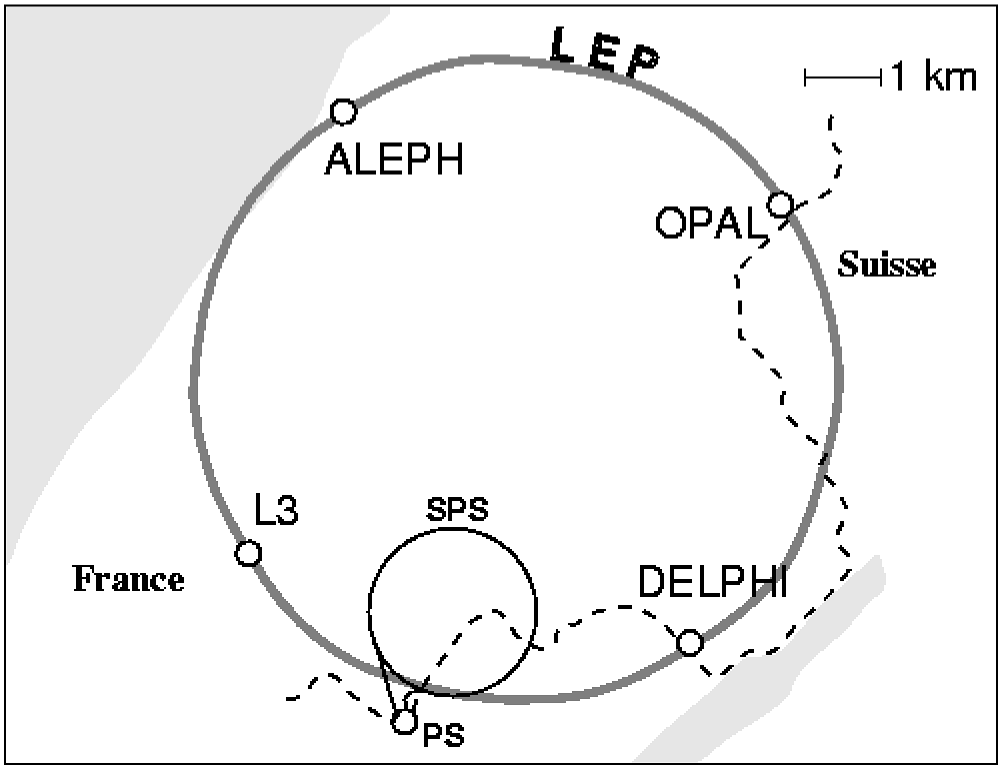
Search for new particles at LEP2



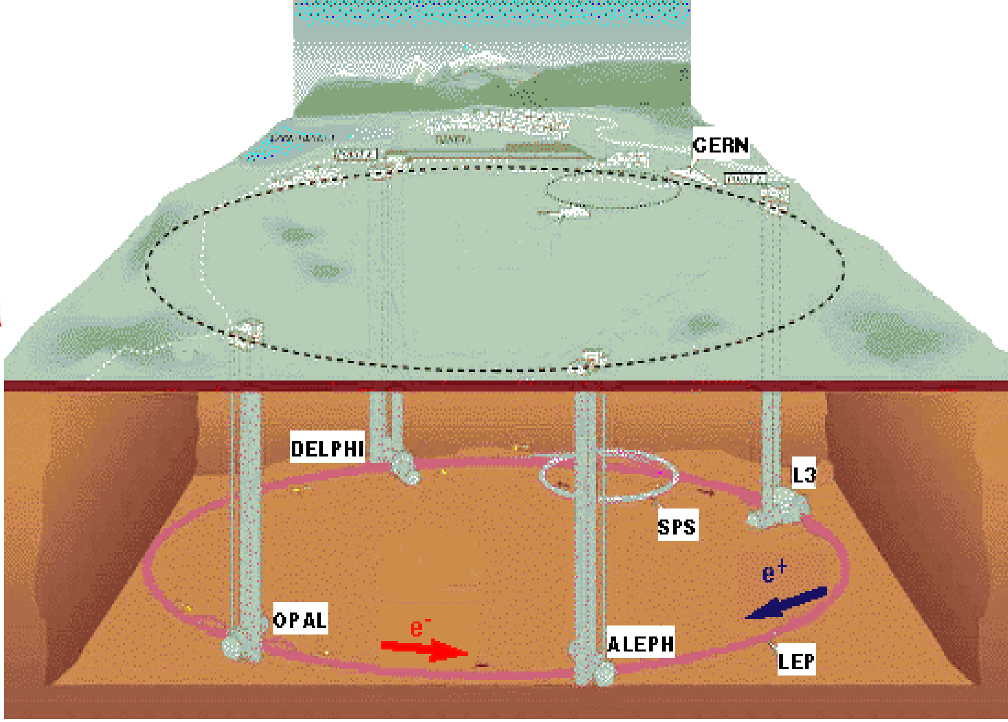
M.C. Espirito Santo / LIP-Lisboa

DESY, 8-9 April 2003

LEP

12 years of excellent e+e- data

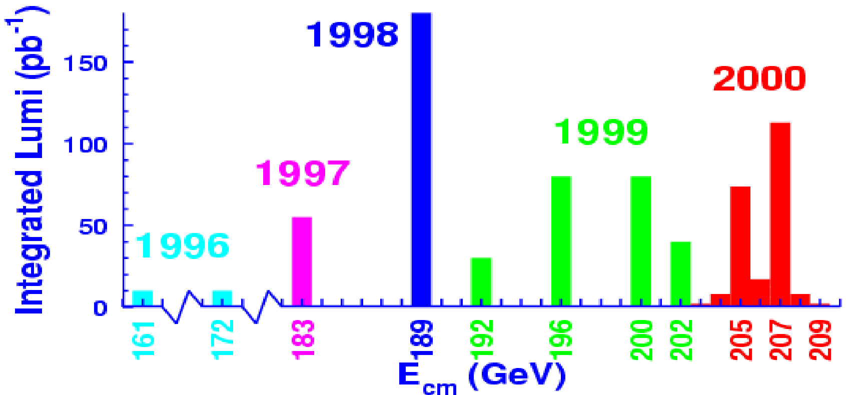
E_{cm} 91-209 GeV, ~1000 pb^{-1}/Exp



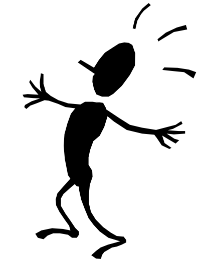
E_{cm} (GeV)	91	130-136	161-172	183	189	192-202	204-209
Lum/Exp (pb^{-1})	175	5	22	55	160	230	220
Year	89-95	1995	1996	1997	1998	1999	2000

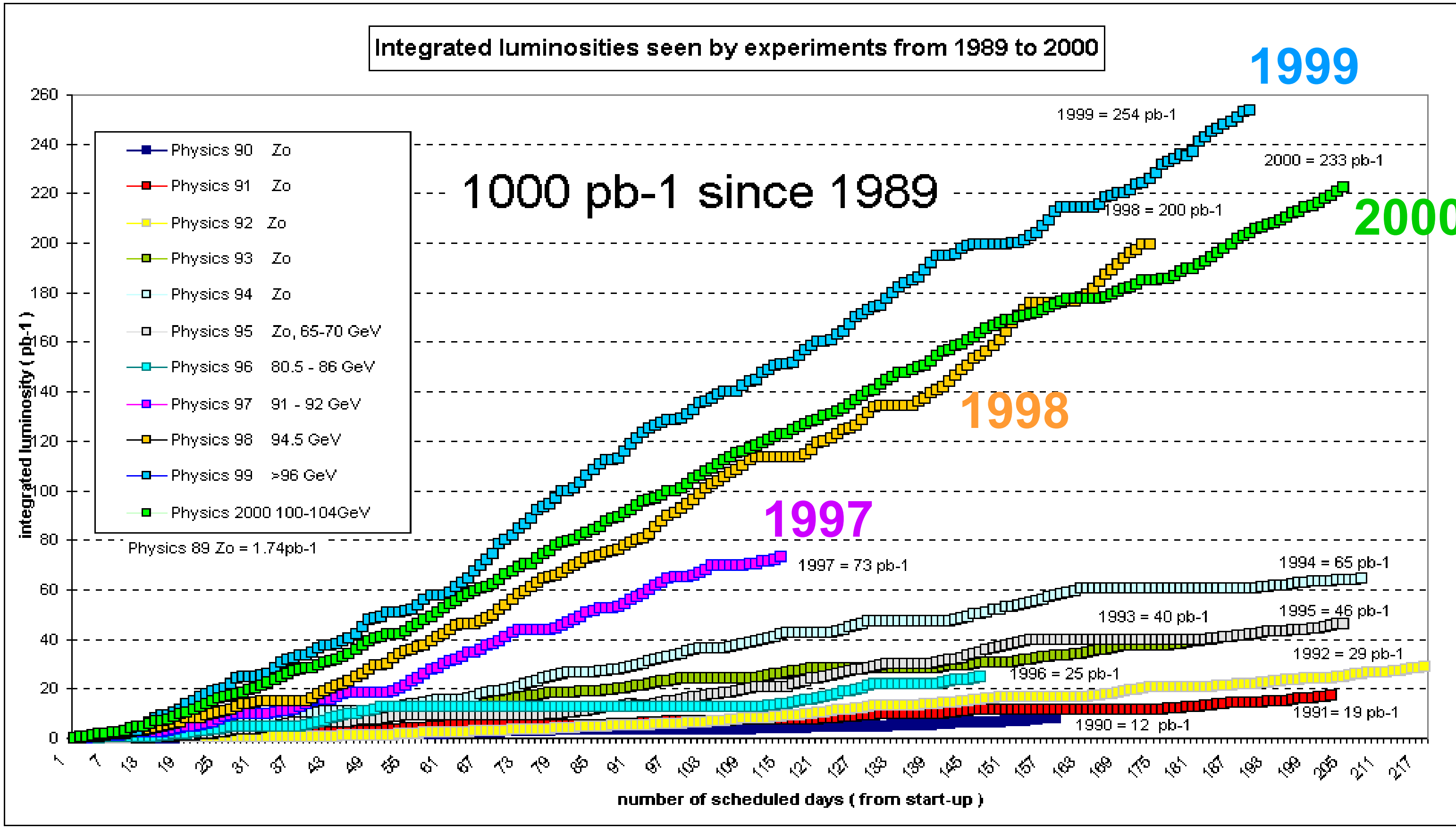
LEP2: E_{cm} 161-209 GeV

Lum ~2700 pb^{-1}



LEP





Last data in 2000, analyses being finalised now...

LEP Working Groups:

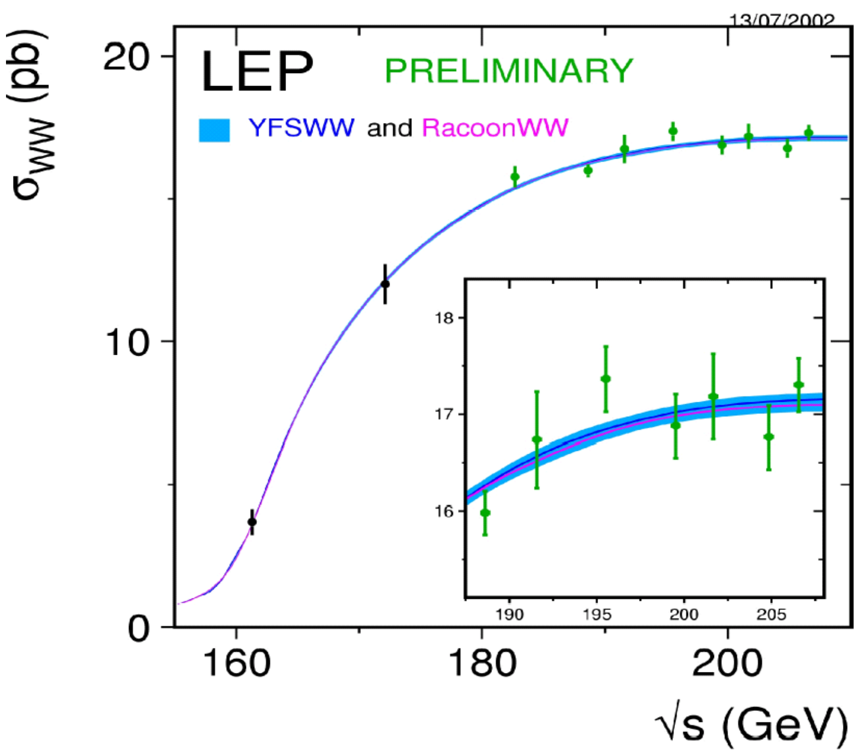
Fruitful collaboration between experiments:

