Searches for mSuGRA and related SUSY at LEP

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on behalf of the LEP collaborations

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Northeastern University
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SuGRA 20

Why search for SUSY at LEP?

a posteriori reasoning:

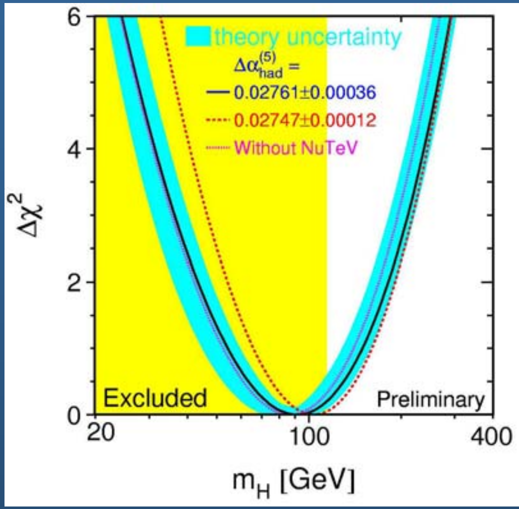
- light Higgs boson:

SUSY prediction: $m_h \leq m_Z$ at tree level

$m_h < 135$ GeV in MSSM

$\Leftrightarrow$

$m_h < 211$ GeV (95%CL) from EW fit



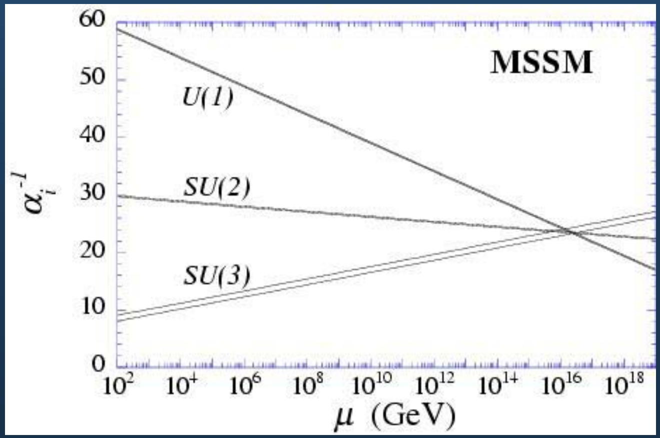
- electro-weak mixing angle:

SUSY-GUT prediction of $\sin^2\theta_W(\alpha_s)$

$\sin^2\theta_W^{SUSY-GUT} = 0.2335(17)$

$\Leftrightarrow$

$\sin^2\theta_W^{LEP/SLD} = 0.2315(02)$



could this be an accident???

How to search for the sparticles?

ℓ	$\tilde{\ell}$
q	$\tilde{q}$
γ, Z, h, H	$\chi^0_{1/2/3/4}$
$W^\pm, H^\pm$	$\chi^\pm_{1/2}$
g	$\tilde{g}$

many different sparticles
many different production mechanisms
many decay modes

} depend on many (~105) parameters (MSSM)

⇨ hopeless to perform a dedicated search for each configuration

⇨ strategy at LEP:

- identify + classify topologies
- perform searches as model-independent as possible
- then use (possibly overlapping) subsets of the searches for the interpretation within a certain model

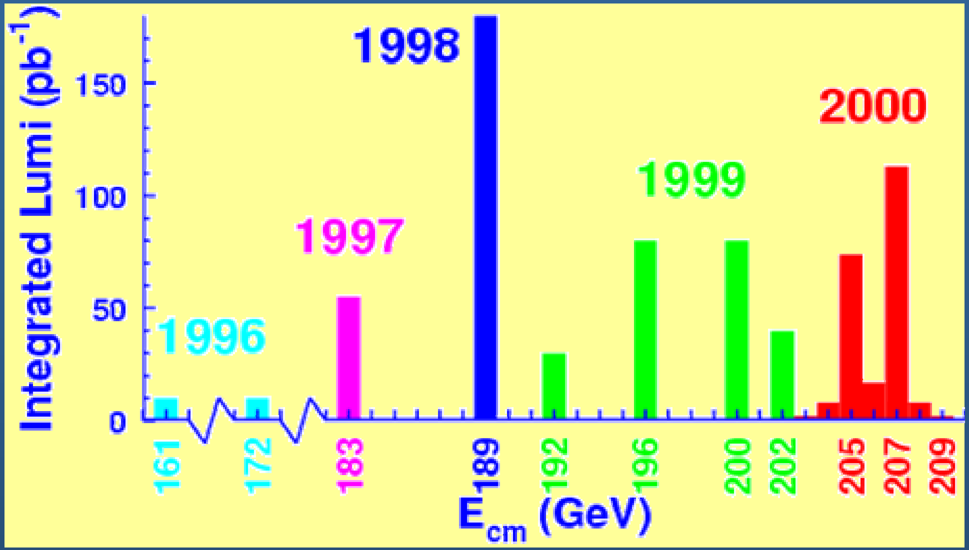
We don’t search for “mSuGRA”, etc. !

"Classic" SUSY Search Strategy

- LSP pair production not (really) visible:
  ⇨ search for the NLSP, which may be a:
  - charged slepton
  - sneutrino
    (invisible, might be disturbing in decay patterns)
  - squark
    (typically too heavy ↳ hadron collider, unless strongly mixed,
    ⇨ stop, sbottom)
  - chargino
  - heavier neutralinos
  - gluino (only higher order process in e+e-, ↳ hadron collider)

The LEP2 data sample

LEP combined sample:
~ 2.6 fb^{-1}



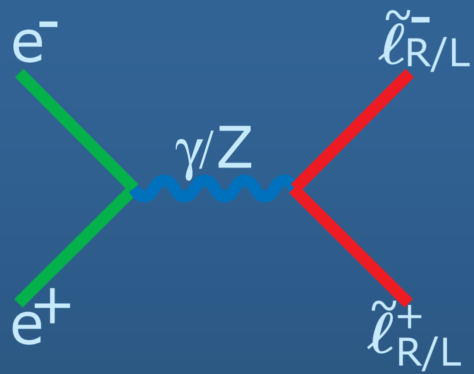
All four experiments ADLO have performed the basic searches for sleptons, squarks, charginos and neutralinos

LEP SUSY Working Group: combination of the results

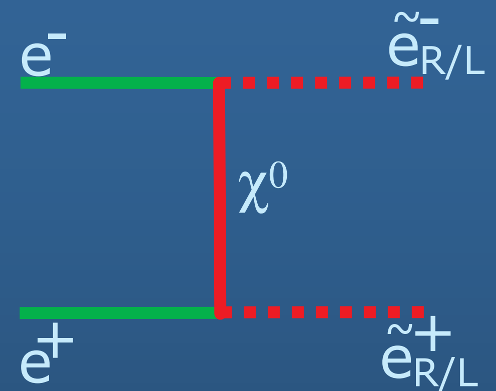
http://lepsusy.web.cern.ch/lepsusy/

Especially important for the highest energies:
ECM>207.5 GeV (ADLO=35.2 pb-1)

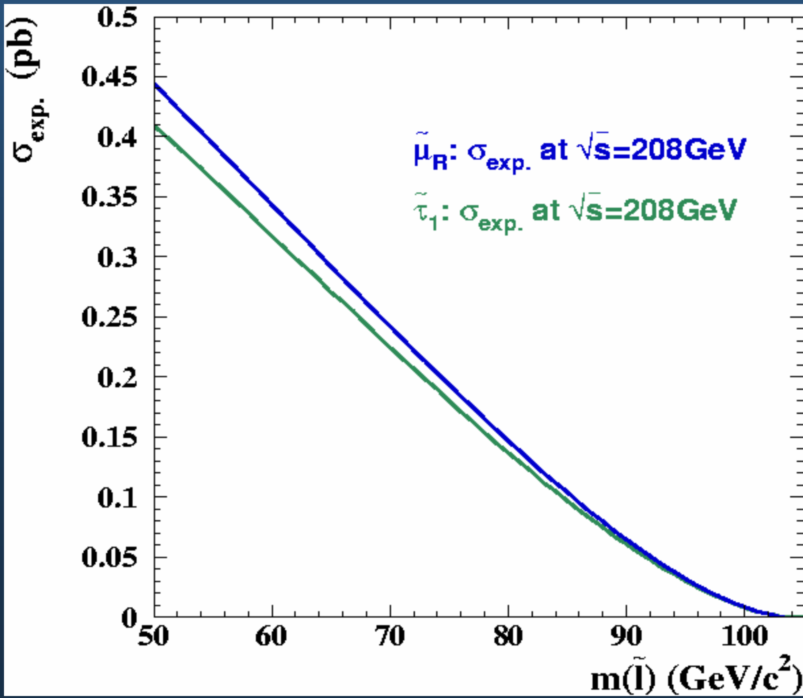
Search for Charged Sleptons



$\tilde{\ell} = \tilde{e}\ , \tilde{\mu}\ , \tilde{\tau}$



- Smuons: almost model-independent cross section
- Staus: mixing (⇨ lighter stau can decouple from Z, reduced cross section)
- Selectrons: t-channel with neutralino exchange (⇨ model dependent, usually constructive interference)



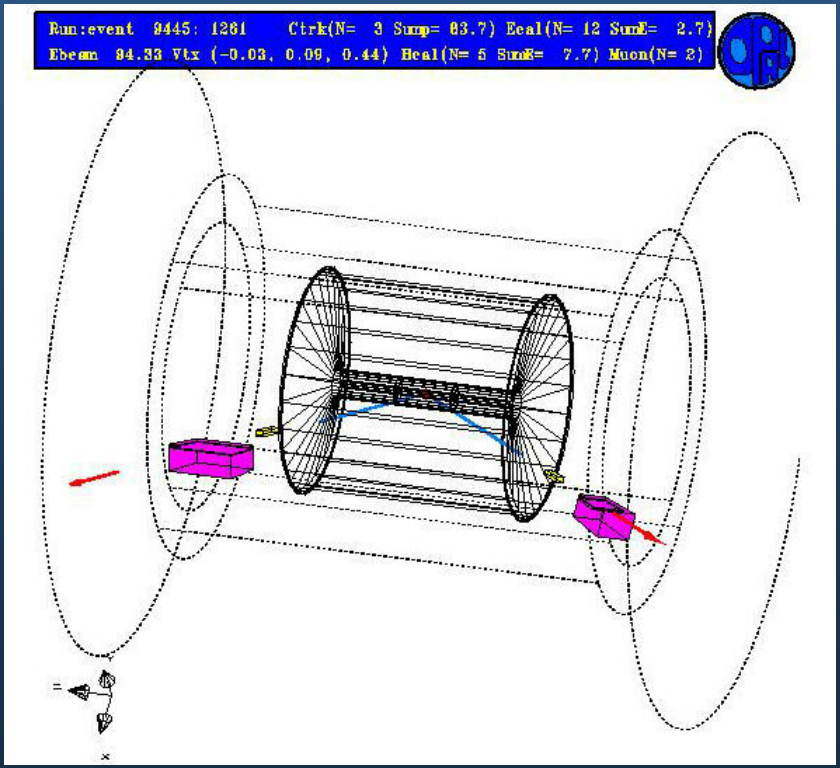
Search for Charged Sleptons

Signature: acoplanar lepton pairs

Main Background: $e^+e^- \rightarrow W^+W^- \rightarrow \ell^+\nu\ell^-\bar{\nu}$

