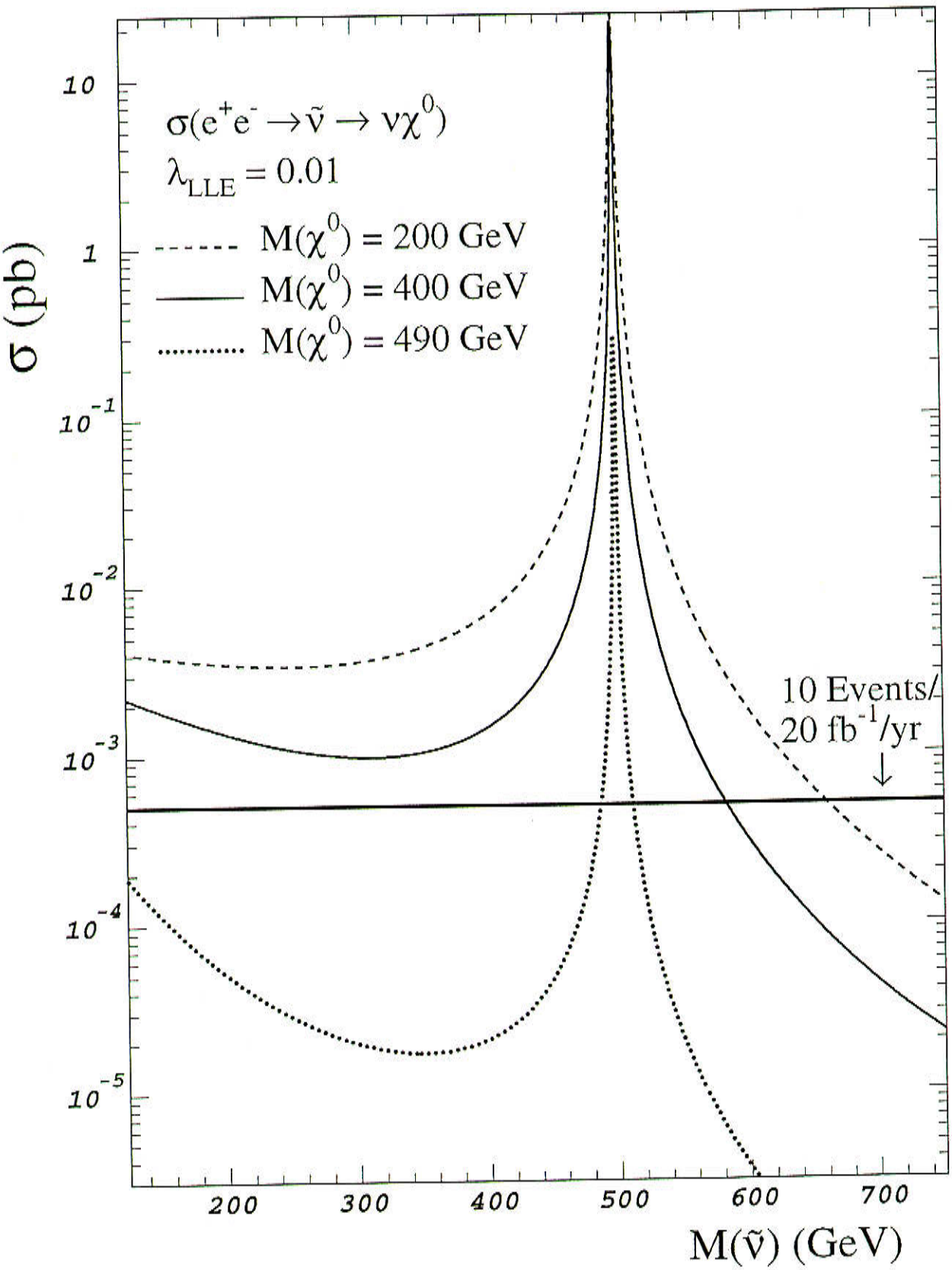


contact interactions spin = 2

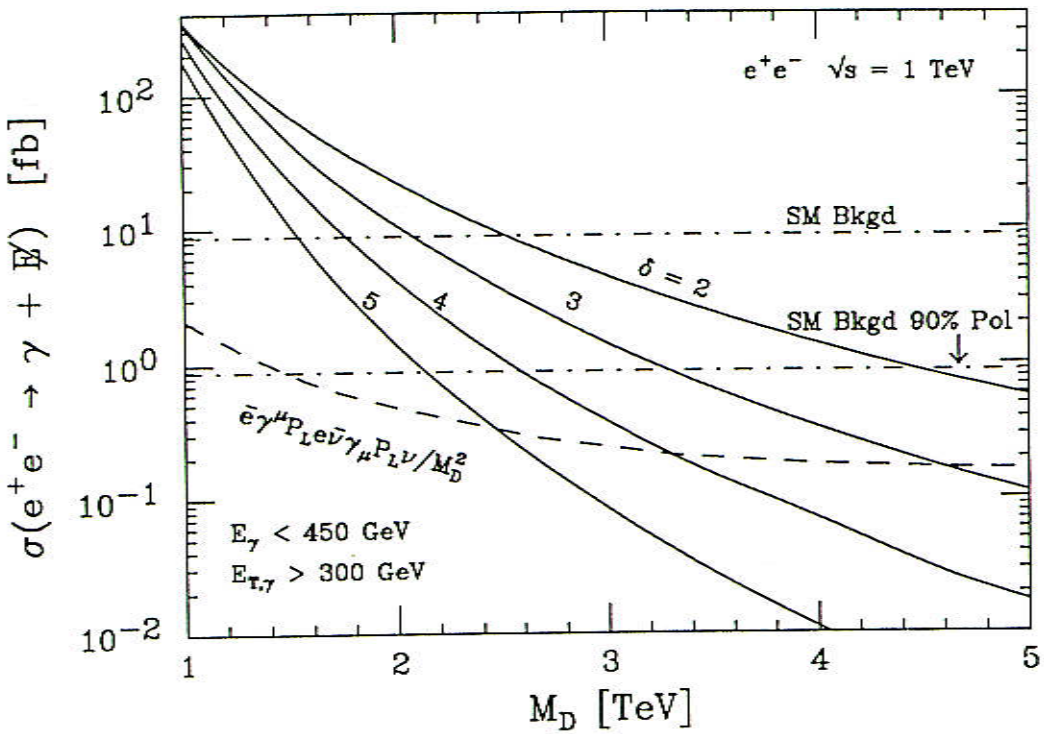
sensitivity $M_s \sim 7 \ldots 8$ TeV

improvem. : other reactions : $\gamma\gamma \to WW$ [pol : ×2] Rizzo

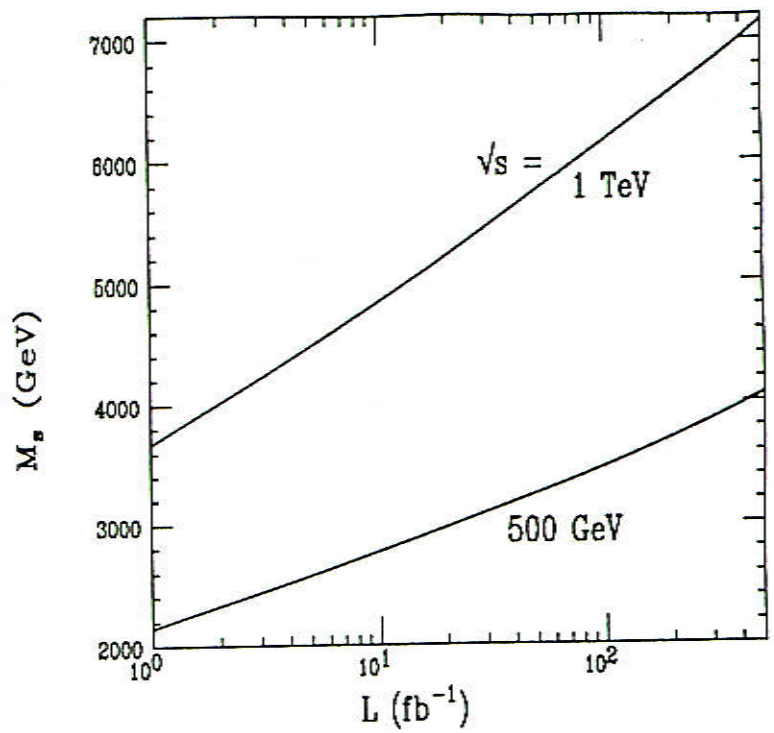
Dreiner ea


$\sigma(e^+e^- \to \tilde{\nu} \to \nu\chi^0)$
$\lambda_{LLE} = 0.01$
$M(\chi^0) = 200$ GeV
$M(\chi^0) = 400$ GeV
$M(\chi^0) = 490$ GeV
10 Events/
20 fb^{-1}/yr
σ (pb)
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
200
300
400
500
600
700
$M(\tilde{\nu})$ (GeV)

Giudice et al



Hewett



4. CONCLUSIONS

LC Phase I : very attractive physics programme up to ~ 1TeV for high-luminosity machine TESLA ..

1. ELECTROWEAK SECTOR :

- fundamental symmetry structure of force fields
- Higgs mechanism : essential elements can be reconstructed experimentally
- trq WW interactions : access to scale $\Lambda \sim 4\pi v \sim 3$ TeV

2. SUPERSYMMETRY :

- access to heavy Higgs bosons
- ensemble of SUSY particles and their interactions can be explored with high precision :