Combined results

LEP Physics

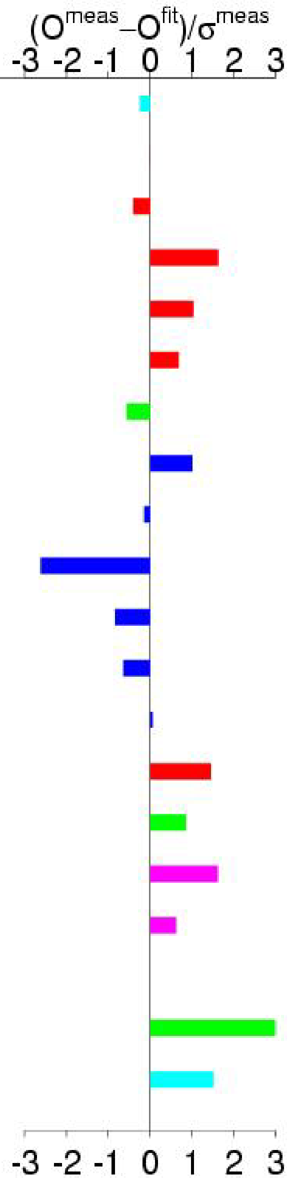
- SM tests to ~0.1%
- m_{top} indirect estimation
- m_{Higgs} indirect limits

$$N_\nu = 2.9841 \pm 0.0088$$



Summer 2002

	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-0.24
m_Z [GeV]	91.1875 ± 0.0021	0.00
Γ_Z [GeV]	2.4952 ± 0.0023	-0.41
σ^0_{had} [nb]	41.540 ± 0.037	1.63
R_l	20.767 ± 0.025	1.04
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.68
$A_l(P_\tau)$	0.1465 ± 0.0032	-0.55
R_b	0.21644 ± 0.00065	1.01
R_c	0.1718 ± 0.0031	-0.15
$A^{0,b}_{fb}$	0.0995 ± 0.0017	-2.62
$A^{0,c}_{fb}$	0.0713 ± 0.0036	-0.84
A_b	0.922 ± 0.020	-0.64
A_c	0.670 ± 0.026	0.06
A_l(SLD)	0.1513 ± 0.0021	1.46
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.87
m_W [GeV]	80.449 ± 0.034	1.62
Γ_W [GeV]	2.136 ± 0.069	0.62
m_t [GeV]	174.3 ± 5.1	0.00
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	3.00
Q_W(Cs)	-72.18 ± 0.46	1.52

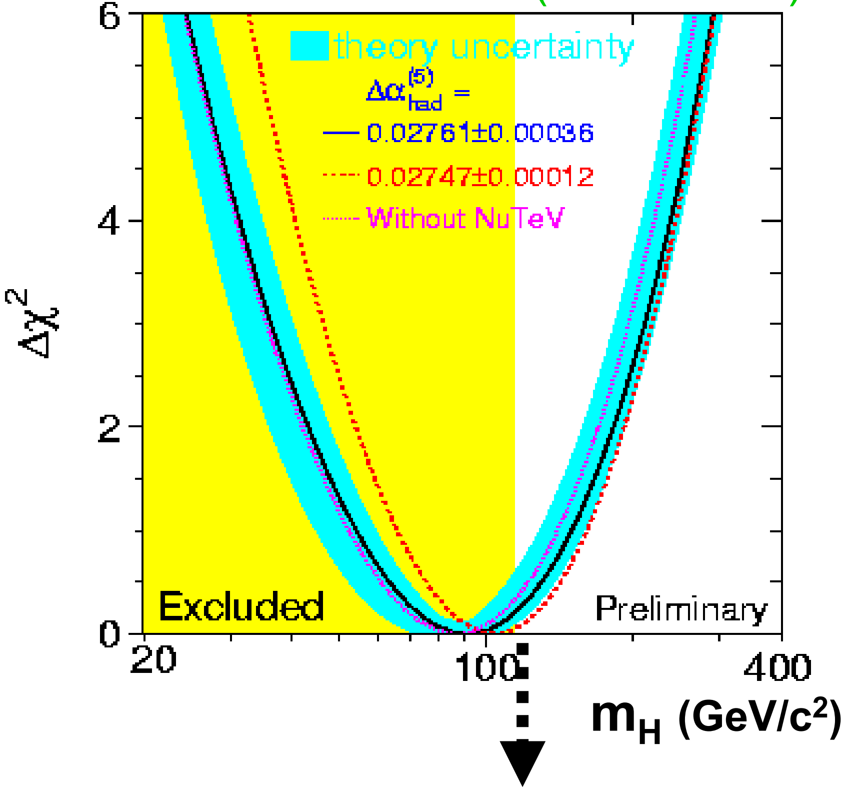


LEP Physics – Indirect limits

Precision measurements at LEP give a hint on what is (or not!) beyond...

Indirect limits on the Higgs mass

from fits to EW data (LEP + SLD)

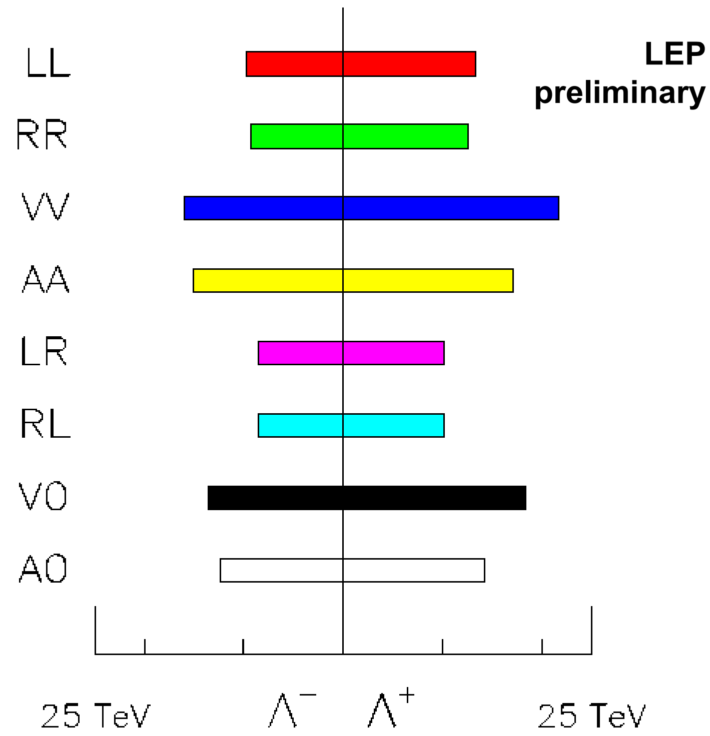


M_H>114.4 GeV/c^2 @ 95% CL

A light Higgs is favoured... and partly excluded by direct searches

Indirect limits on new physics scale Λ

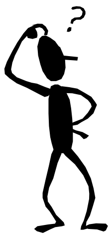
from e+e- → l+l- cross-sections



Λ = New physics scale in the Contact Interactions effective Lagrangian

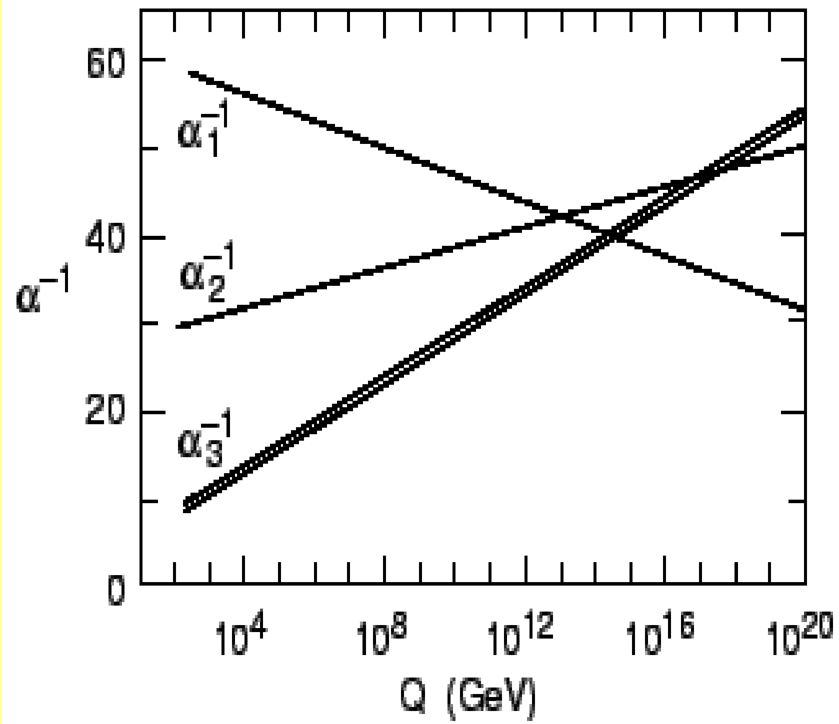
Exclusion depends on type of coupling

Searches at LEP – why?



SM: still very successful, but...

- EW symmetry breaking
  => we need the Higgs
- Fine tunning /Mass hierarchy problem
  $M_{Planck} >> M_{EW}$, $M_H \sim M_{EW}$ but $\delta M^2_H \sim M^2_{Planck}$
- Flavour pattern => 3 families?
- Many free parameters
  - Quantum numbers of particles?
  - Mass values?
- Unification?
- Gravity?



Λ should be:

- Large enough to explain decoupling of new physics
- Close enough to EW scale to address hierarchy problem

Around the corner?

Searches at LEP – what?

$\gamma, W^{\pm}, Z$

H

$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$

$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$

Extended fermion sector

- A fourth family ?
- Exotic ?
- Composite ?

b'

ν_L

L

LQ

q^*

ℓ^*

ν^*

~~Hierarchy problem?~~

SUSY $\left\{ \begin{array}{cccc} \tilde{\chi} & \tilde{q} & \tilde{\nu} & \tilde{\ell} \\ h & A & H & H^{\pm} \end{array} \right.$

~~SUSY~~ →

SUGRA
GMSB
AMSB
(RPV)

Technicolor
Extra dimensions
....

Searches at LEP – how?

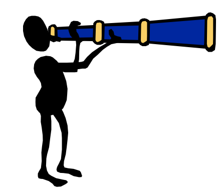
Clean e^+e^- environment => excellent conditions for new physics searches

- Increasing E_{cm} ➡ Threshold channels
- Luminosity ➡ Sensitivity
- Phase-space and cross-section…?

Many and exhaustive searches

- Direct / indirect
- New particles / new interactions

... Trying to look everywhere!



Model independent (topologies)

Systematic exploration of model(s)

some “golden” topologies:
acoplanar jets and leptons, 4 jets, photons only

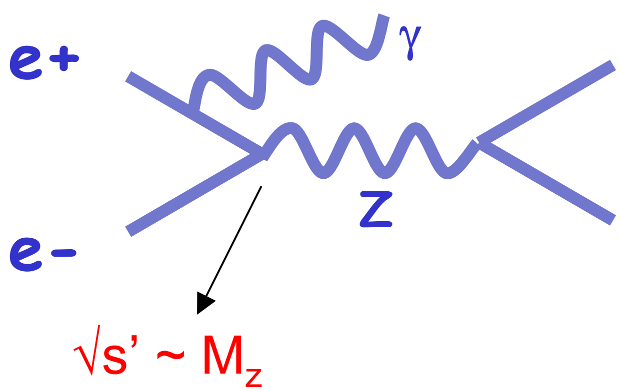
Search at LEP – how?

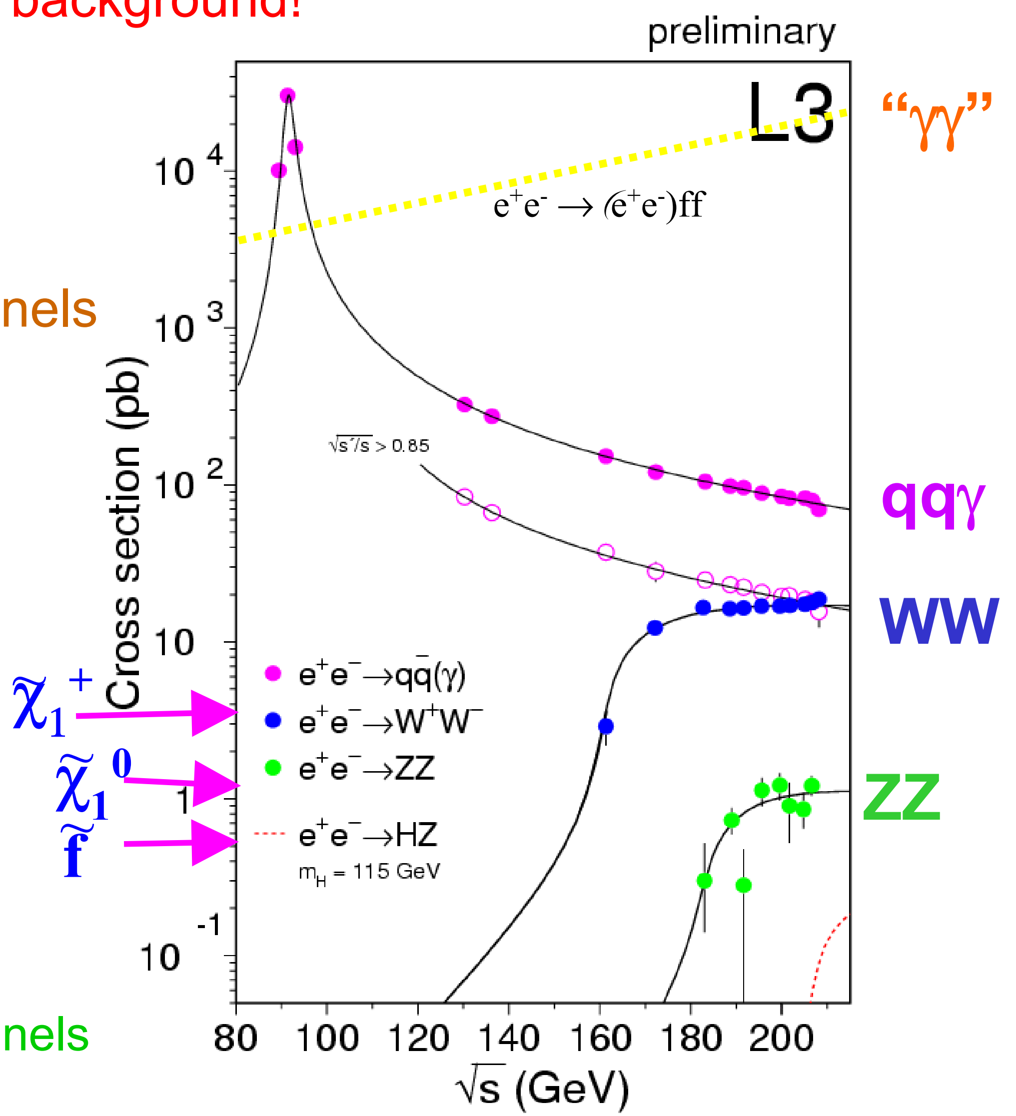
Clean e+e- environment... Still some background!