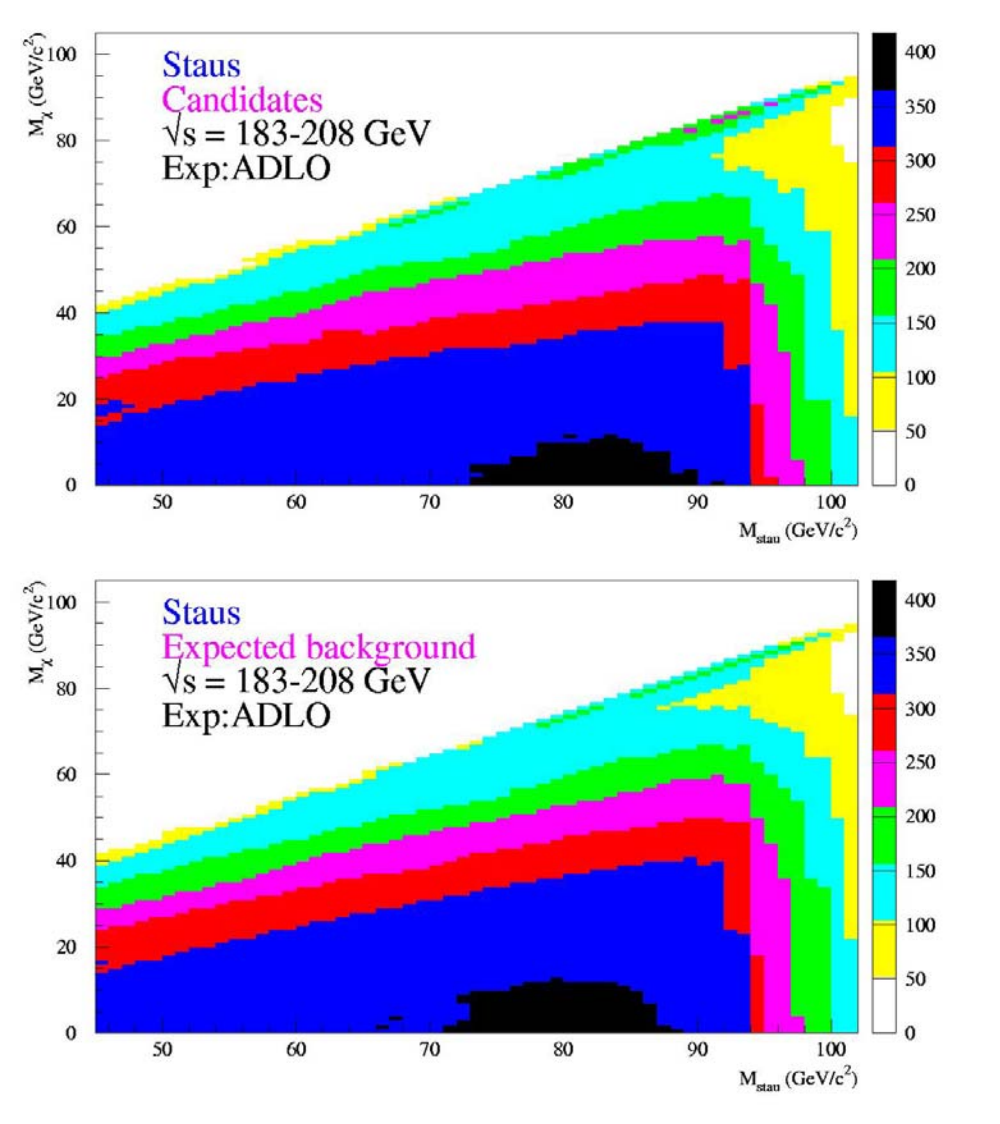
No mass reconstruction possible ⇨ use multi-variate technique to exploit kinematical differences between signal and background (depends on assumed slepton mass)

A typical smuon candidate (and background) event:



Search for Charged Sleptons

Numbers of observed events and expected background events:



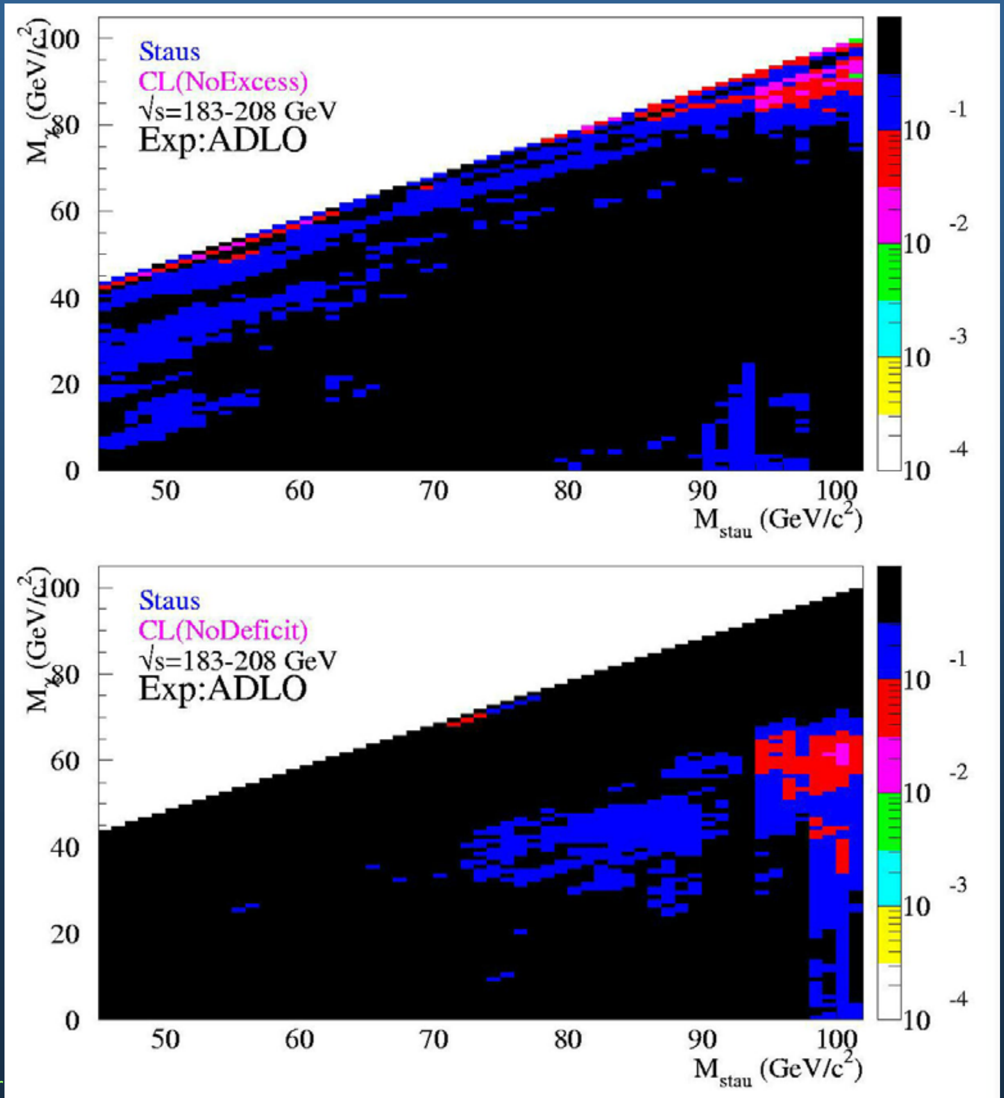
Search for Charged Sleptons

any significant excess or deficit ?
Calculate confidence level for excess/deficit using likelihood ratio method

Note:

Selected events are correlated over wide areas in the plane

For a "true" signal, would expect significant excess over a wide area



No significant excess
⇨ cross section upper limits

Search for Charged Sleptons

Cross section limits:

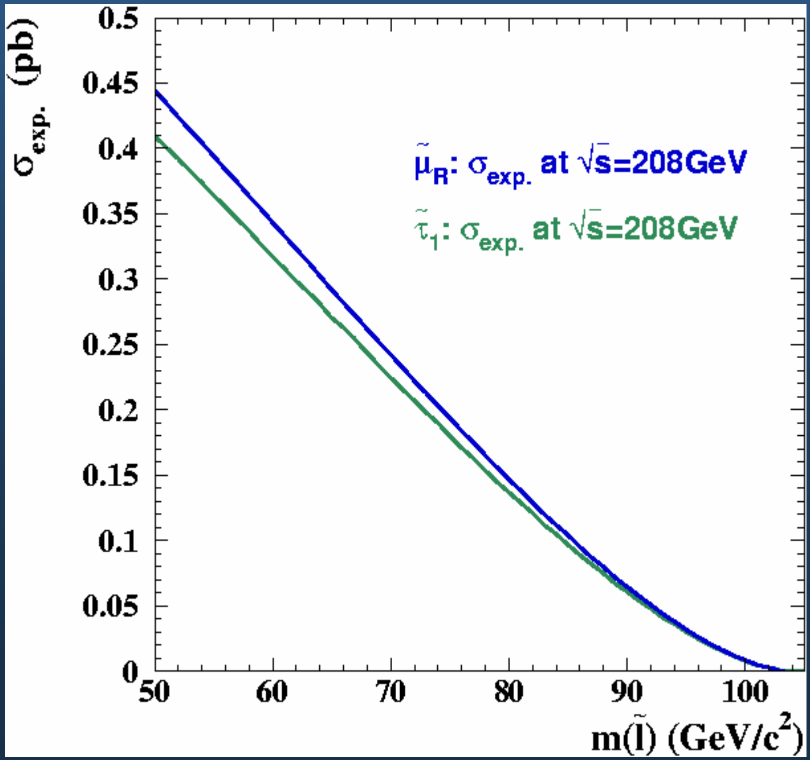
Selectrons: ~10 – 80 fb

Smuons: ~10 – 50 fb

Staus: ~40 – 150 fb

Except for the region with small (few GeV) mass difference

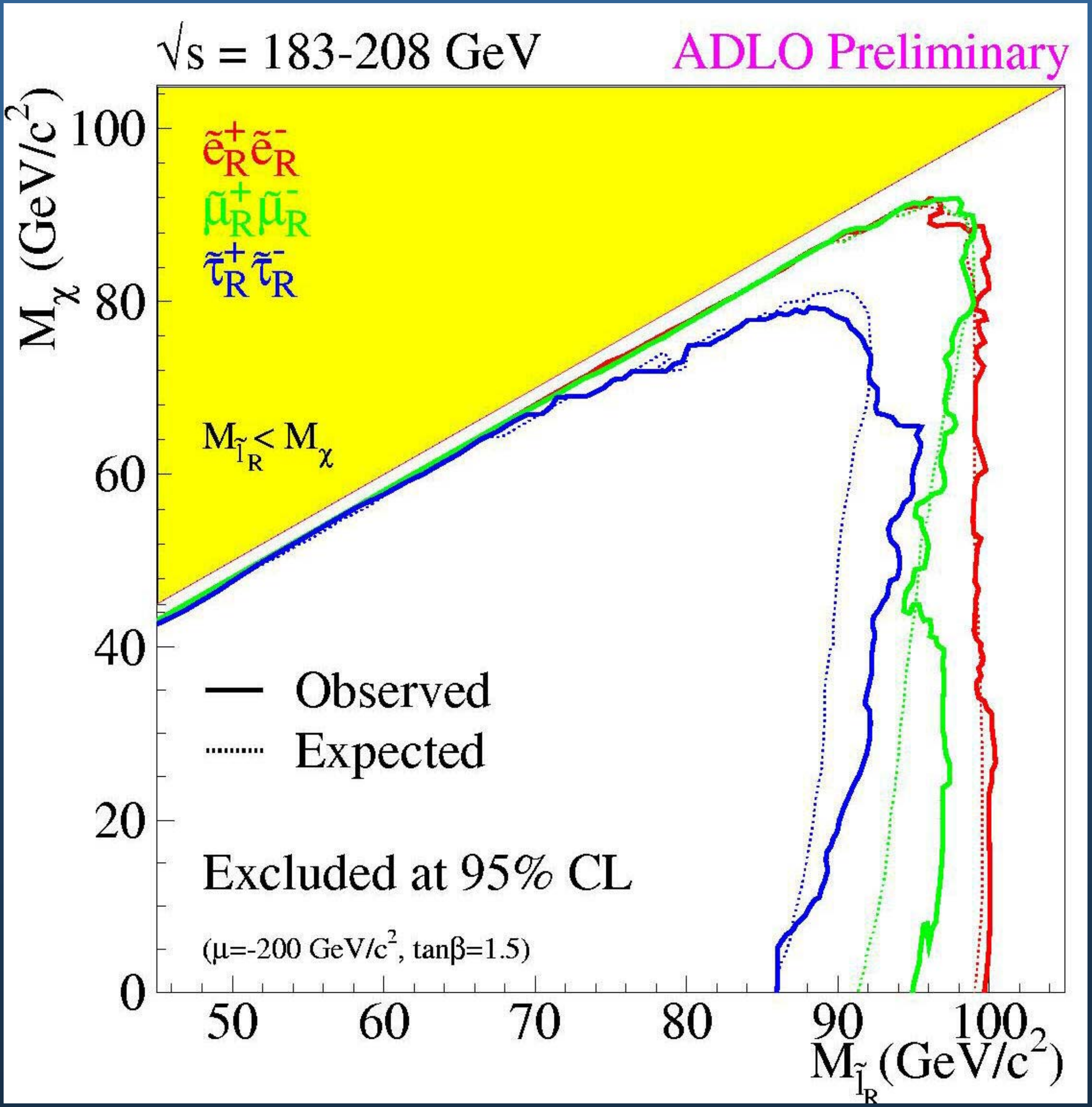
$$\Delta M = m_{\tilde{\ell}} - m_{\chi_1^0}$$