  - clarify SUSY breaking :
  - model-indep. extrapolation to theory at unif. scale

3. EXTRA SPACE DIMENSIONS ?

- access to possibly new structures of space and time

CHANNEL	WEAK CPLG STRING	STRONG CPLG STRING
tt thresh	50	50
tt contn	<500>	<500>
W properties	200	** 1,000
Higgs properties	** 500	–
SUSY particles	** ~ 1,000	–
Extra dimensions	<500>	–
WW strg interact.	–	** > 1,000
	~ 1,750 fb^{-1}	> 1,000 fb^{-1}
TESLA : ... 1 TeV	6 a	3 a
1 gigaZ	1 a	1 a

	LC / TESLA	LHC	μe for < 1 TeV
Higgs	M: 50 MeV Γ: 5 - 10 % profile → Higgs mechanism	discovery mode, ? profile [?]	M: 1 MeV Γ: few - % profile [e]
SUSY	discov. $\tilde{\ell}$ sector overall prec. meas: reconstruct SB + GUT/PL extrapol.	discovery mode, ? ⟨partly prec.⟩ meas. test SB	SUSY Higgs sector $\tilde{f}$: [e]
Z, W Z' ..	$10^{-3} \to 10^{-5}$ precision 10 TeV indirect	5 TeV direct	[e]
WW sbg	Λ up to 3 TeV	resonances but peaks?	[e]
tt	thresh. ~ 200 MeV elw ~ 1%	thr ≳ 1 GeV anom. QCD cplg	thr ≲ 200 MeV [?] elw ~ 3 % [e]