- Well understood (ISR, ...)
- well modeled by MC simulation

- "γγ": affects low visible energy channels
- 4-fermions: sometimes irreducible

Radiative return to the Z





Open triggers => wide coverage of channels

Sensitivity ~ fraction of pb

Mass reach ~ $\sqrt{s}/2$

Outline

Non-SUSY

- Motivation
- 4^{th}
- Excited/exotic leptons

SUSY

- Motivation
- Exotic – GMSB, AMSB
- SUGRA
- CMSSM
- (RPV)

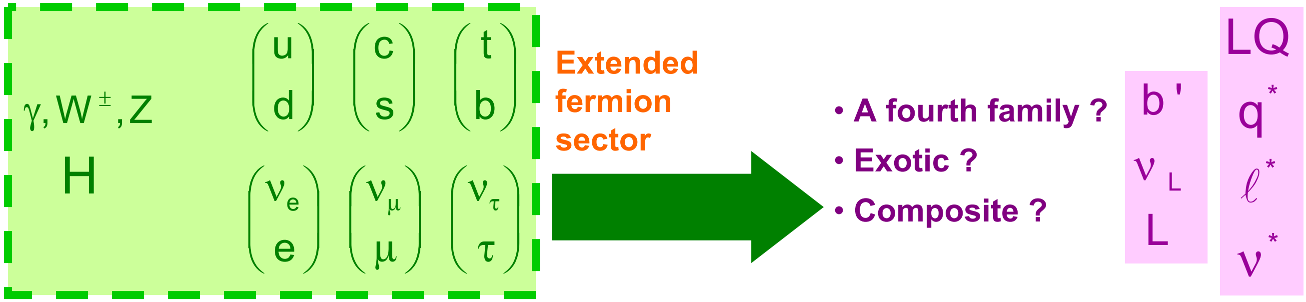
Thank you!

To the LEP accelerator team and many many people in the 4 LEP collaborations!!

No signal in any of the channels...

... Many searches not covered:
All Higgs (many extended/exotic scenarios), Technicolor, FCNC, Extra-dims....

Complicating the fermionic sector...



• Fermion flavour pattern and Interactions group not justified in the SM

- Additional families?
- Fermions with different SU(2)x(U1) quantum numbers?
- Additional bosons?

... May arise in gauge unification theories or extended EW models

• Are we at the fundamental level? **=> Composite models**

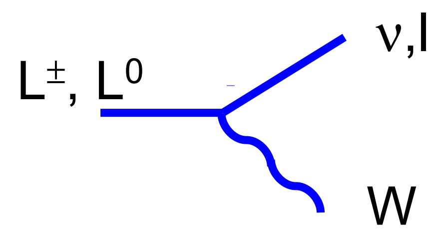
- Excited states
- Particles with L and B

Powerful limits exist: LEP1 (Z total and invisible width, direct searches)

- Low energy $\mu \to e\gamma$, g-2, ...
- ...

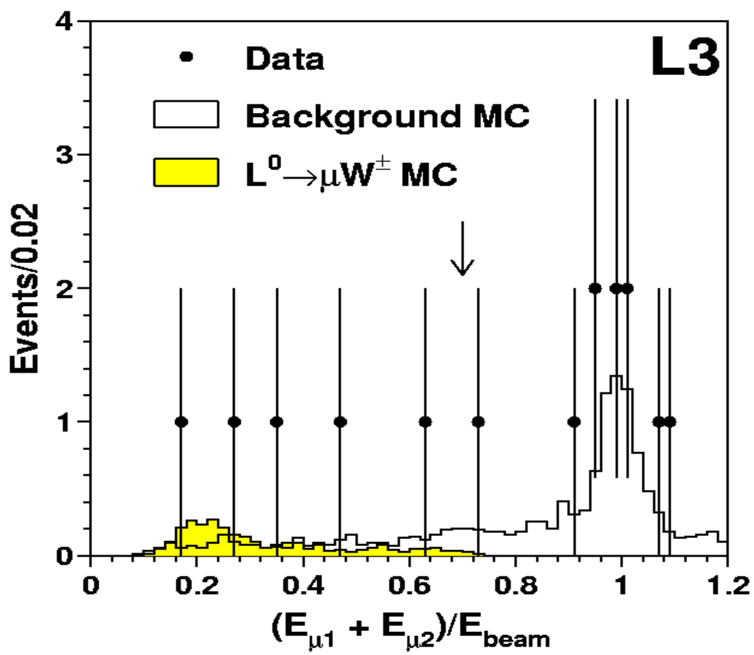
4^{th} family leptons

Observable production cross-sections



Decay through mixing with light lepton

$L^0L^0 \rightarrow W\,W\,l\,l$



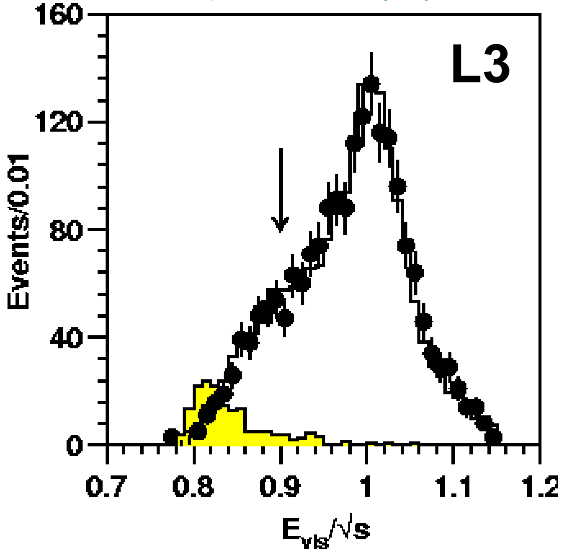
Mass limits (GeV/c^2) **L3**

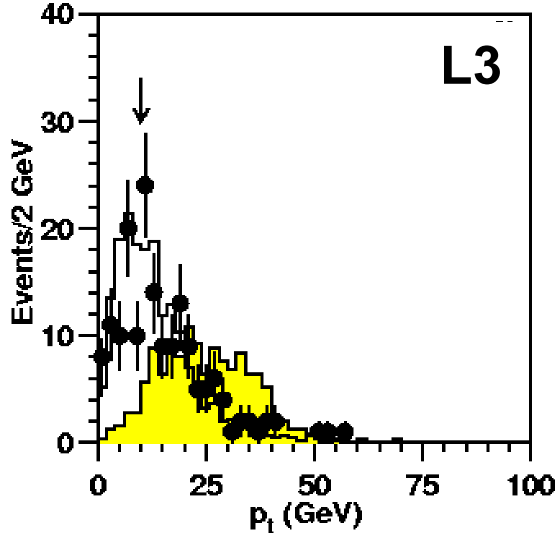
	$L^0 \rightarrow eW$	$L^0 \rightarrow \mu W$	$L^0 \rightarrow \tau W$
Dirac	101.3	101.5	90.3
Majorana	89.5	90.7	80.5

... Considerably extending LEP1 limits

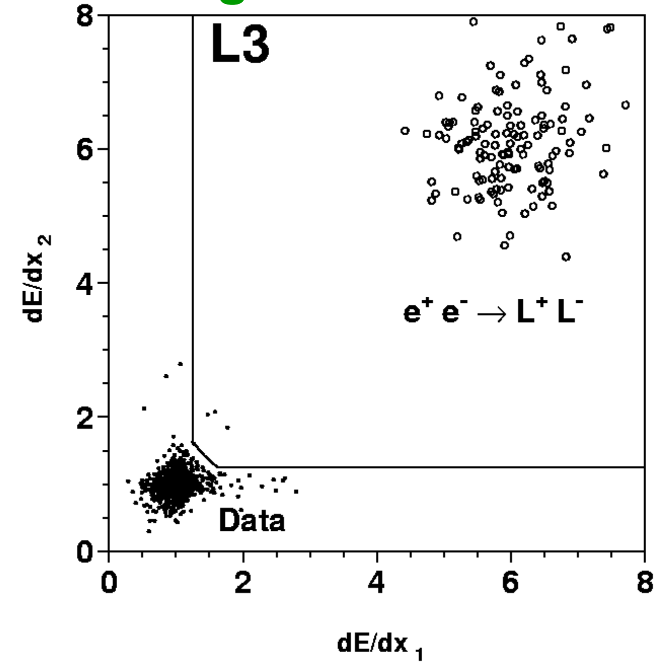
4^{th} family leptons $L^{\pm}$ search

$L^{\pm} \rightarrow W\,W\,\nu\,\nu$

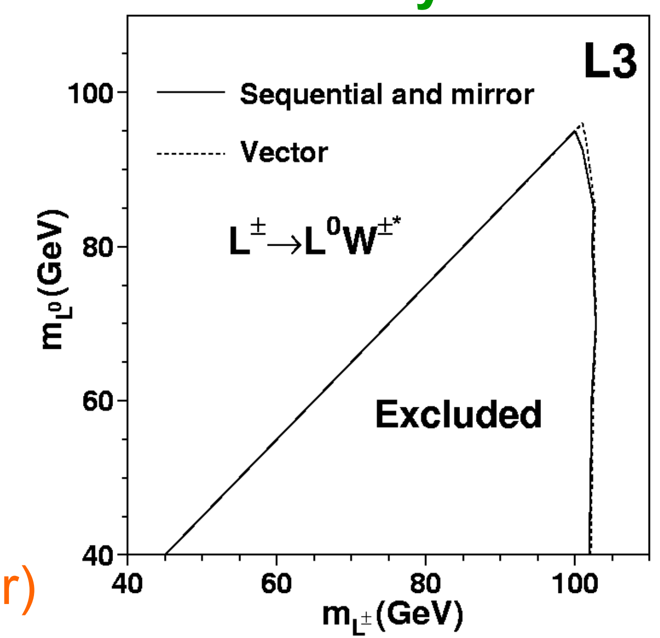




Long lived



Chain decays ...



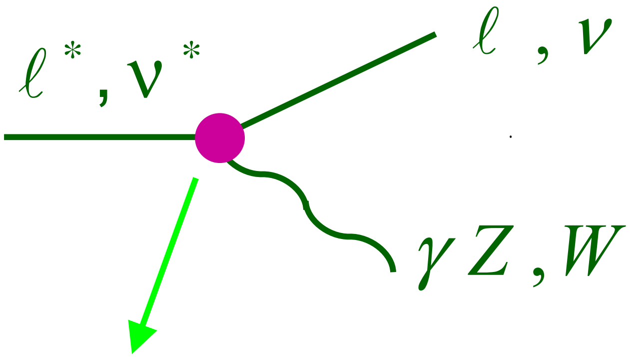
Mass limits (GeV/c^2) **L3**

$L^{\pm} \rightarrow \nu W$	$L^{\pm} \rightarrow L^0 W$ ($\Delta m > 15$)	$L^{\pm}$ stable
100.8	101.5	90.3

Comparable limits for exotic fermions (Vector, Mirror)

Excited leptons

Substructure in the fermionic sector => Excited states



Effective model

$$\mathcal{L}_{eff} = \frac{1}{2\Lambda} \cdot \overline{\ell}^{*} \cdot \sigma^{\mu\nu} \left[g \cdot f \frac{\tau}{2} W_{\mu\nu} + g' \cdot f' \frac{Y}{2} B_{\mu\nu} \right] \ell^{*} + h.c.$$

e.g. Boudjema, Djouadi, Kneur Z.Phys.C57 (1993)
Hagiwara, Zeppenfeld, Komamiya Z.Phys.C29 (1985)

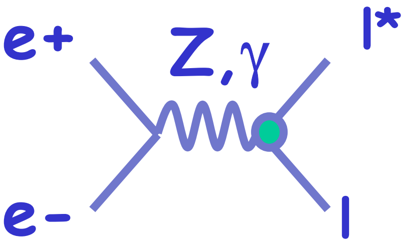
Λ compositeness scale
f, f ' weight factors

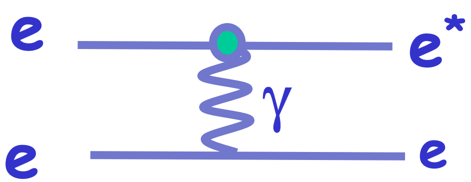
We assume |f | = |f '|

Mass and coupling of the excited lepton: $f / \Lambda = \sqrt{2} \cdot \lambda / m_{\ell^*}$