Compare this again to the MSSM predicted cross sections

⇨ mass exclusion almost up to kinematic limit possible

Charged Sleptons: Mass Limits



Charged Sleptons: Mass Limits

Examples of Mass Lower Limits (@ *95% Confidence Level*):

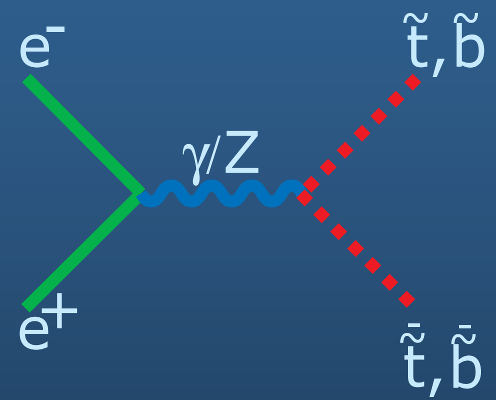
Channel	Comment	Neutralino Mass	Observed Slepton Mass Lower Limit	Expected Slepton Mass Lower Limit
Selectron	RR coupling	0 GeV 40 GeV	99.6 GeV 99.4 GeV	99.2 GeV 99.4 GeV
Smuon	RR coupling	0 GeV 40 GeV	94.9 GeV 96.5 GeV	91.4 GeV 94.7 GeV
Stau	Z decoupled	0 GeV 40 GeV	85.0 GeV 91.7 GeV	84.7 GeV 88.8 GeV
	RR coupling	0 GeV 40 GeV	85.9 GeV 92.5 GeV	85.8 GeV 89.6 GeV

Only very weakly model-dependent

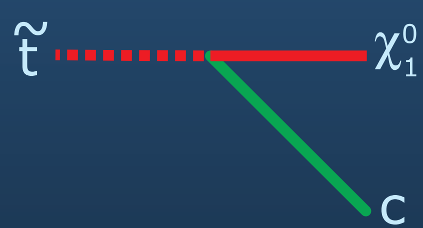
Search for Sbottom/Stop

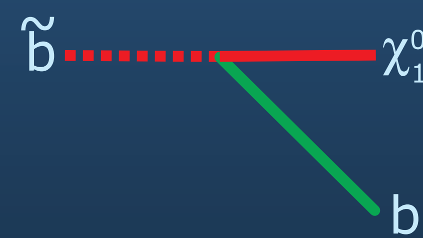
In most (GUT-related) models, squarks are heavier than sleptons and charginos, unless there is strong mixing between L and R states.
Off-diagonal elements of mixing matrix are ~ m(q) ⇨ 3rd family
LEP experiments concentrate on search for stop and sbottom

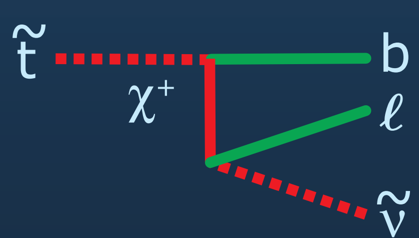
Production:



Decay:





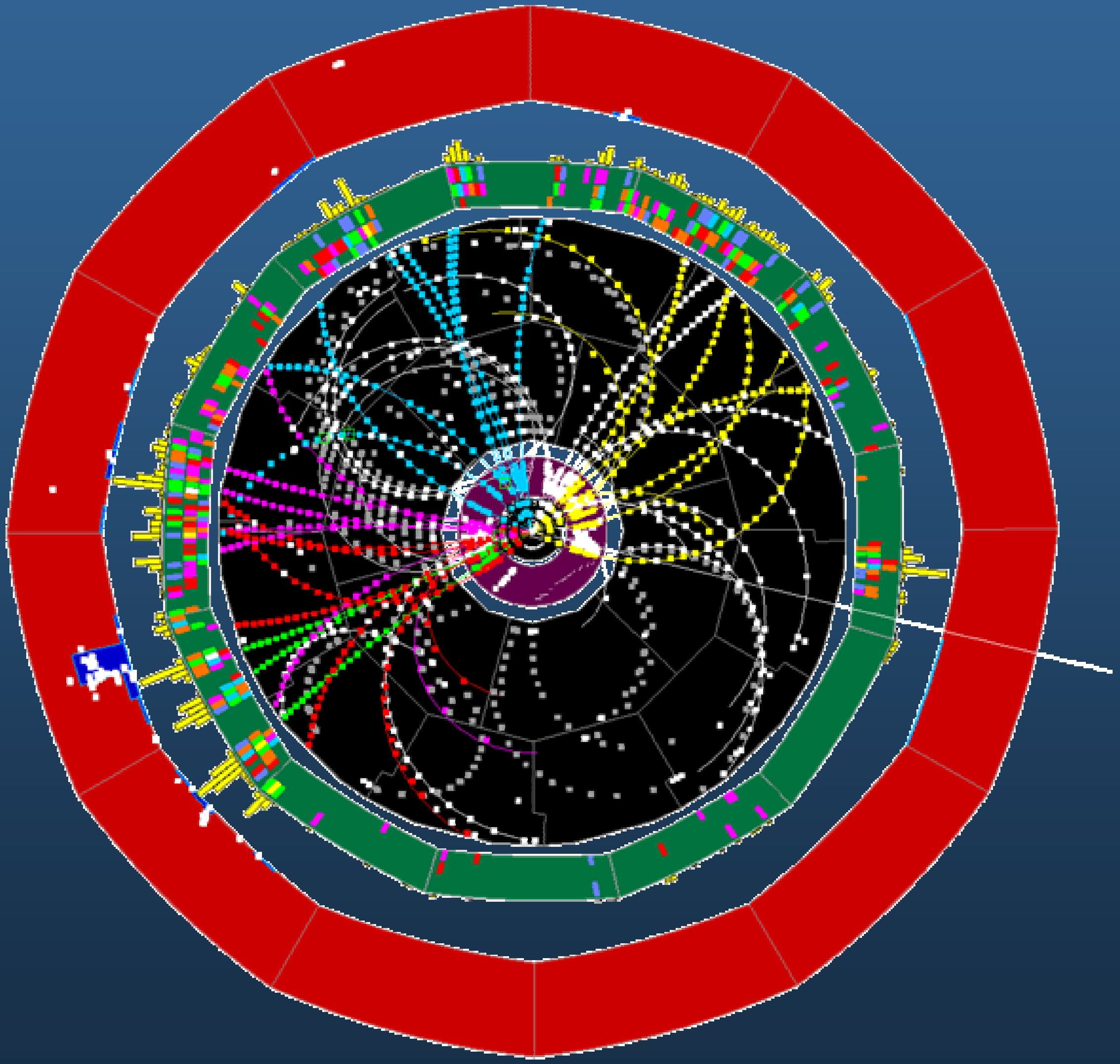


some experiments also look for 4-body decay:

$$e^+e^- \to \tilde{t}\bar{\tilde{t}} \to b\chi f_1 f_2 \; \bar{b}\chi f_3 f_4$$

Search for Sbottom/Stop

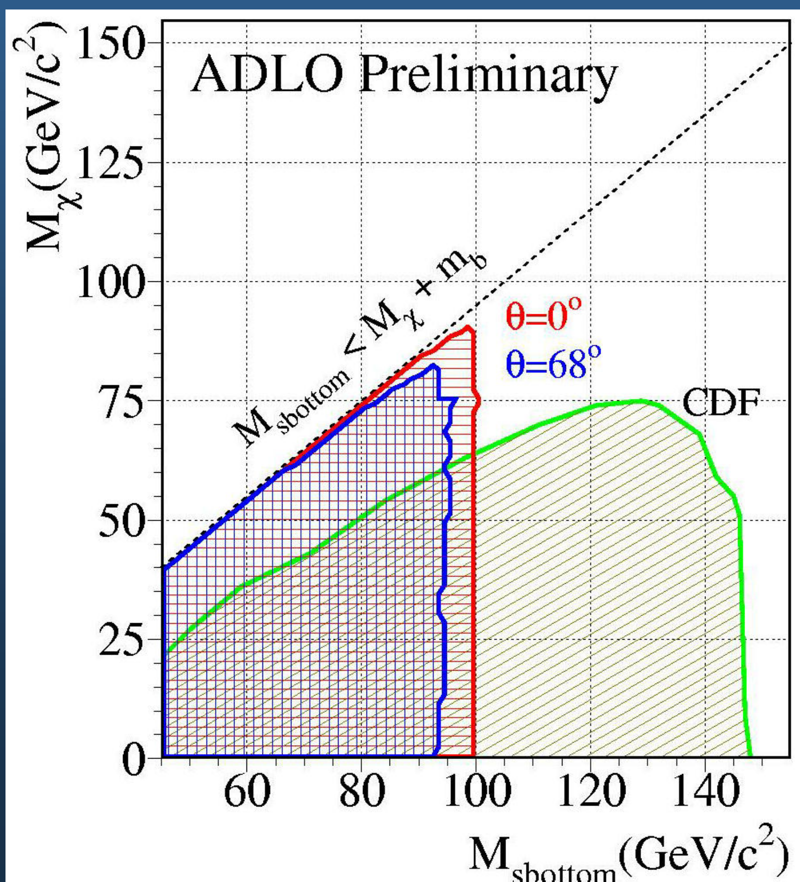
ALEPH example of a multi-jet + missing energy event:



Search for Sbottom/Stop

To make it short: no excess found in any of the 4 experiments
Exclusion (partially complementary to Tevatron):

Example: $\tilde{b} \to b\chi_1^0$



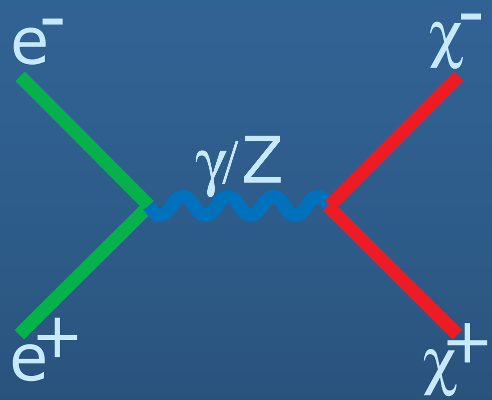
Mass limits (ADLO)