Excited leptons

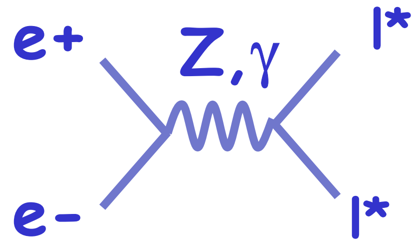
Single production



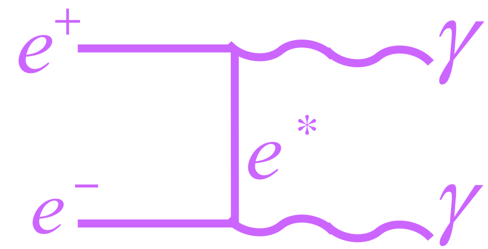


1/Λ suppression but sensitive up to E_{cm}

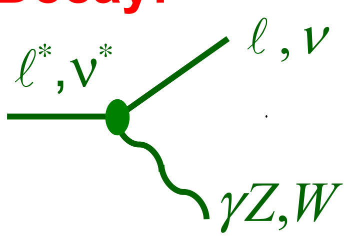
pair production



Indirect mode

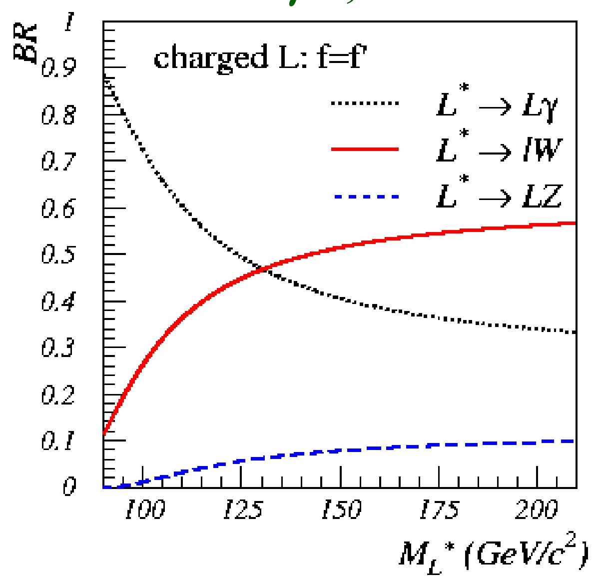


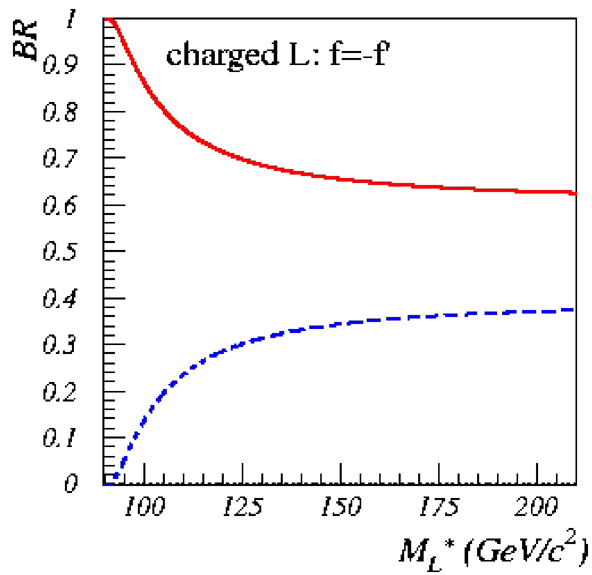
Decay:



All BR matter... Many topologies

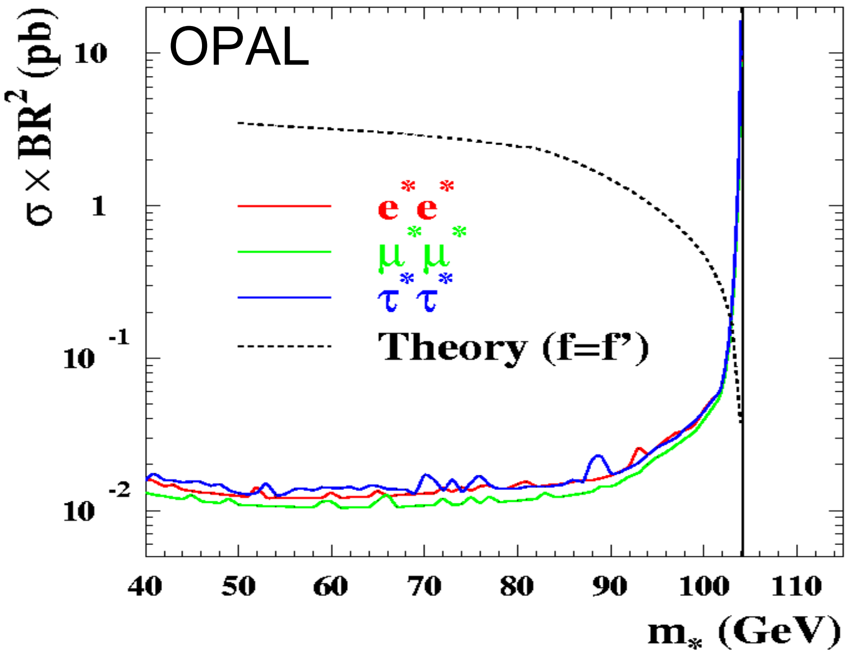
$\ell\ell\gamma, \gamma, jj\ell, jj, \ell\ell, jj\ell\ell, \ldots$





Excited leptons

Pair production

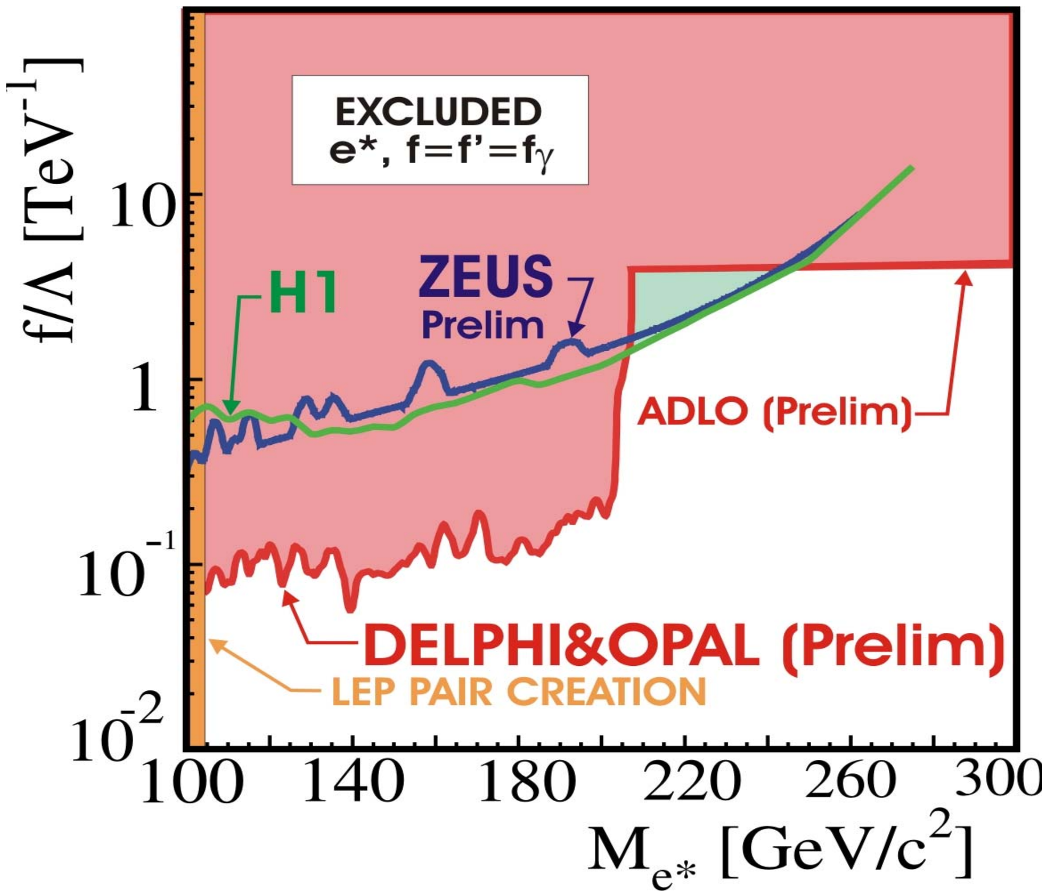


Mass limits (GeV/c^2)

DELPHI	e*	μ*	τ*
f=f'	103.1	103.2	102.7
f=-f'	102.0	102.0	102.0

Single production: direct + indirect

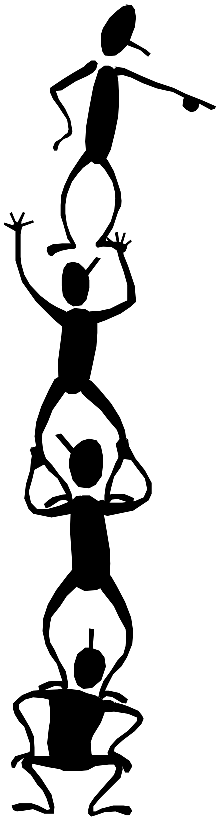
Excited electron (f=f´)



Outline

Non-SUSY

- Motivation
- 4th family leptons
- Excited/exotic leptons



SUSY

- **Motivation**
- **Exotic – GMSB, AMSB**
- **SUGRA**
- **CMSSM**
- **(RpV)**

No signal in any of the channels...

... Many searches not covered:
All Higgs (many extended/exotic scenarios), Technicolor, FCNC, Extra-dims....

SUSY – why, what, how?

Why ?

Hierarchy problem | Grand unification | Connection to gravity
Light Higgs | Possible dark matter candidate

What ?

Sparticles = SUSY partners of SM particles (s±1/2) **(MSSM)**

	SM particles			SUSY partners	
fermions	e μ τ	**leptons**	**sleptons**	$\tilde{e}$ $\tilde{\mu}$ $\tilde{\tau}$	bosons
	ν_e ν_μ ν_τ	**neutrinos**	**sneutrinos**	$\tilde{\nu}_e$ $\tilde{\nu}_\mu$ $\tilde{\nu}_\tau$	
	u c t d s b	**quarks**	**squarks**	$\tilde{u}$ $\tilde{c}$ $\tilde{t}$ $\tilde{d}$ $\tilde{s}$ $\tilde{b}$	
bosons	$W^\pm$ $H^\pm$		**charginos**	$\tilde{\chi}_1^\pm$ $\tilde{\chi}_2^\pm$	fermions
	γ Z^0 h^0 H^0 A^0		**neutralinos**	$\tilde{\chi}_1^0$ $\tilde{\chi}_2^0$ $\tilde{\chi}_3^0$ $\tilde{\chi}_4^0$	
	g_i	**gauge particles**	**gluinos**	$\tilde{g}_i$	
	G		**graviton**	$\tilde{G}$	

Many parameters...

M_1, M_2, M_3 Gaugino masses

$m_{\tilde{f}}$ Sfermion masses

$\tan\beta$, μ, m_A Higgs(ino) mass/mixing

A_τ, A_b, A_t

SM + 105

(+45 RPV)

SUSY – how?

How ?

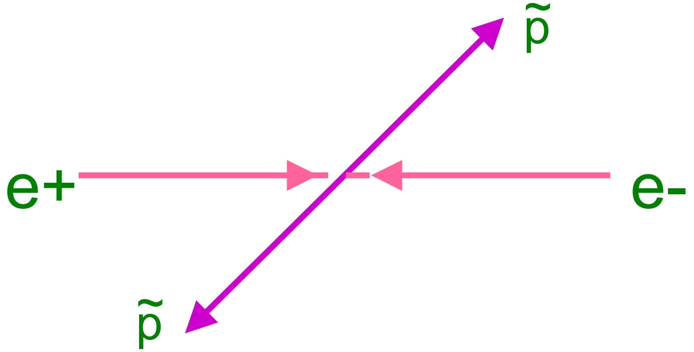
$$R_p = (-1)^{3B-L+2S}$$

SUSY is a broken symmetry => ~~SUSY~~ Mechanism?

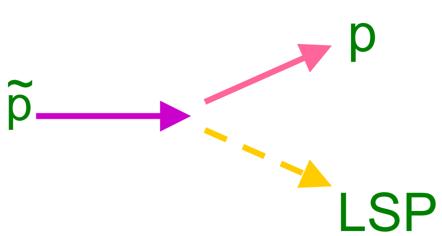
=> phenomenology

R-parity conservation:

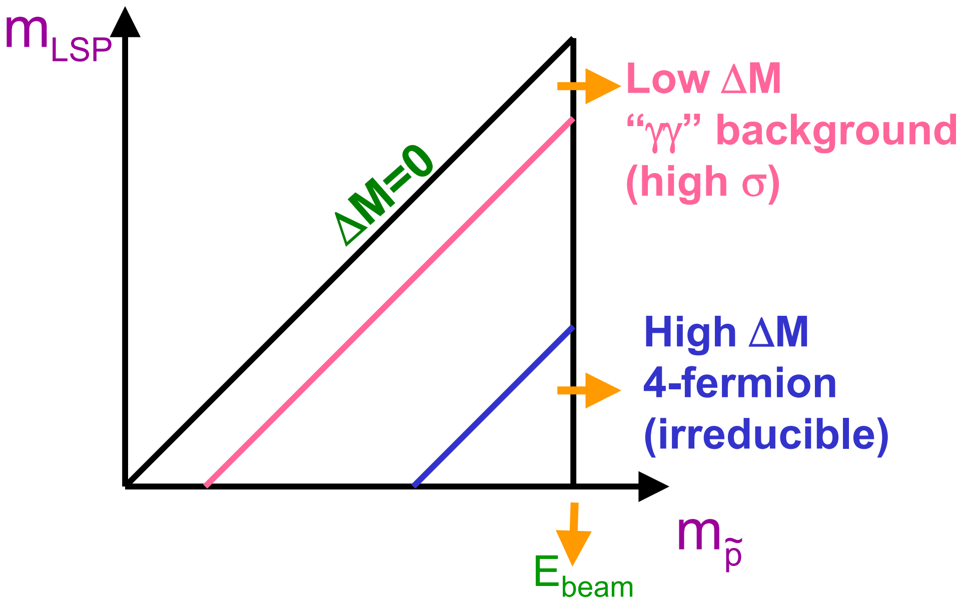
Pair production of Sparticles



Decay to stable (neutral) LSP



$$\Delta M = m_{\tilde{p}} - m_{LSP}$$



Decay chains to NLSP: several ΔM involved

SUSY – how?

Mechanism of SUSY breaking has deep implications on phenomenology

Hiden ~~SUSY~~ → Visible sector

SUGRA
Gravity mediated
LSP :
frequently $\tilde{\chi}_1^0$

GMSB
Gauge mediated
LSP : $\tilde{G}$ (m << GeV)

Other
e.g. **AMSB**
LSP : $\tilde{\chi}_1^0, \tilde{\nu}, \tilde{G}$

Signatures & dominant channels depend on specific scenario considered

Increased predictability, but still large number of free parameters

GMSB:

Hiden ~~SUSY~~ → Gauge forces → Visible sector

$10^3 < \sqrt{F} < 10^{10}$ GeV $\Rightarrow$ Light $\tilde{G}$ (LSP) (order 1 KeV/c^2, or less)

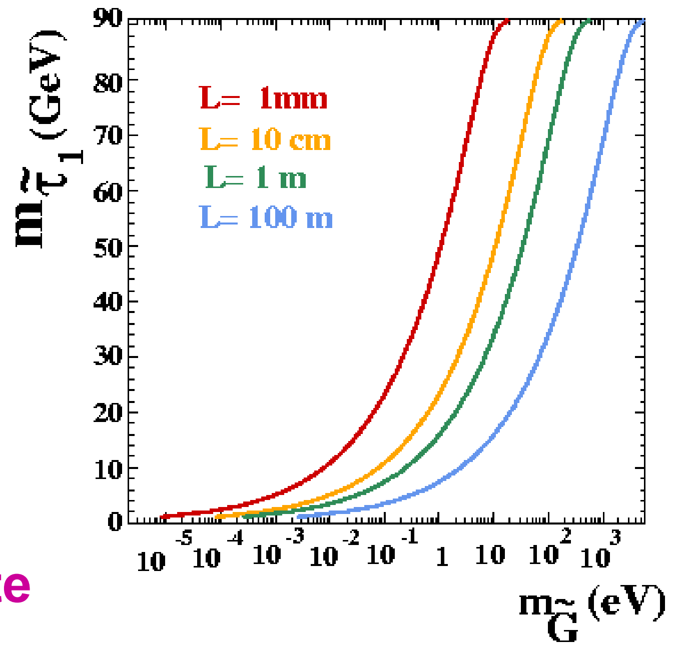
- No severe FCNC (Gauge forces flavour blind)
- No dark matter candidate

$\tilde{G}$ couples weakly with all particles $\Rightarrow$ **only NLSP decays directly into $\tilde{G}$**

Gravitino mass and Nature of NLSP determine phenomenology

$$\tau_{NLSP} \propto \frac{m^2_{\tilde{G}}}{m^5_{NLSP}}$$

=> Lifetime signature



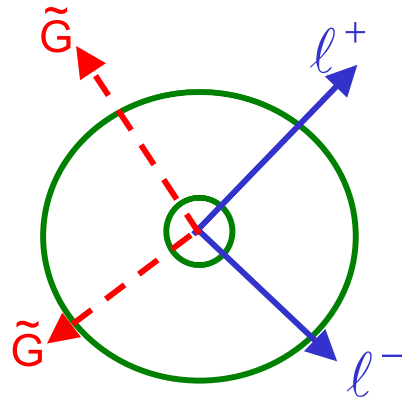
NLSP:

$\tilde{\chi}^0_1 \rightarrow \gamma\tilde{G}$ or $\tilde{\ell} \rightarrow \ell\tilde{G}$

=> Additional photons/leptons in the final state

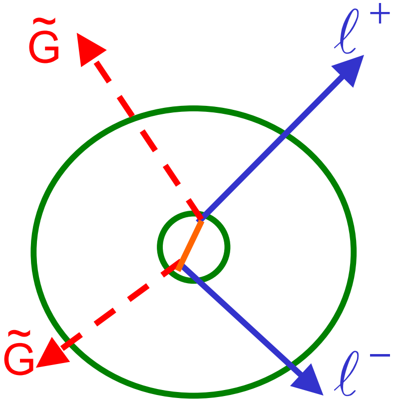
GMSB – lifetime signature

$$e^+e^- \to \tilde{\ell}^+\tilde{\ell}^- \to \ell^-\tilde{G}$$
$$\quad\quad\quad\quad\quad\hookrightarrow \ell^+\tilde{G}$$



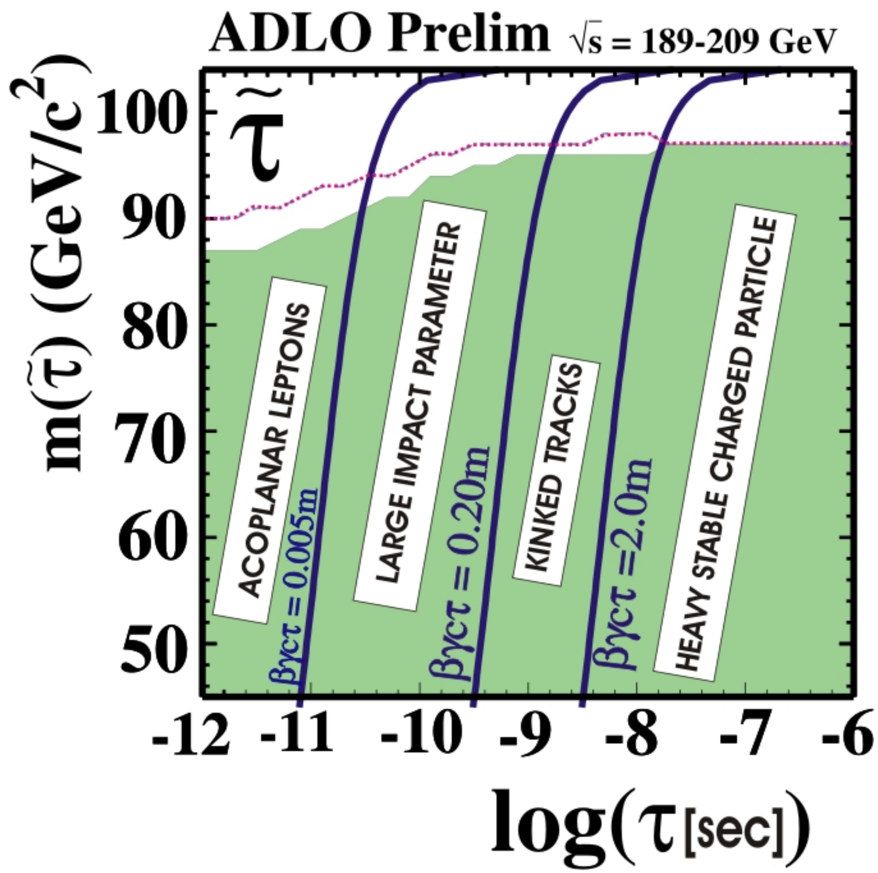
Acoplanar leptons

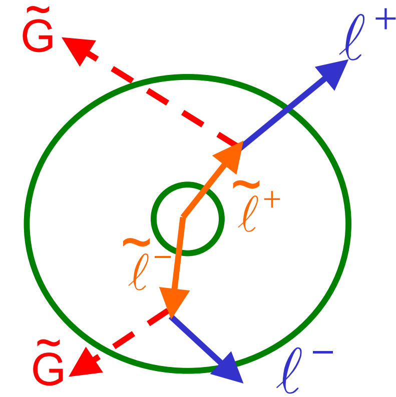
$m_{\tilde{G}} \leq$ few eV/c^2



Large impact parameter

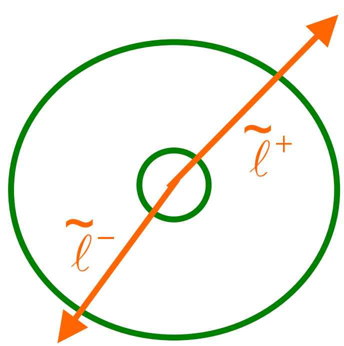
$m_{\tilde{G}} \approx$ eV/c^2 - 0.1KeV/c^2





Kinked tracks

$m_{\tilde{G}} \geq$ few KeV/c^2

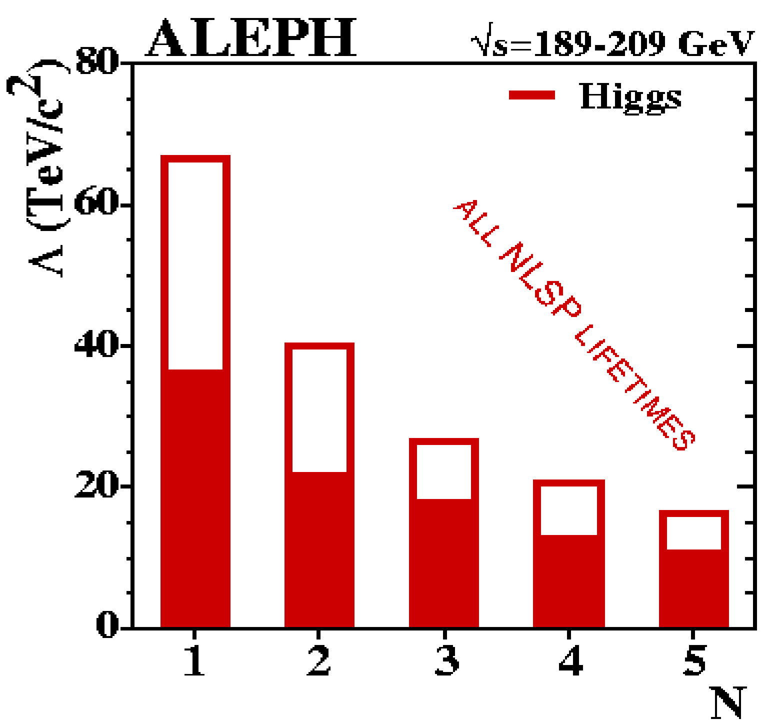


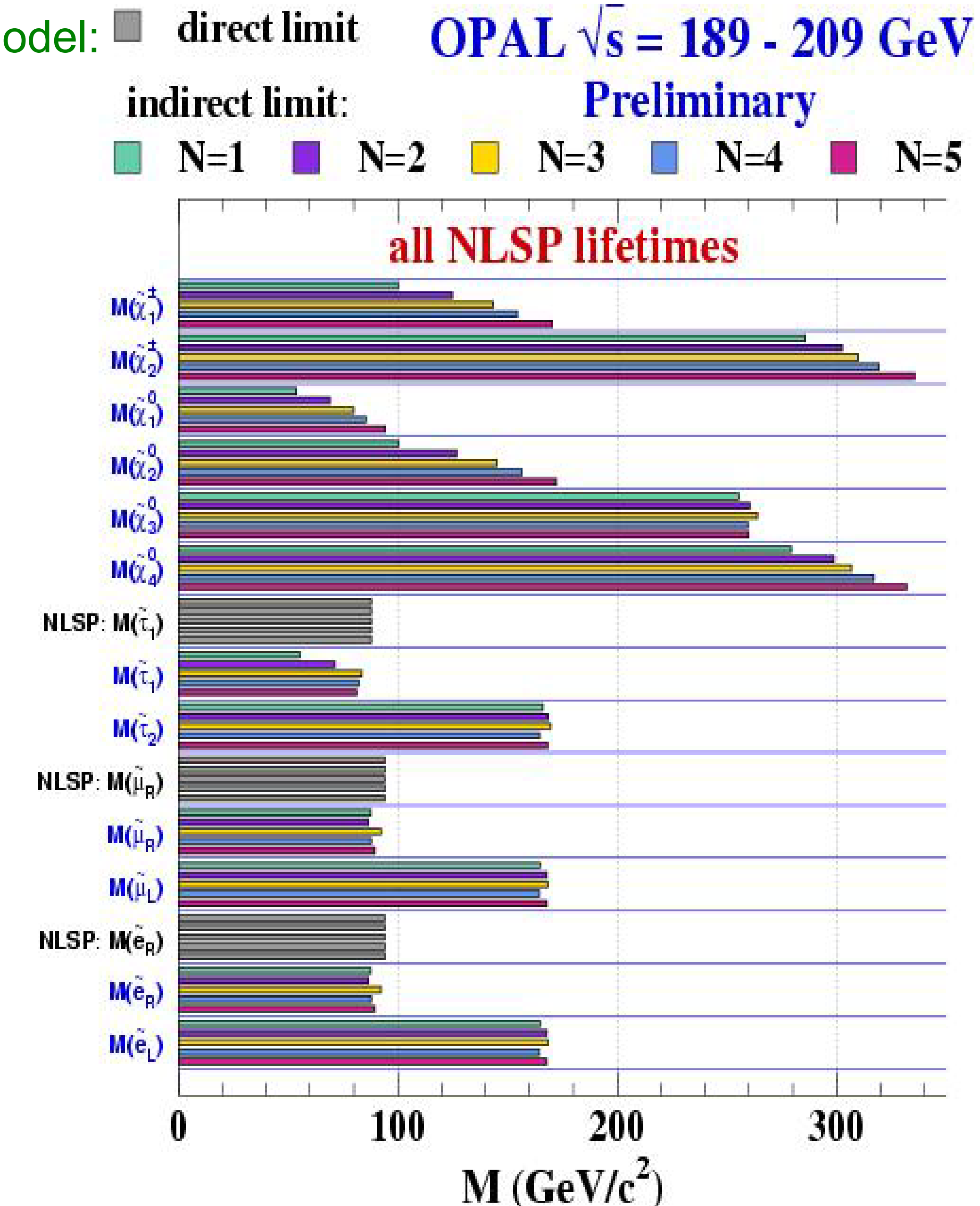
Stable charged particles

GMSB – Constraints on parameters

Few parameters to define the minimal model:

- √F: scale of SUSY breaking
- M: messengers mass scale
- N: number of messenger generations
- tanβ
- sign(μ)
- Λ ≈F/M : effective SUSY breaking scale





AMSB:

Hiden ~~SUSY~~ → Superconformal Anomaly → Visible sector

- **Rescaling anomalies in supergravity lagrangian => soft mass parameters in visible sector**
- **Additional non-anomaly contributions to avoid tachyonic sleptons**
- **Could solve SUSY FCNC problem**

Rather characteristic phenomenology:

LSP: $\tilde{\chi}_1^0, \tilde{\nu}$ or $\tilde{\tau}$

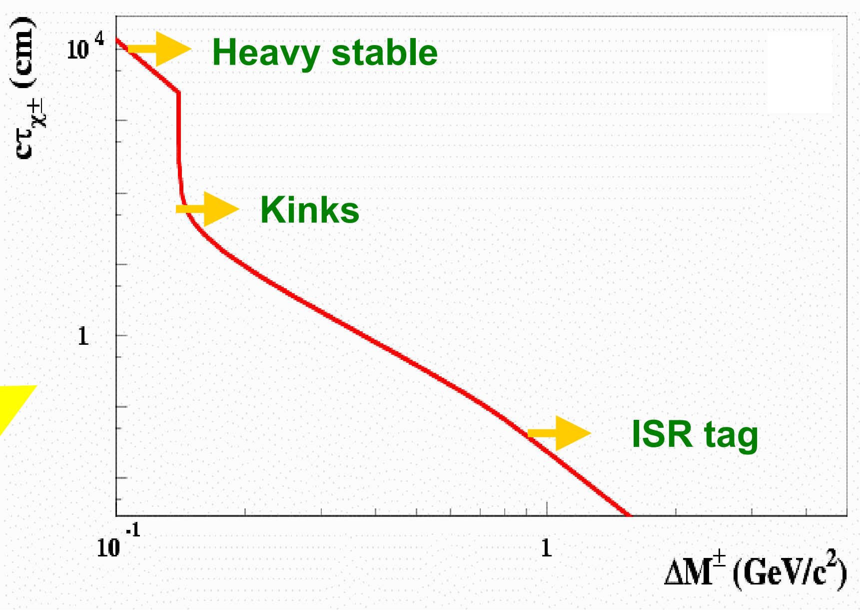
Heavy squarks

Light Higgs

$M_1 : M_2 : M_3$ » 2.8 : 1 : -8

$\tilde{\chi}_1^0$ and $\tilde{\chi}_1^\pm$:

Nearly mass degenerate and gaugino-like



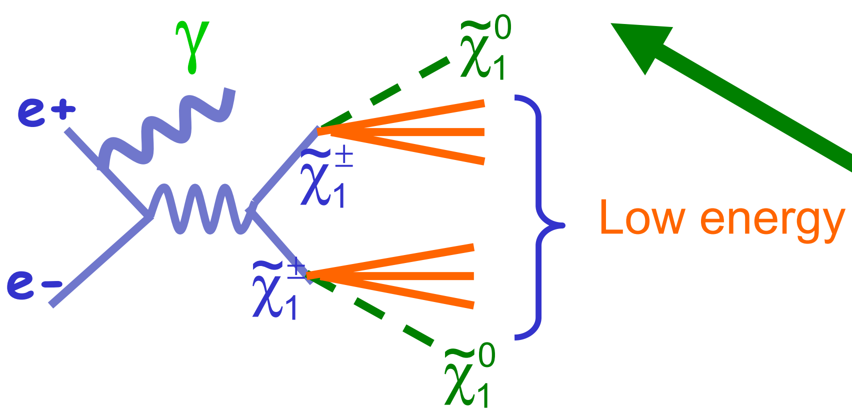
Small ΔM Chargino search

$$\Delta M = m_{\tilde{\chi}_1^{\pm}} - m_{\tilde{\chi}_1^0}$$

Low ΔM => => large "γγ" background

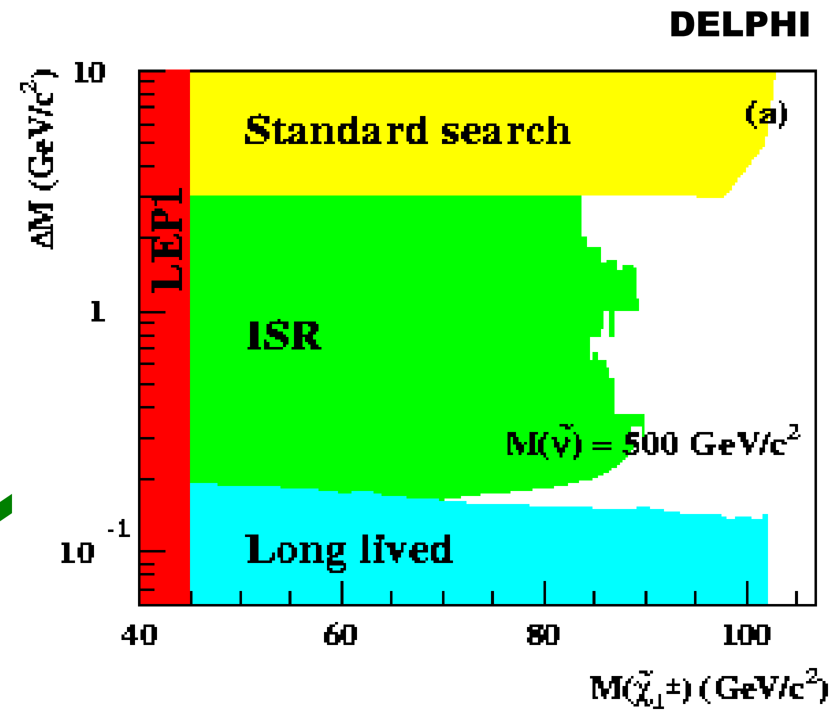
- Low visible energy
- Low transverse momentum
- Very high cross-section

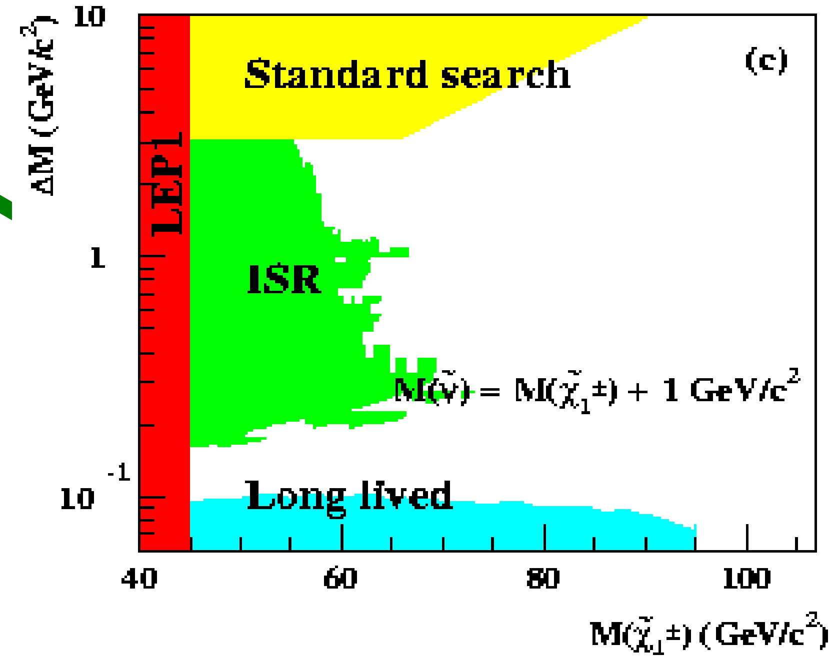
=> ISR tag !



Signal cross-section still OK

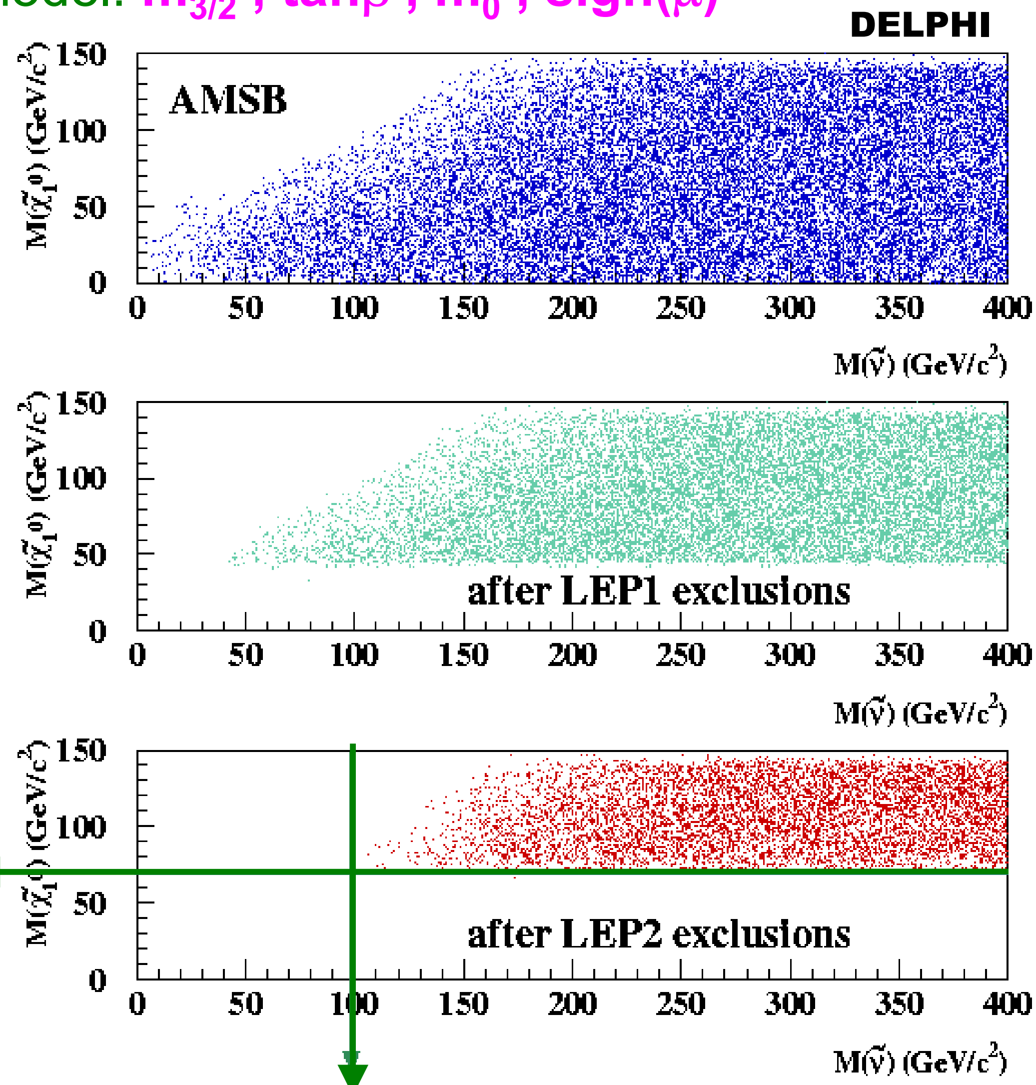
$\tilde{\nu}$ mass dependence!





AMSB – Constraints on parameters

Four parameters to define minimal model: $m_{3/2}$, $\tan\beta$, m_0 , sign(μ)



- LEP1 constraints (Z width)
- SM Higgs search

  $M_H > 114.4$ GeV/c^2 @ 95% CL
- Invisible Higgs search
- Small ΔM chargino search
- Search for $\tilde{\chi}^{\pm} \rightarrow \tilde{\nu}\, l^{\pm}$

$m(\tilde{\chi}_1) > 68$ GeV/c^2

AMSB scan with **Isajet 7.63**

$1 < m_{3/2} < 50$ TeV/c^2

$0 < m_0 < 1$ TeV/c^2

$1.5 < \tan\beta < 45$

$m(\tilde{\nu}) > 98$ GeV/c^2

SUGRA:

Hiden ~~SUSY~~ → **Gravity** → Visible sector

• LSP dark matter candidade

• Possible FCNC problems

Explored at LEP in an exhaustive way

Searches for

- Charginos **- Sleptons**

- Neutralinos **- Squarks**

1) Searches conducted in "model-independent" way:

- Minimal set of assumptions
- Interpretations in terms of involved masses/cross-sections

"Baseline" search + "difficult cases/corners"

2) Common interpretations in terms of model parameters

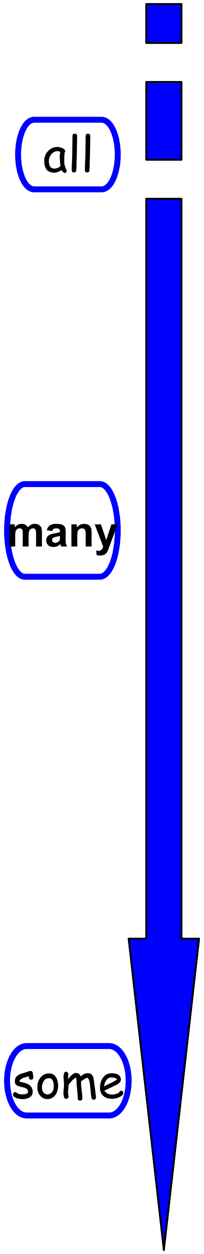
=> Manageable number of free parameters

=> Specific scenarios

⇒" LEP-CMSSM"

⇒ mSUGRA

MSSM => SUGRA => CMSSM => mSUGRA



- Minimal particle/field content (MSSM)
- Soft SUSY breaking
- R parity conservation $R_p = (-1)^{3B-L+2S}$
- Gravity mediated SUSY breaking
- Neutralino LSP
- Assumptions on BR's — e.g. $BR(\tilde{p} \rightarrow p\,LSP) = 1$
- Gaugino mass unification $m_{1/2}$ — $M_1 = \frac{5}{3}\tan^2\theta_W M_2 \approx 0.5 M_2$
- Assumptions on sfermion masses — e.g. Heavy sfermions
- Assumptions on trilinear couplings — e.g. No mixing
- sfermion mass unification m_0
- Scalar mass unification
- Unification of trilinear couplings A_0
- EW breaking scale