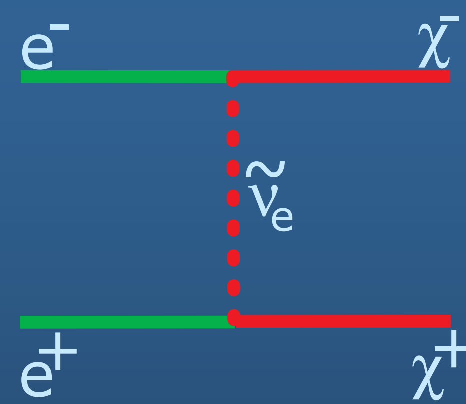
Channel	M(squark) - M(LSP)	Observed mass limit no mixing	Observed mass limit max mixing
stop -> c chi	20 GeV 40 GeV 60 GeV	100 GeV 98 GeV 98 GeV	98 GeV 95 GeV 95 GeV
sbottom -> b chi	20 GeV 40 GeV 60 GeV	99 GeV 99 GeV 99 GeV	95 GeV 95 GeV 94 GeV
stop -> b l snu	20 GeV 40 GeV	99 GeV 99 GeV	96 GeV 97 GeV

ALEPH: search for stable stop-hadrons: absolute limit on m(stop) > 63 GeV independent of ΔM

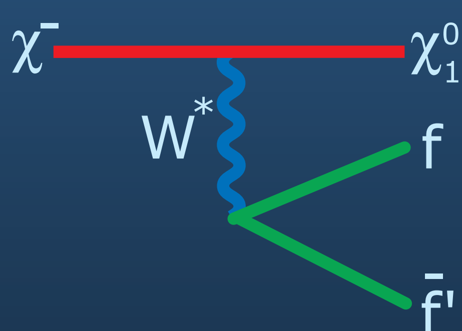
Search for Charginos

Production:

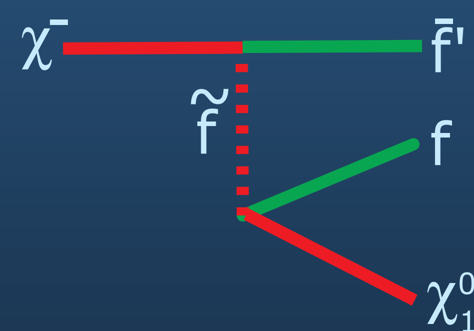




Decay:

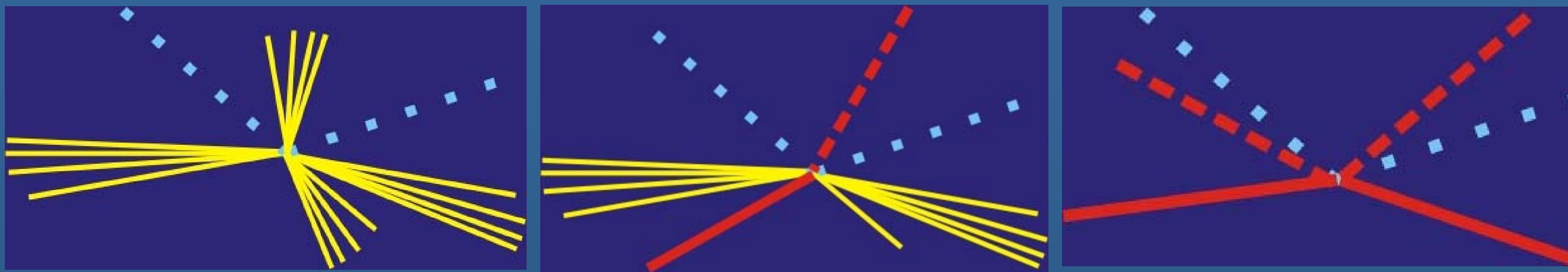


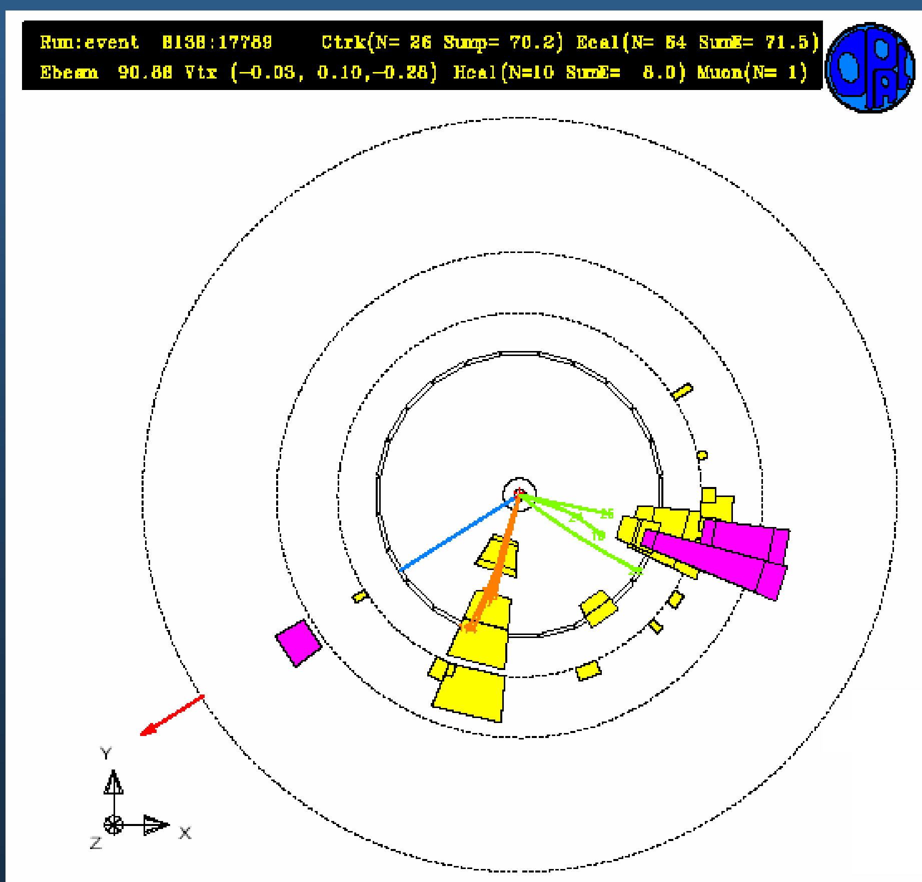
3-body decay dominant for heavy $\tilde{f}$



2-body decay dominant if any $\tilde{f}$ lighter than χ^-

Search for Charginos

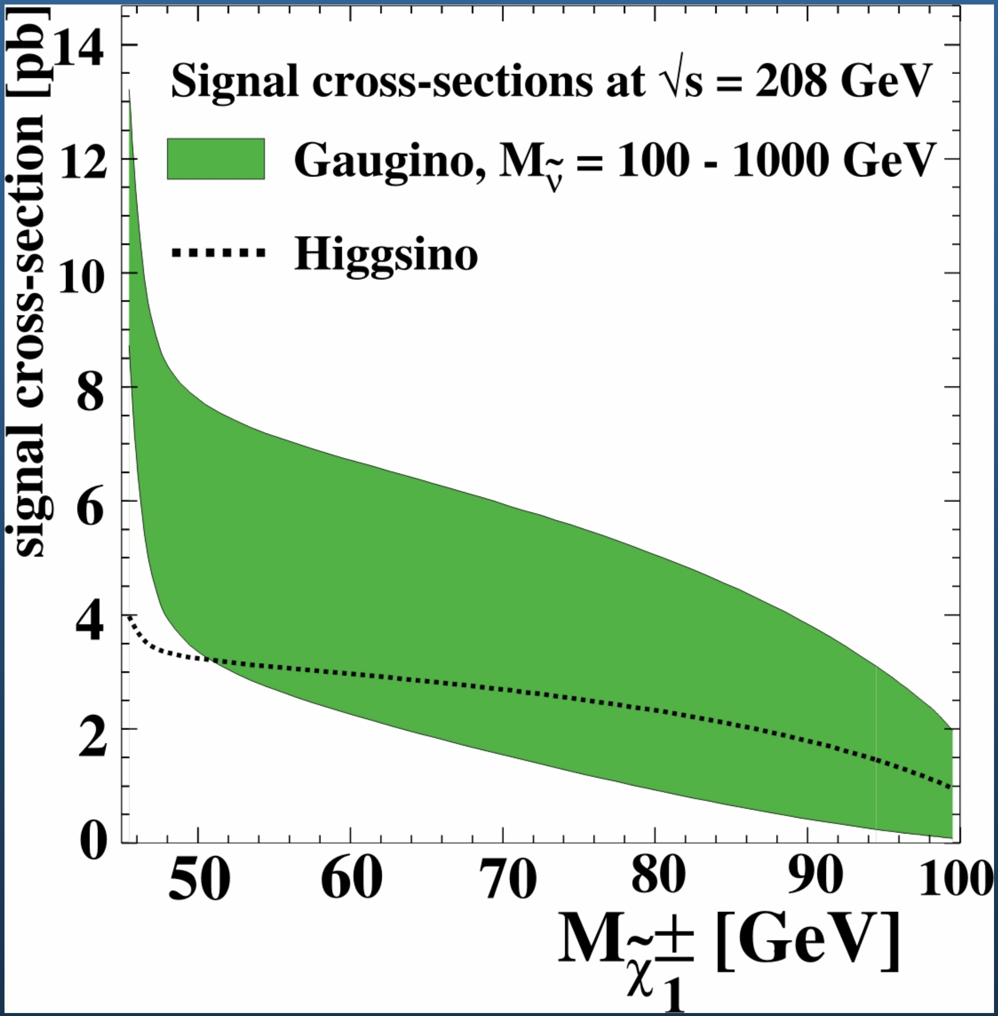




Typical candidate in the $qq\ell + \not{E}$ channel

(but also compatible with WW)

Search for Charginos



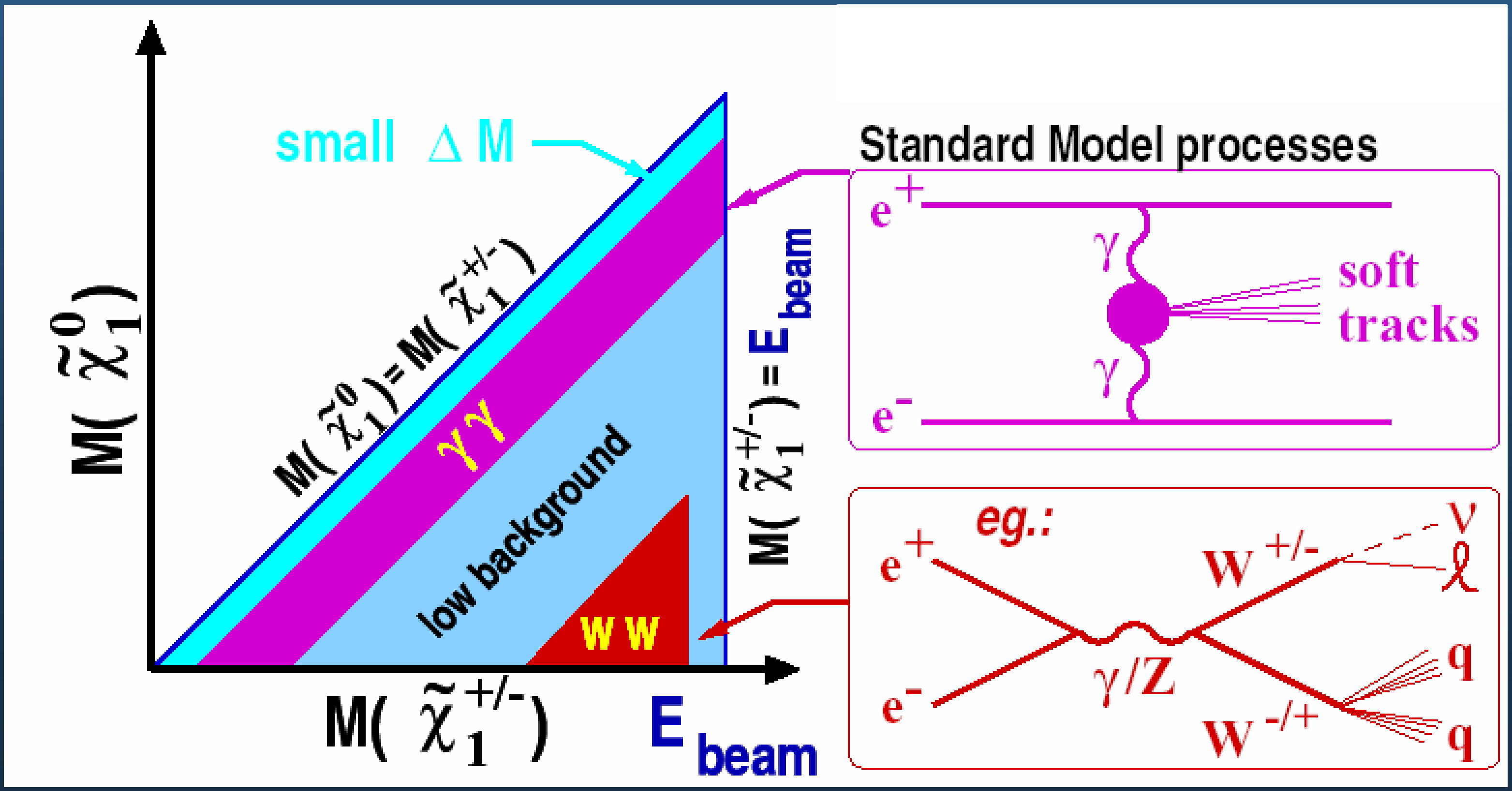
- large cross sections up to kinematical limit
- universal cross section in Higgsino region
- model-dependency due to destructive interference with t-channel sneutrino exchange