"LEP-CMSSM"

$$m_0, m_{1/2}, A_\tau, A_b, A_t, \tan\beta, \mu$$

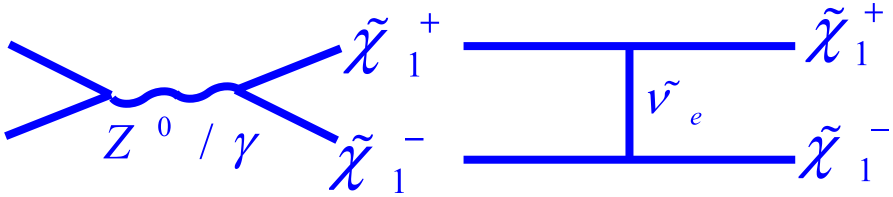
mSUGRA

$$m_0, m_{1/2}, A_0, \tan\beta, \mathrm{sign}(\mu)$$

Chargino searches

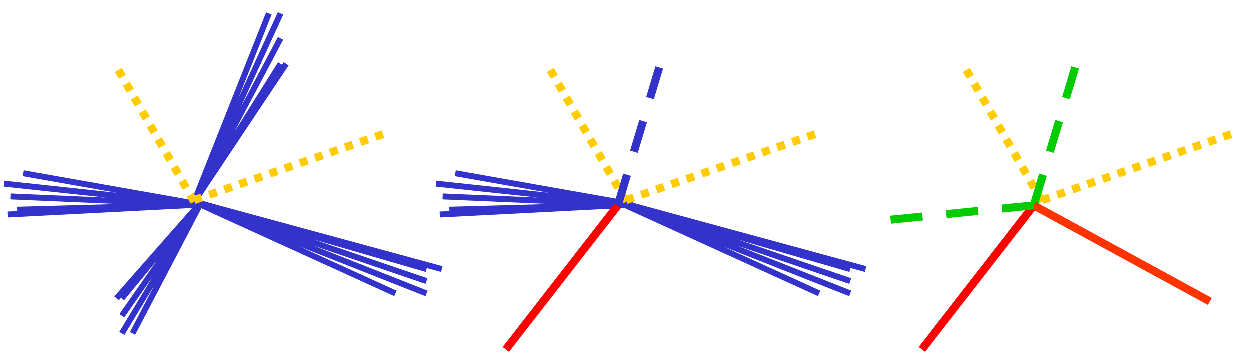
Main direct SUSY detection channel in large region of parameter space

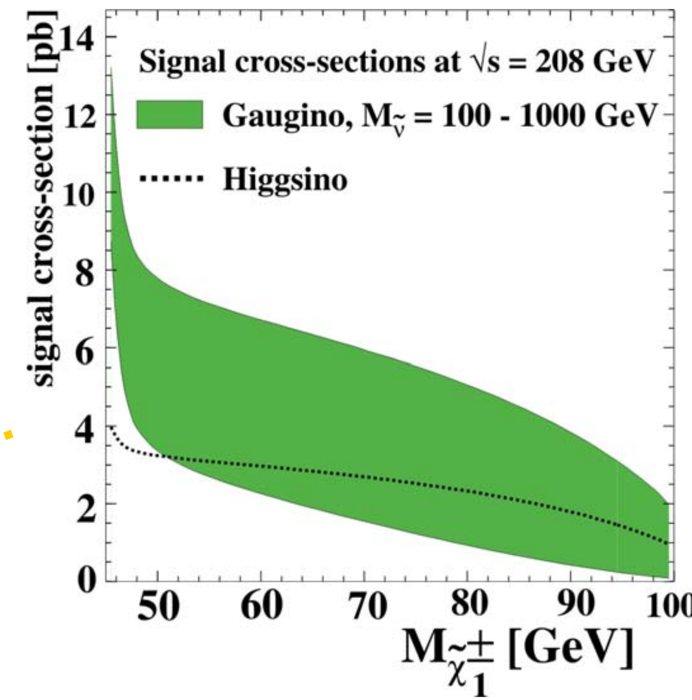
=> Large cross-sections



Negative interference. Is there a light sneutrino?

$$\tilde{\chi}_1^{\pm} \rightarrow \tilde{\chi}_1^0 W^* \rightarrow \tilde{\chi}_1^0 jj \,, \tilde{\chi}_1^0 \ell\nu$$



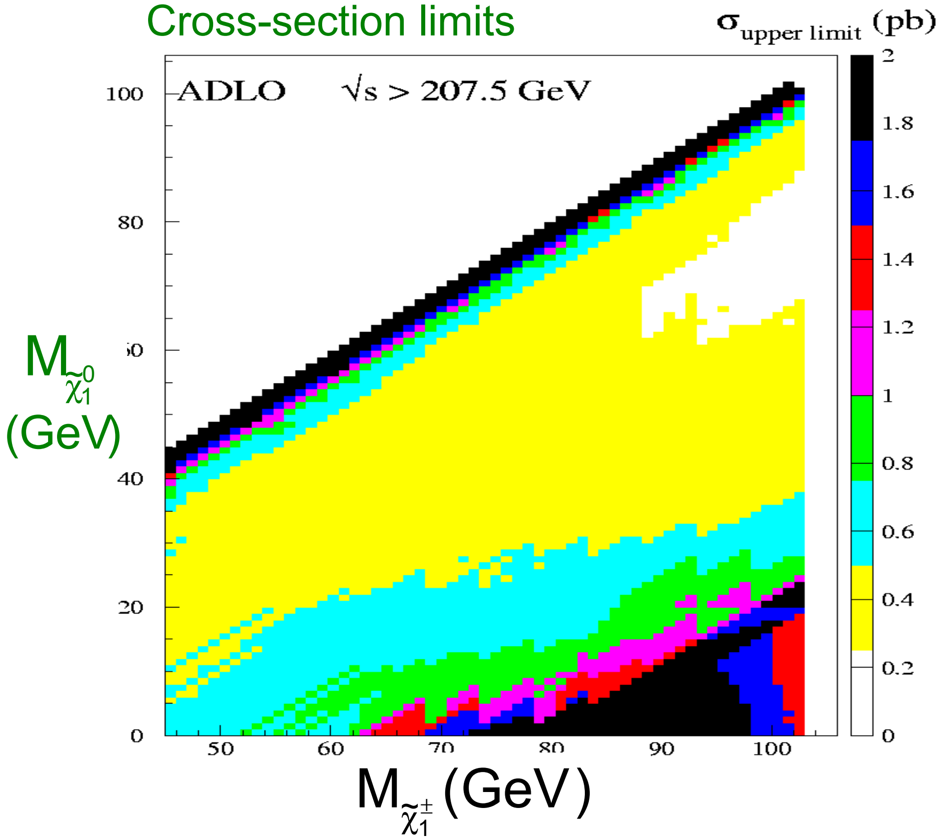


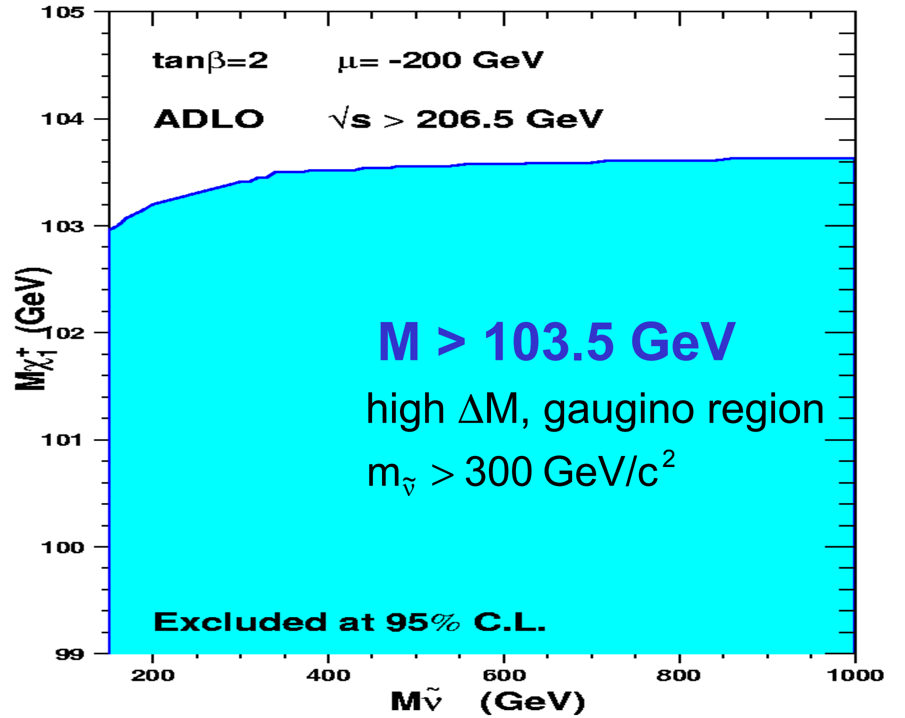
- Leptonic BR enhanced if sleptons are light
- cascades $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \gamma$