Search for Charginos

Signal topolgy and SM backgrounds depend strongly on the mass difference $\Delta M = M(\chi^{\pm}) - M(\chi^{0})$

Large ΔM: only moderate missing energy
Small ΔM: little visible energy
Very Small ΔM: lifetime effects

"Deep Higgsino region μ<<M2"



Search for Charginos

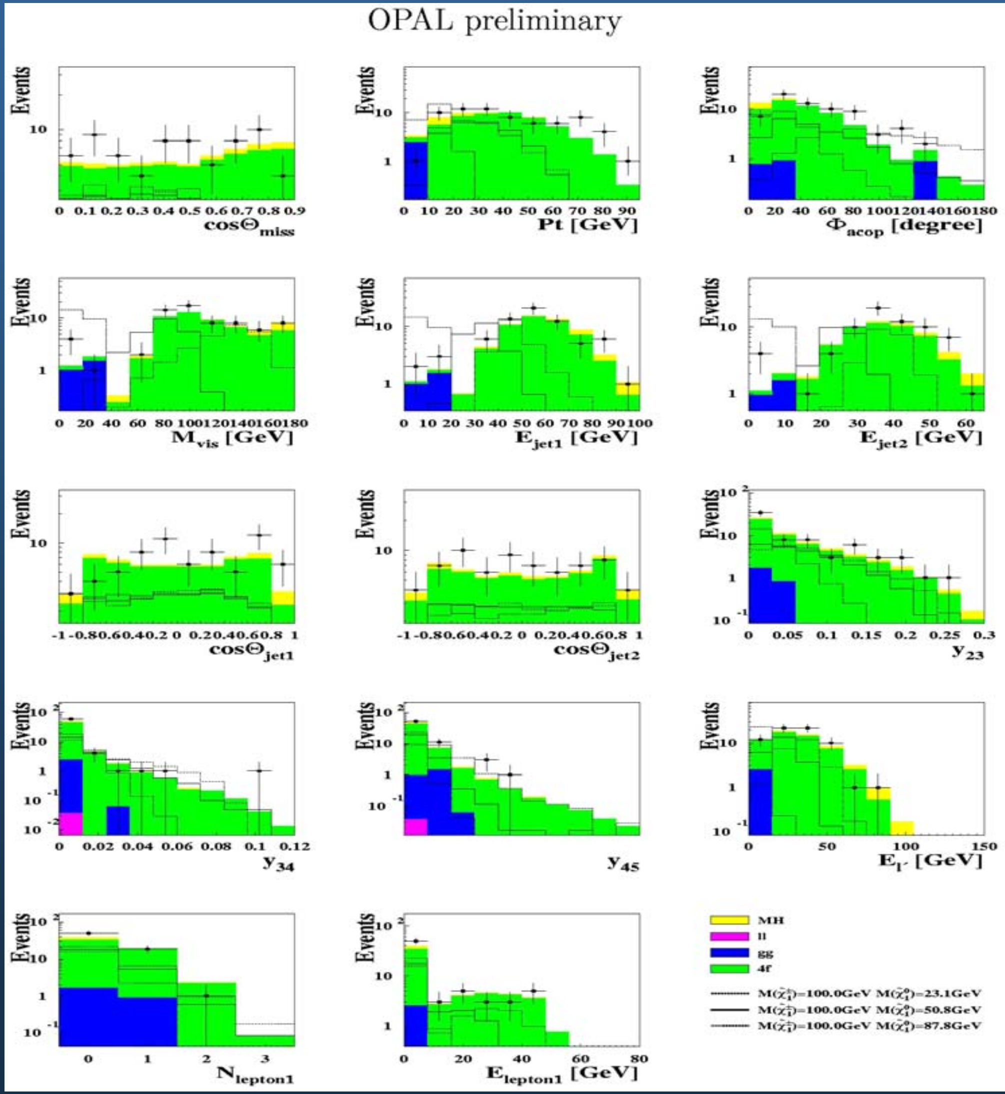
- Search for a wide grid in $M(\chi)$ and ΔM and at many different $\sqrt{s}$ is technically non-trivial

- Need (in principle) many millions of MC events

- Development of sophisticated interpolation techniques

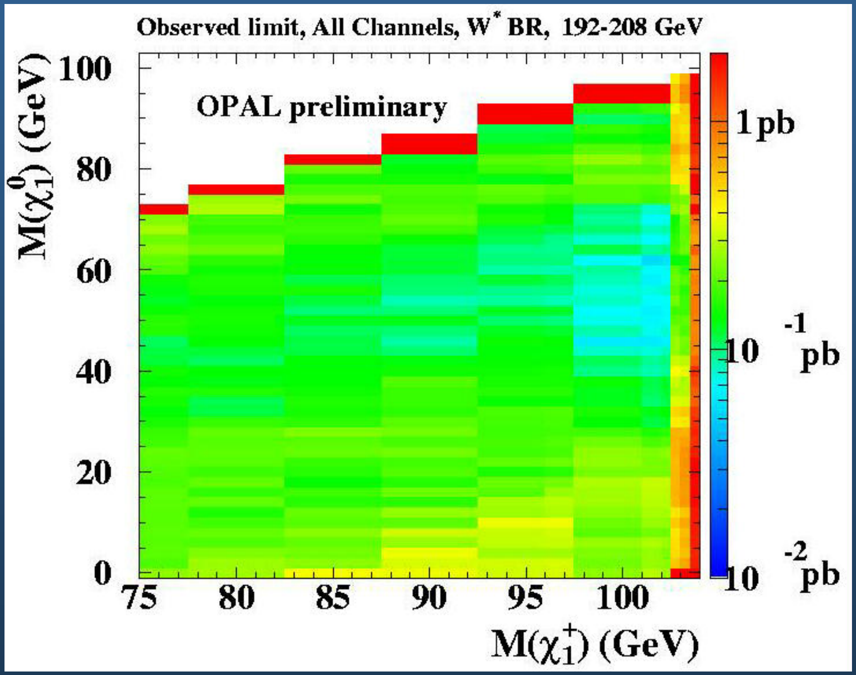
- Increased sensitivity through modern selection techniques (likelihoods)

Example: input variables to hadronic chargino search in OPAL at $\sqrt{s}$ = 206 GeV

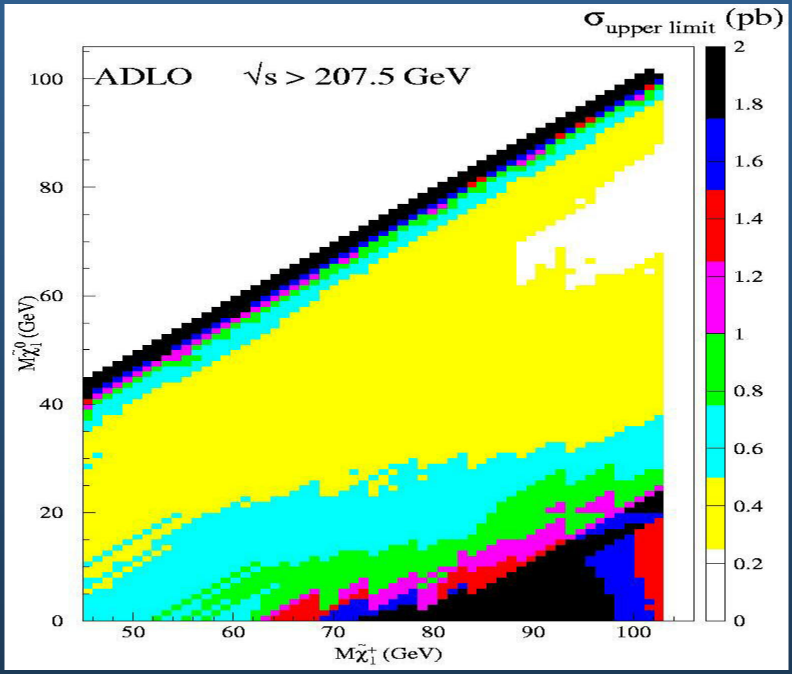


Charginos: cross section limits

Single experiments:



ADLO combination for highest energies:



$\sigma < 100$ fb

for large part of mass plane

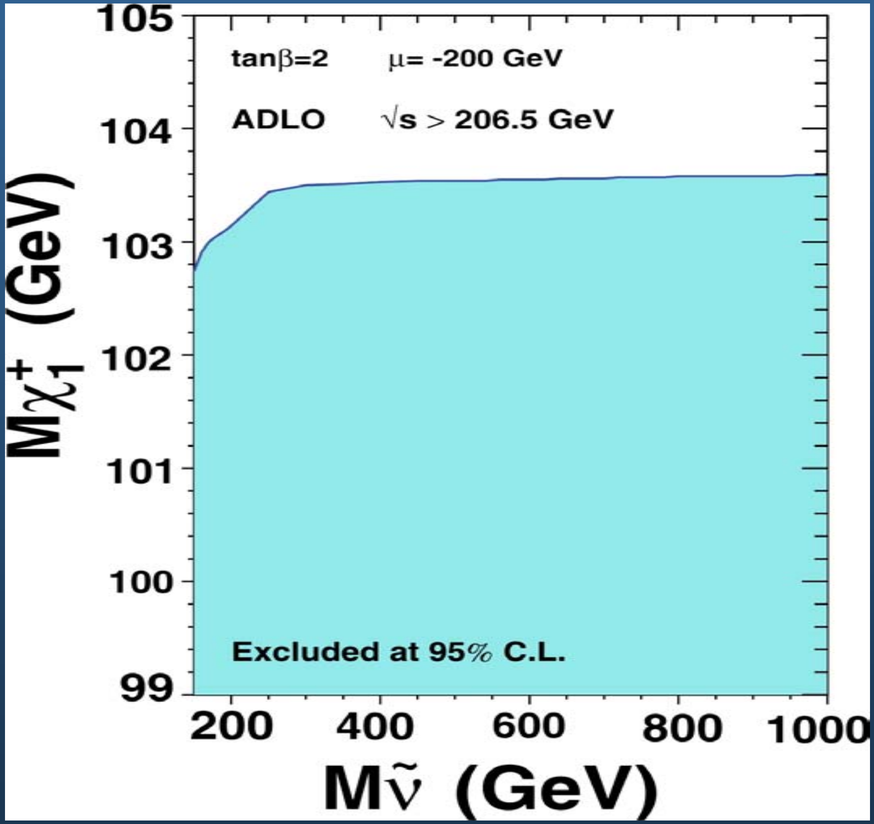
$\sigma < 1$ pb

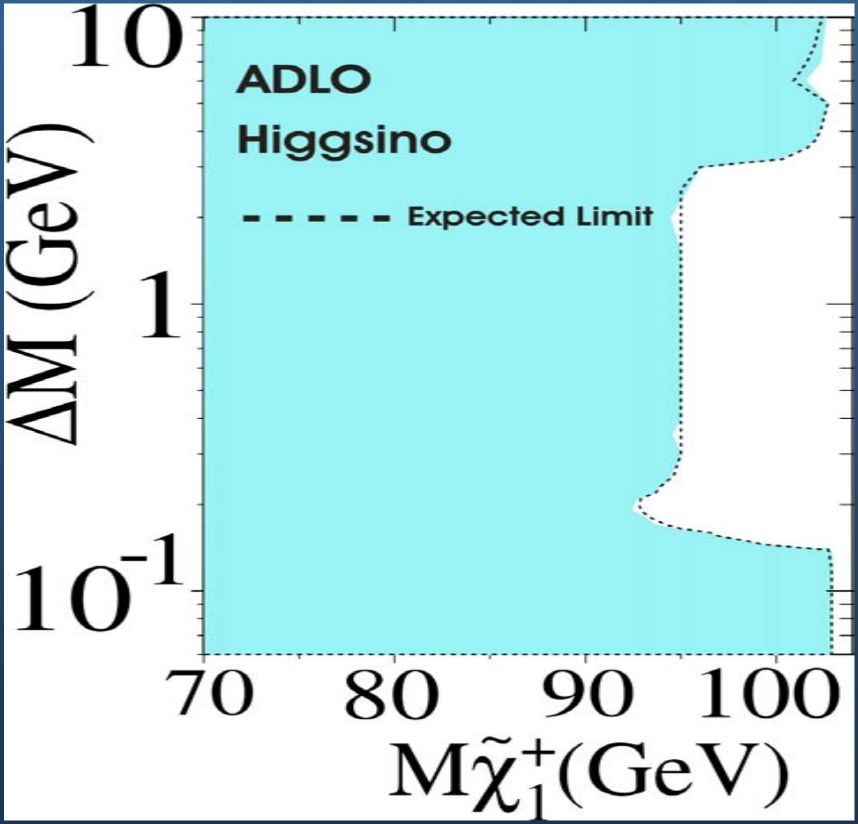
even close to kinematical limit (104 GeV)

Chargino Mass Limit

Mass limit for pure $\chi^{\pm} \rightarrow W^{*}\chi_1^0$ decays

Only somewhat weakened for low ΔM (see talk by A.Perrotta)





M > 103 GeV

M > 92.4 GeV

Interpretation of the Results in Specific Models

None of the LEP2 searches for sparticles showed any significant excess
⇨ exclusion limits in the parameter space of constrained SUSY models

“Classic” SUSY searches are interpreted within:

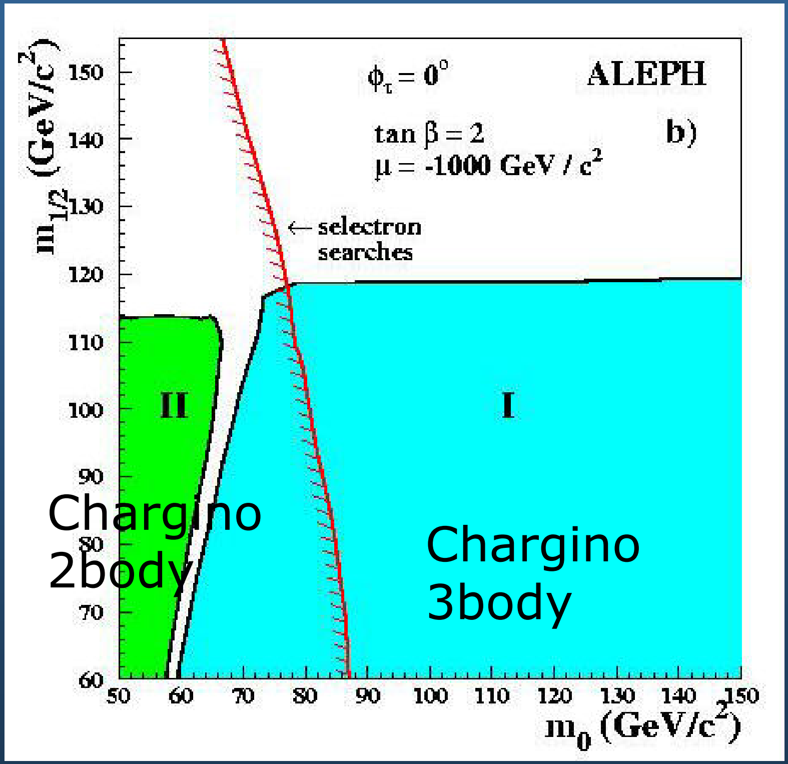
CMSSM
“LEP” Constrained MSSM
(6 parameters)

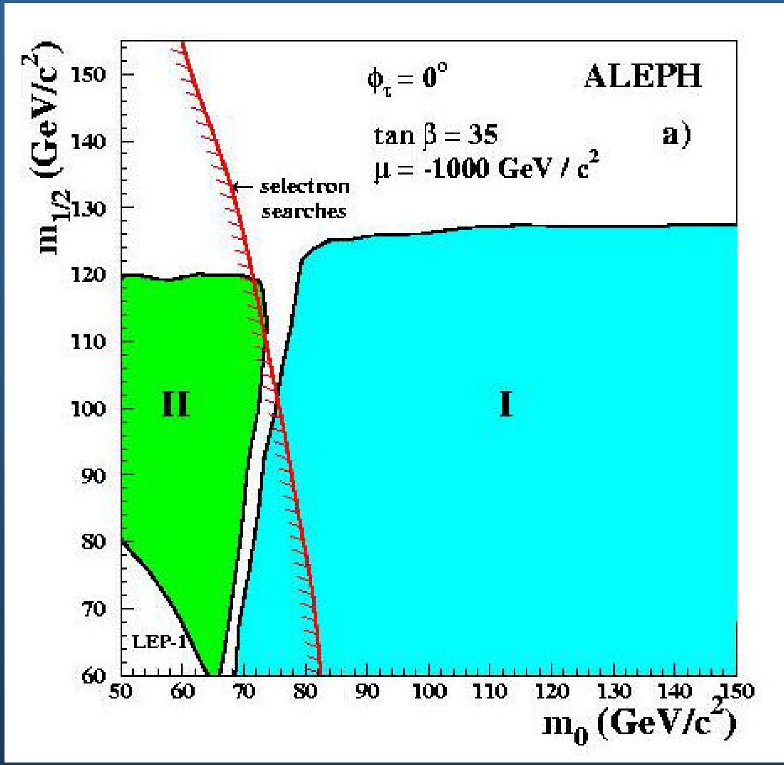
$m_{1/2}$	Gaugino mass at GUT scale
m_0	Scalar mass at GUT scale
$\tan\beta$	Ratio of Higgs field v.e.v.'s
A_0	Common trilinear coupling
sign(μ)	
μ	Higgsino mixing parameter
M_A	CP odd Higgs mass

mSugra (4.5 parameters): $m_{1/2}$, m_0, $\tan\beta$, A_0, sign(μ)

CMSSM exclusion

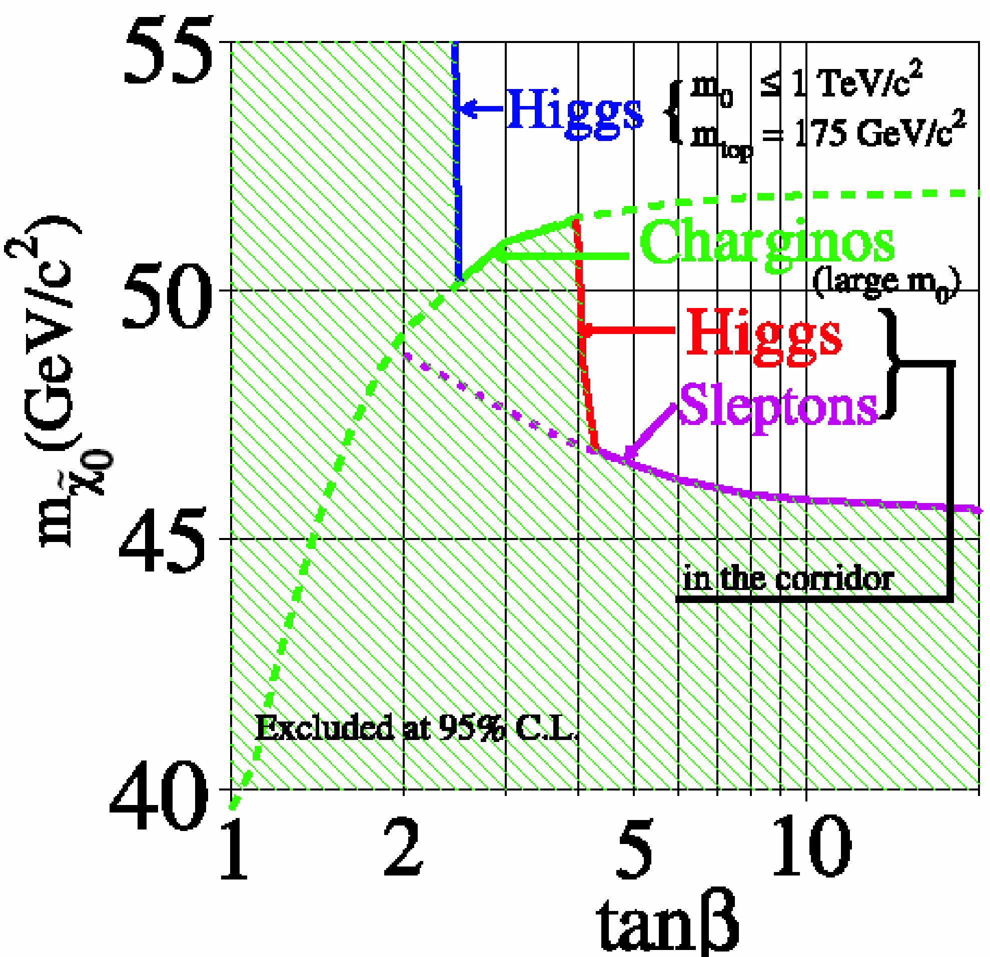
Exclusion in the m0-m1/2 plane:





Chargino exlcusion weakly tanβ dependent but
"light sneutrino" corridor ⇨ (partially) covered by slepton searches

CMSSM LSP mass limit



- Chargino dominant
  - ◇ except in "corridor" with $M(\tilde{\nu})$, $M(\tilde{\ell}) \approx M(\tilde{\chi}_1^{\pm})$
    $\Rightarrow$ slepton searches
- Higgs
  - ◇ large m_0:
    small $\tan\beta$ region excluded
  - ◇ in corridor, low m_0:
    stronger limits
- Result:

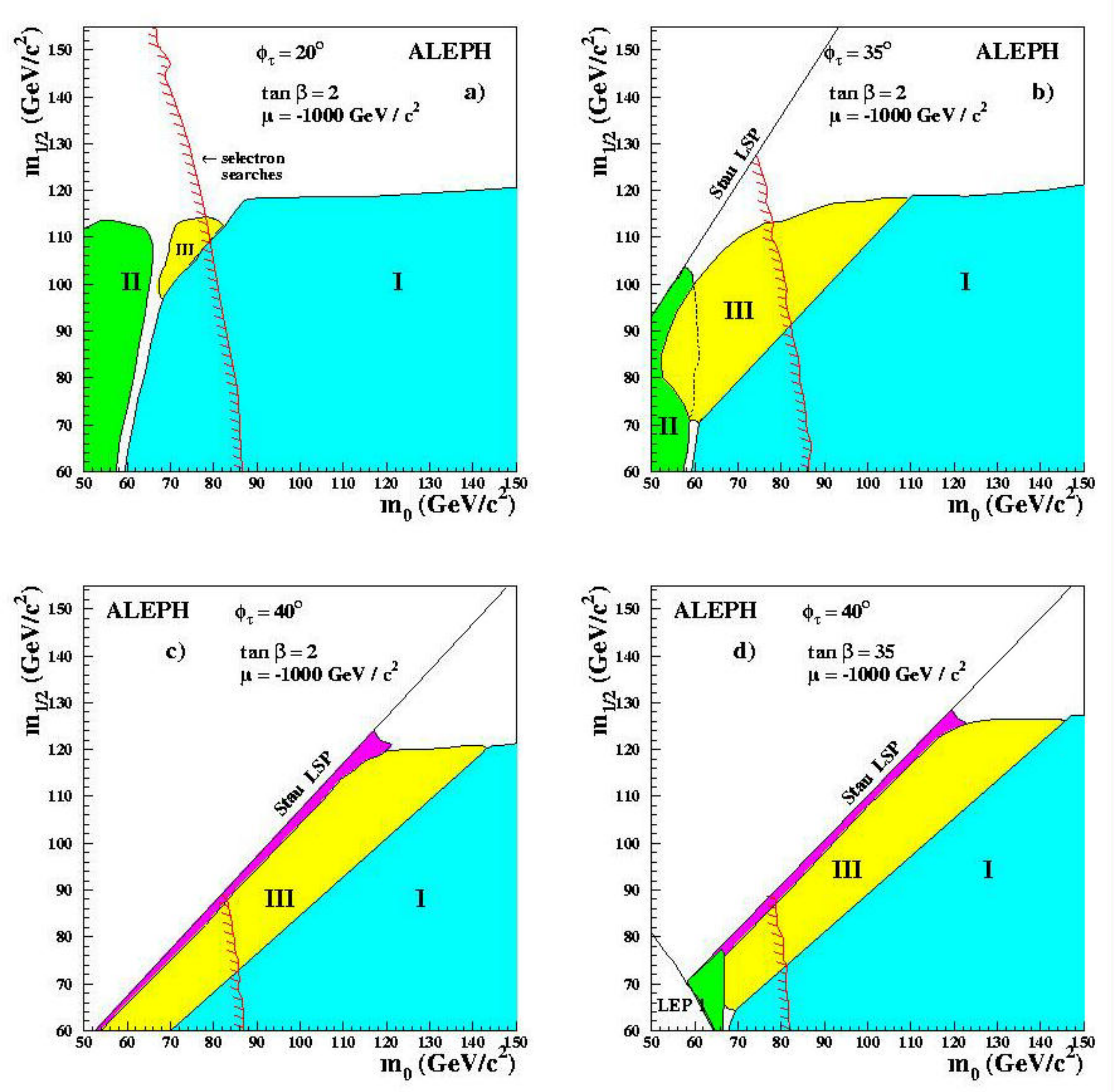
  $M(\tilde{\chi}_1^0) > 45$ GeV

- ... but no $\tilde{\tau}$ mixing

LSP limit (in CMSSM) set by slepton searches in the corridor for large tan β

Higgs tan β exclusion depends on top mass
(but not so critical for CMSSM LSP limit)

CMSSM Stau mixing



Mixing in stau sector can make stau = NLSP

Critical case:

Small $\Delta m = m(\chi^\pm) - m(\tilde{\tau})$

Dedicated searches needed for

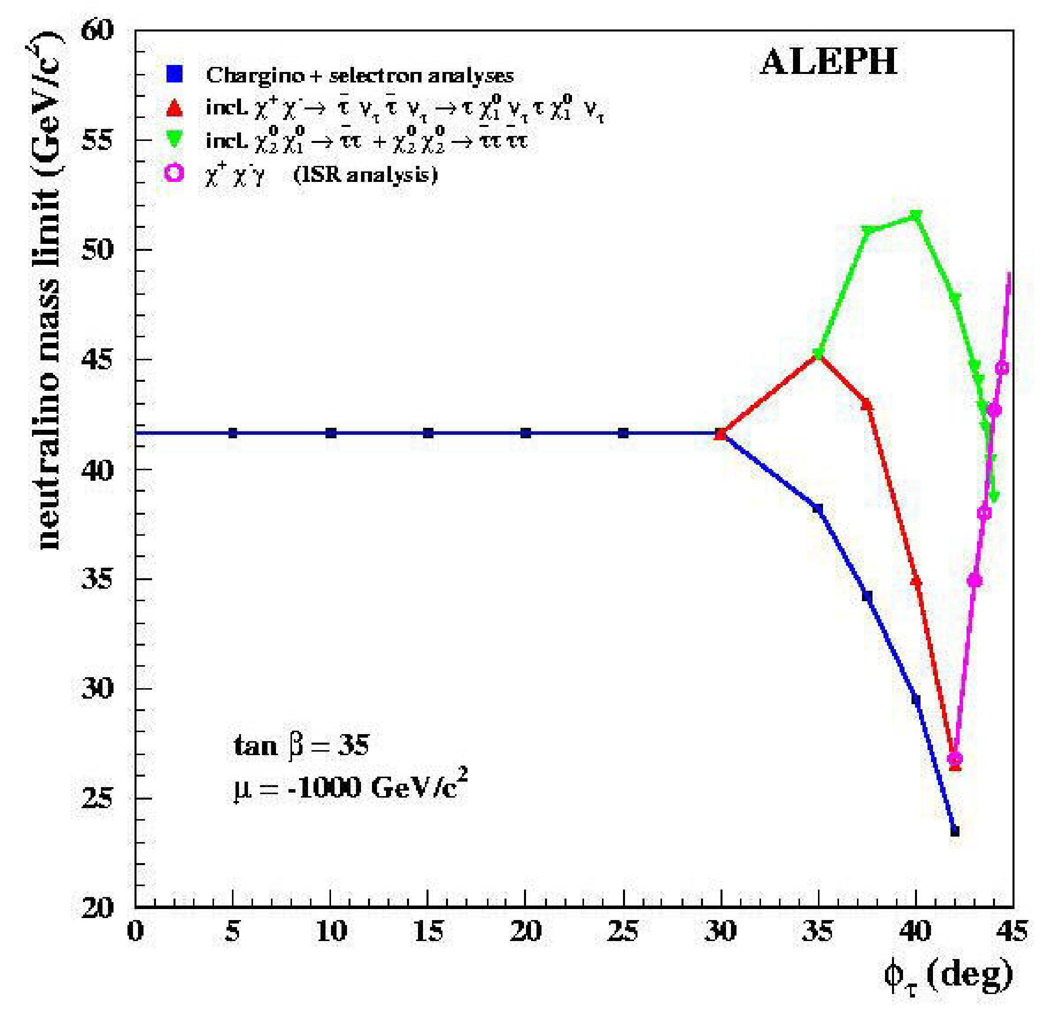
$$\chi_2^0\chi_1^0 \rightarrow \tau\tau\chi_1^0\chi_1^0$$

and

$$\chi_2^0\chi_2^0 \rightarrow \tau\tau\tau\tau\chi_1^0\chi_1^0$$

to recover sensitivity (Region III)

CMSSM Stau mixing

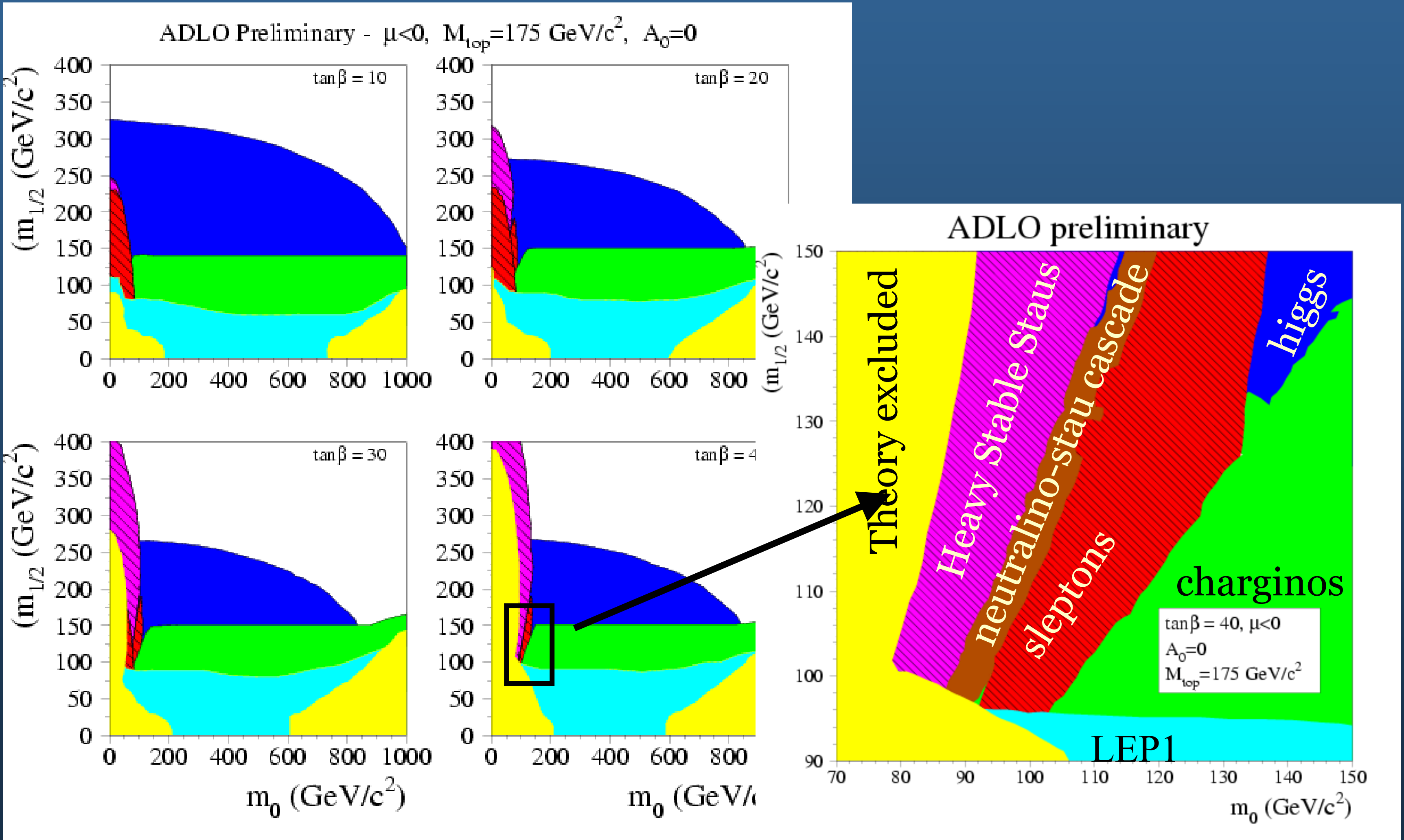


Preliminary ALEPH result:

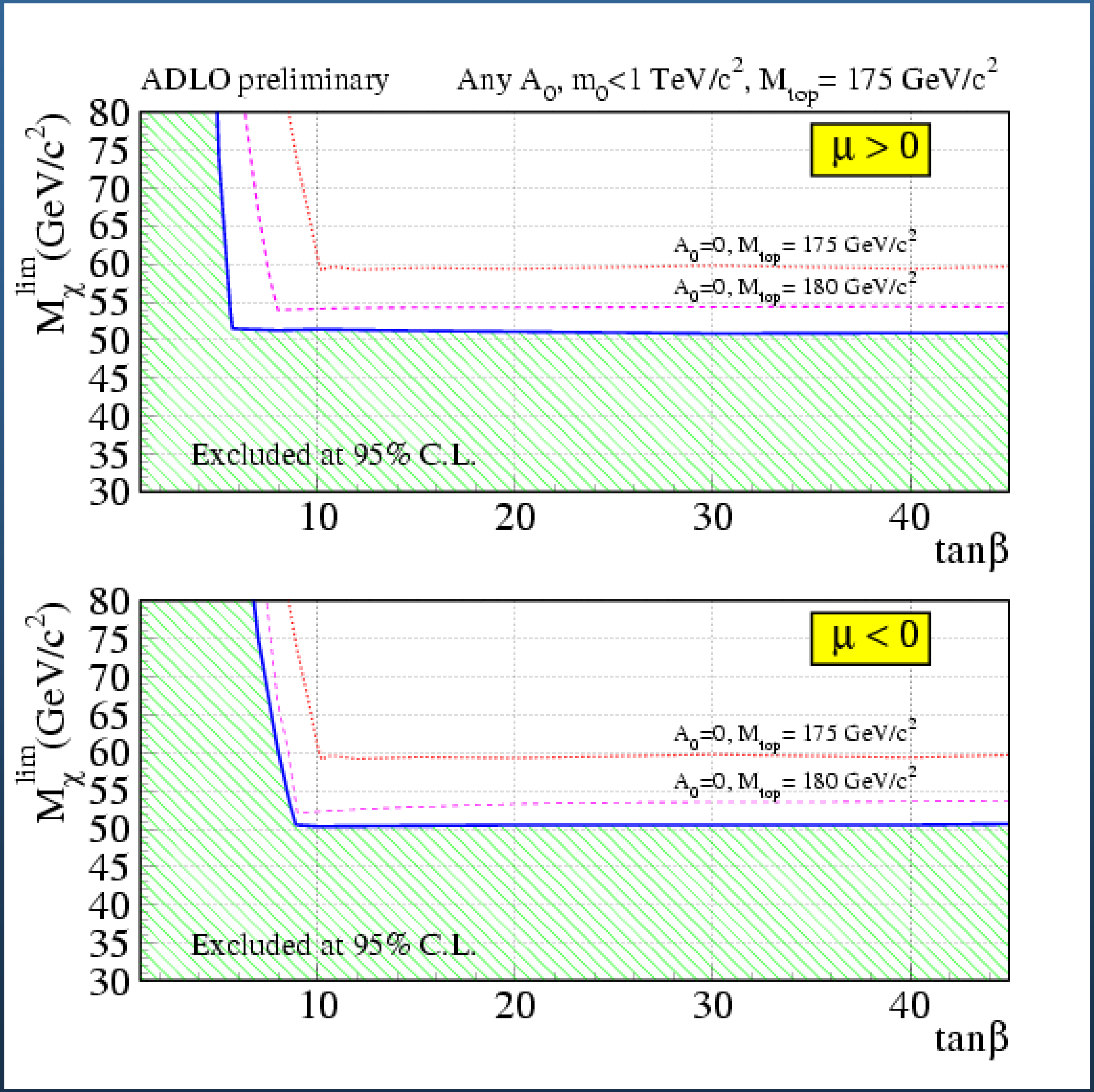
Stau mixing effects do not lower the CMSSM LSP limit for tanβ>2

mSuGRA Interpretation

Impact of Higgs searches becomes larger (Higgs sector coupled to sparticle sector in mSuGRA)
Exclusion in m0-m1/2 plane:



mSuGRA LSP Mass Limit



M(LSP) (any A0, mtop=175)

50.3 GeV

roughly: 1 GeV less per
1 GeV larger mtop

Large tanβ: limit set by
Charginos searches

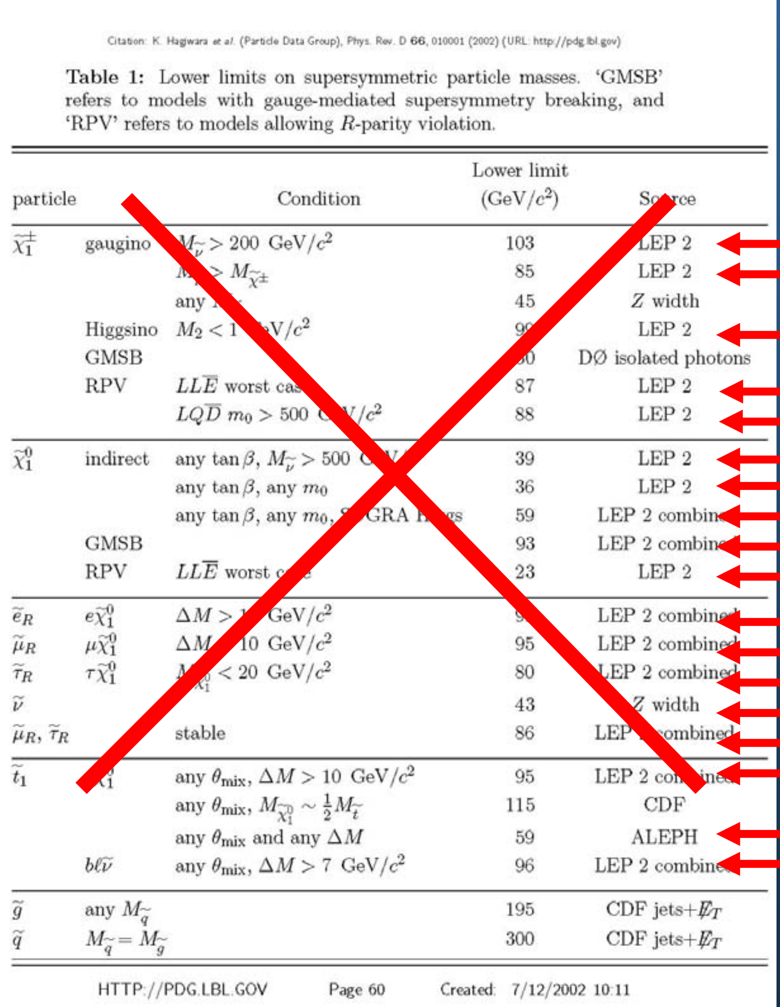
Small tanβ: limit set by
Higgs searches

Epilogue

SuGRA 20

SuGRA 25

PDG 2002:



Citation: K. Hagiwara et al. (Particle Data Group), Phys. Rev. D **66**, 010001 (2002) (URL: http://pdg.lbl.gov)

Table 1: Lower limits on supersymmetric particle masses. 'GMSB' refers to models with gauge-mediated supersymmetry breaking, and 'RPV' refers to models allowing R-parity violation.

particle		Condition	Lower limit (GeV/c^2)	Source
$\widetilde{\chi}_1^\pm$	gaugino	$M_{\tilde\nu} > 200\ \mathrm{GeV}/c^2$	103	LEP 2
		$M_{\tilde\nu} > M_{\tilde\chi^\pm}$	85	LEP 2
		any [illegible]	45	Z width
	Higgsino	$M_2 < 1$[illegible]eV/c^2	9[illegible]	LEP 2
	GMSB		[illegible]0	DØ isolated photons
	RPV	$LL\overline{E}$ worst ca[illegible]	87	LEP 2
		$LQ\overline{D}$ $m_0 > 500$ [illegible]V/c^2	88	LEP 2
$\widetilde{\chi}_1^0$	indirect	any $\tan\beta$, $M_{\tilde\nu} > 500$ [illegible]	39	LEP 2
		any $\tan\beta$, any m_0	36	LEP 2
		any $\tan\beta$, any m_0, [illegible]GRA H[illegible]gs	59	LEP 2 combin[illegible]
	GMSB		93	LEP 2 combin[illegible]
	RPV	$LL\overline{E}$ worst c[illegible]	23	LEP 2
$\widetilde{e}_R$	$e\widetilde{\chi}_1^0$	$\Delta M >$ [illegible] GeV/c^2	9[illegible]	LEP 2 combined
$\widetilde{\mu}_R$	$\mu\widetilde{\chi}_1^0$	ΔM [illegible] $10\ \mathrm{GeV}/c^2$	95	LEP 2 combined
$\widetilde{\tau}_R$	$\tau\widetilde{\chi}_1^0$	$M_{\widetilde{\chi}_1^0} < 20\ \mathrm{GeV}/c^2$	80	LEP 2 combined
$\widetilde{\nu}$			43	Z width
$\widetilde{\mu}_R$, $\widetilde{\tau}_R$		stable	86	LEP [illegible] combined
$\widetilde{t}_1$	[illegible]$\widetilde{\chi}_1^0$	any θ_{mix}, $\Delta M > 10\ \mathrm{GeV}/c^2$	95	LEP 2 co[illegible]ined
		any θ_{mix}, $M_{\widetilde{\chi}_1^0} \sim \frac{1}{2} M_{\tilde t}$	115	CDF
		any θ_{mix} and any ΔM	59	ALEPH
	$b\ell\widetilde{\nu}$	any θ_{mix}, $\Delta M > 7\ \mathrm{GeV}/c^2$	96	LEP 2 combine[illegible]
$\widetilde{g}$	any $M_{\tilde q}$		195	CDF jets+$\not{E}_T$
$\widetilde{q}$	$M_{\tilde q} = M_{\tilde g}$		300	CDF jets+$\not{E}_T$

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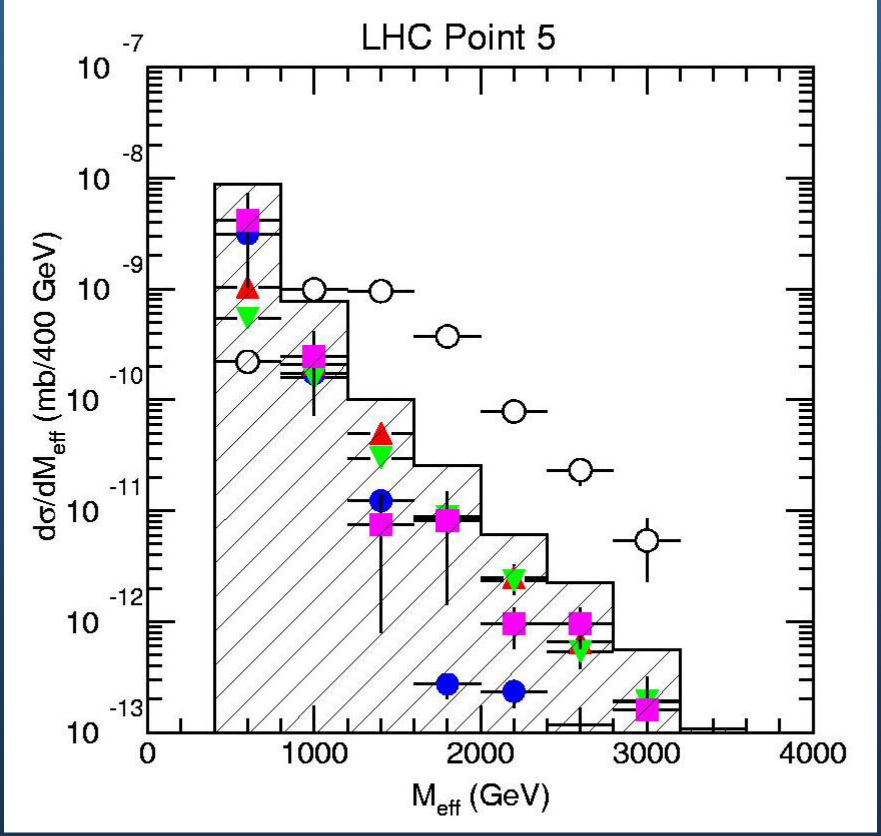
25 years of SUGRA will hopefully be a real celebration!



…and then the real work (+fun) begins:
How is SUSY broken: LHC + LC can find out

Special thanks to

G. Ganis
K. Jakobs
R. McPherson
L. Pape
C. Rembser
G. Sguazzoni