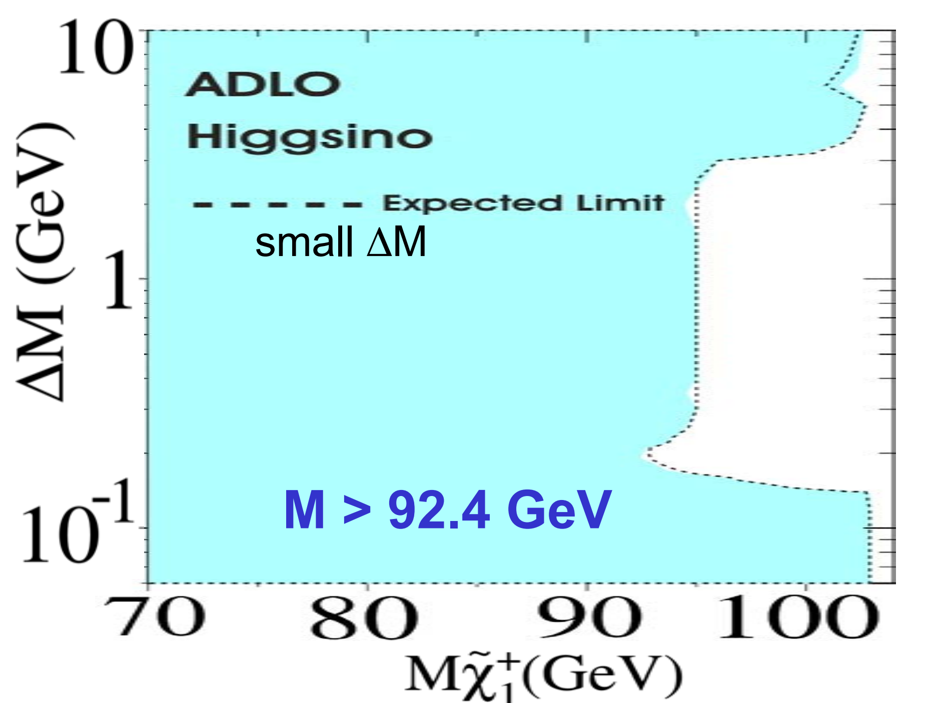
Chargino searches

Exclusion nearly up to kinematic limit

Cross-section limits



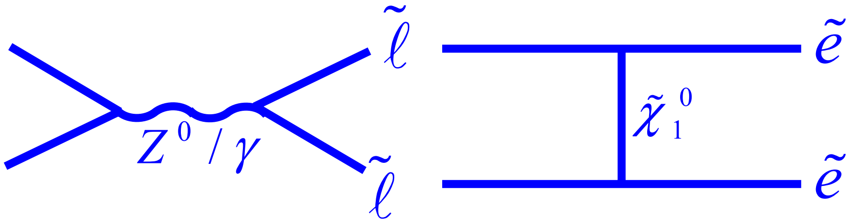


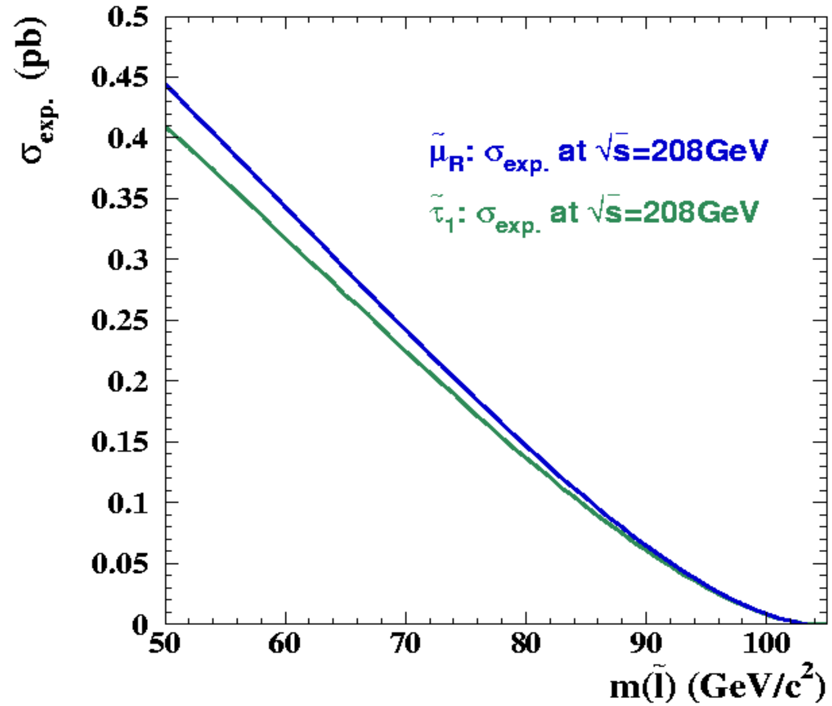


If sleptons are light

- Cross-sections may be suppressed
- Undetectable final states may arise

Slepton searches





Smuons

Almost model-independent

Selectrons

t-channel => cross-section very model-dependent

Staus

Mixing: Stau could be charged LSP

affects cross-section => decouple from Z

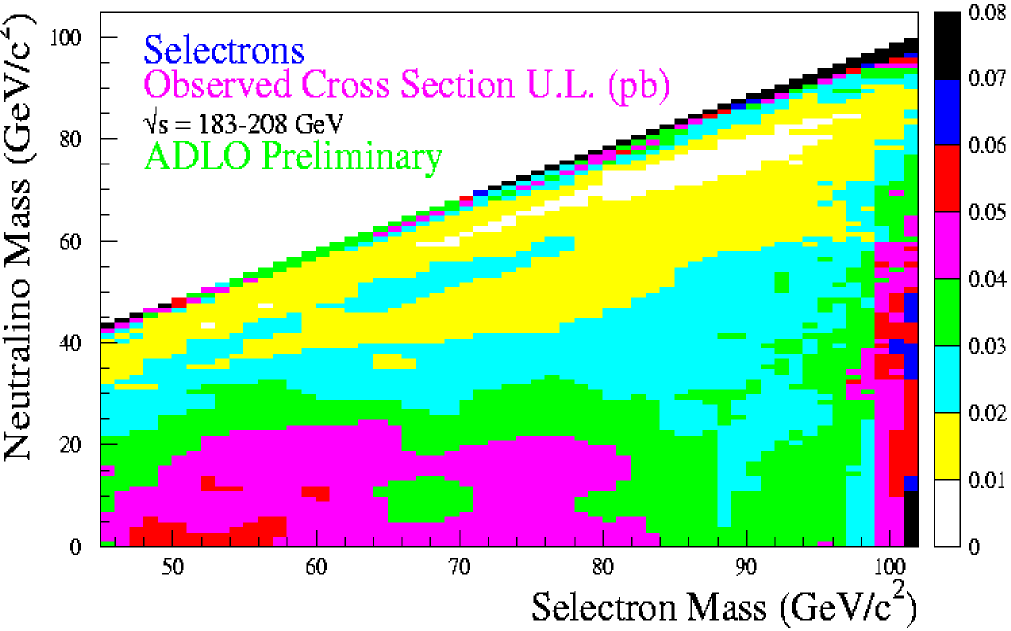
- No mixing θ=0
- Minimal cross-section

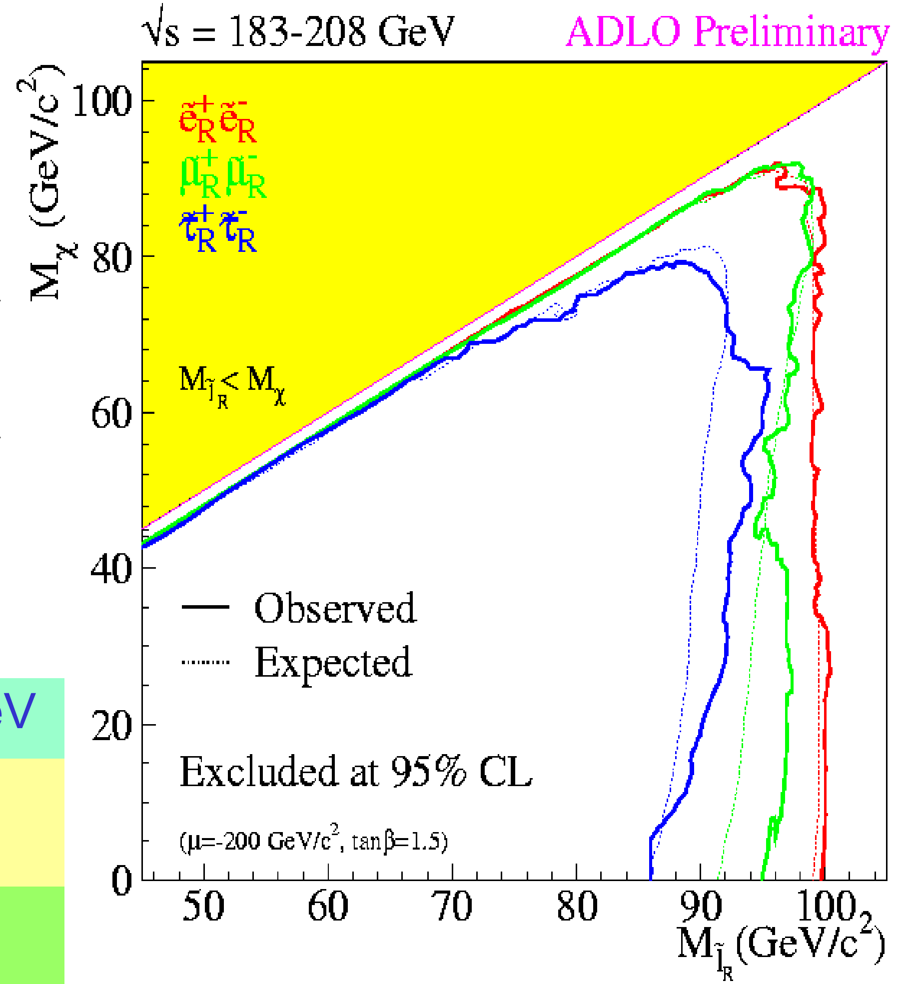
$$\tilde{\ell} \rightarrow \ell \, \tilde{\chi}_1^0$$

BR:
- BR = 1
- BR @ μ=-200, tan β=1.5

=> 2 acoplanar leptons

Slepton searches





		$m_{\tilde{\chi}^0_1} = 0$ GeV	$m_{\tilde{\chi}^0_1} = 40$ GeV
$\tilde{e}$	RR	99.6	99.4
$\tilde{\mu}$	RR	94.9	96.5
$\tilde{\tau}$	RR	85.9	92.5
	Z – decoupled	85.0	91.7

If light enough to be observed, seriously affect production and decay of charginos and neutralinos

More constrained models : CMSSM

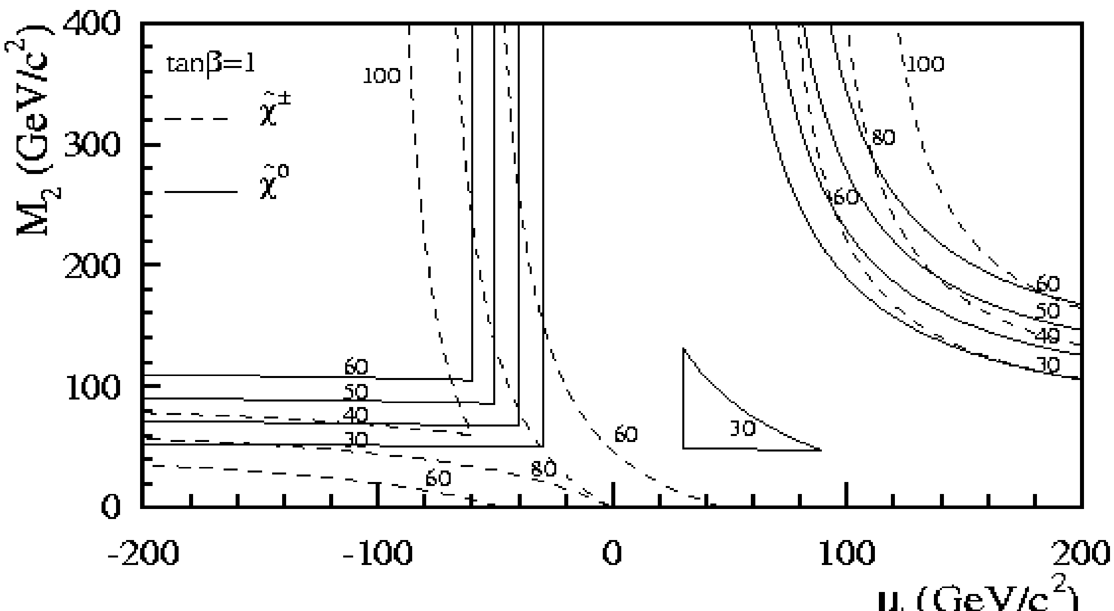
$m_0, m_{1/2}, \tan\beta, \mu, A_\tau, A_b, A_t$

… Combining negative results of different searches:

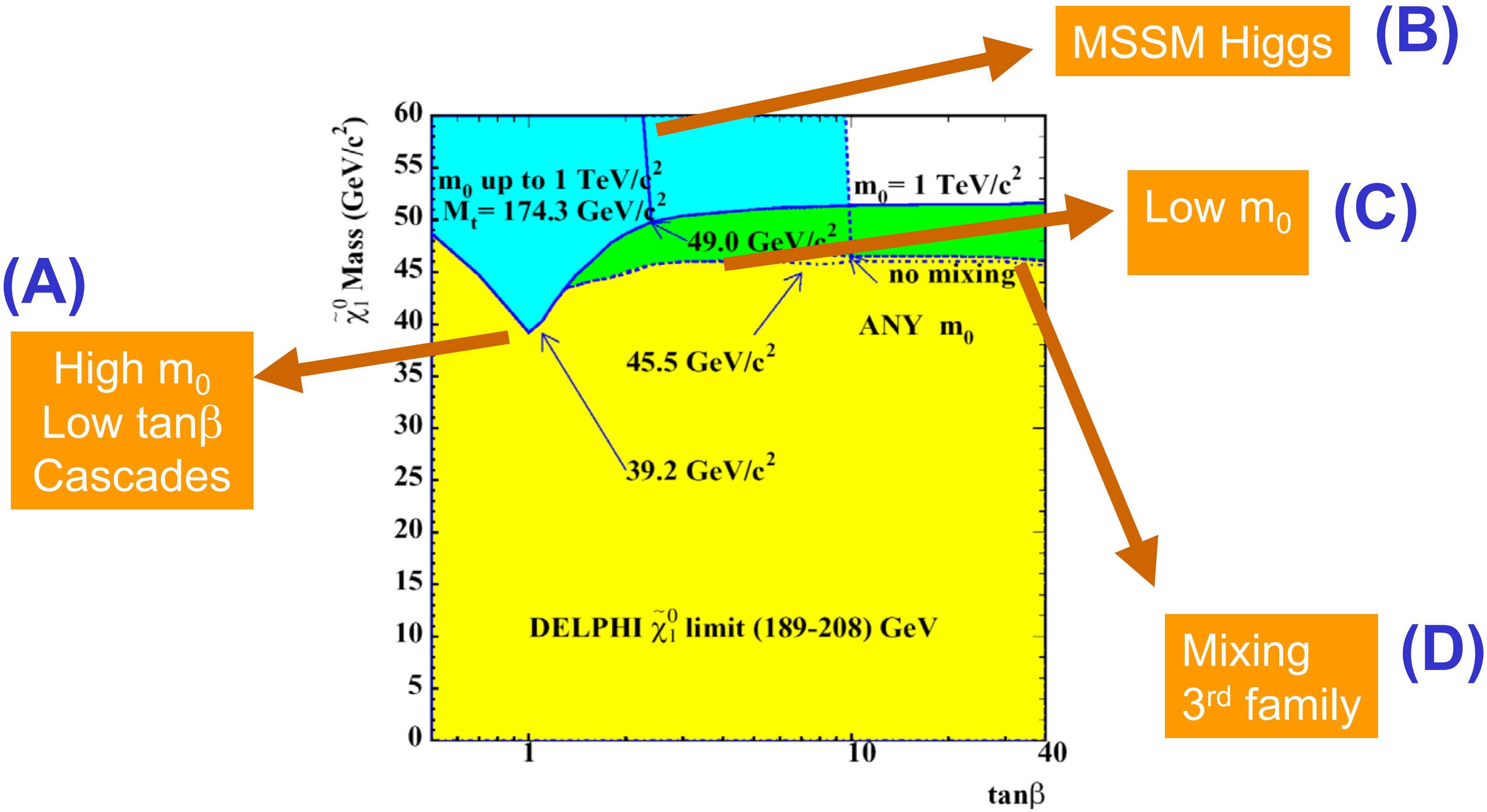
Charginos   Higgs   Sleptons   Neutralinos   Squarks

Exclusion in (M_2, μ) plane for different tanβ, m_0 values

Lower limits on smasses (M_{LSP})



LSP mass limit in CMSSM



(A) LSP mass limit in CMSSM – High m_0

Heavy sfermions => no effect on phenomenology

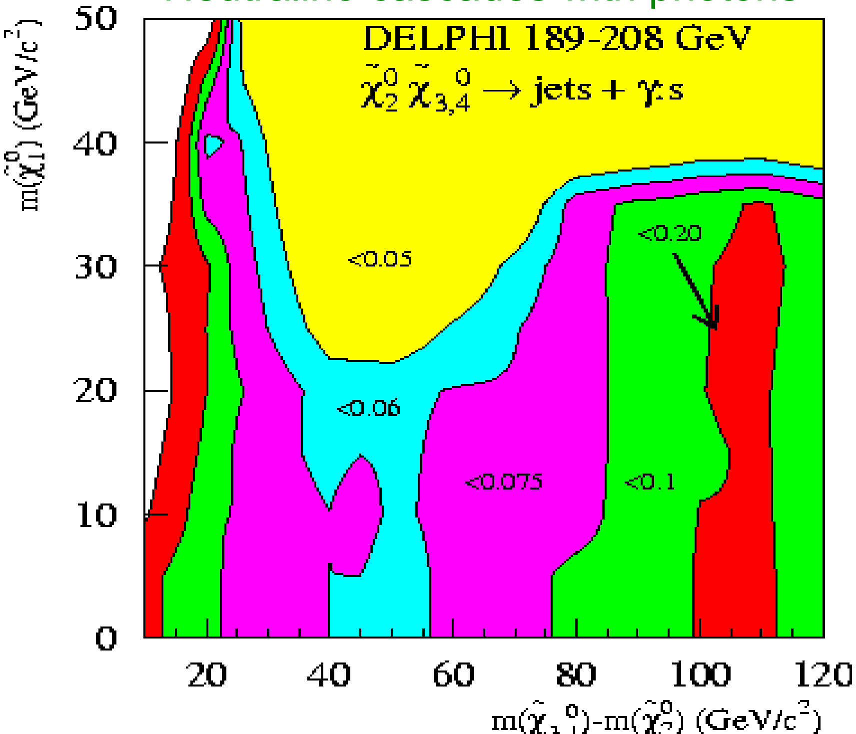
Chargino exclusion dominates

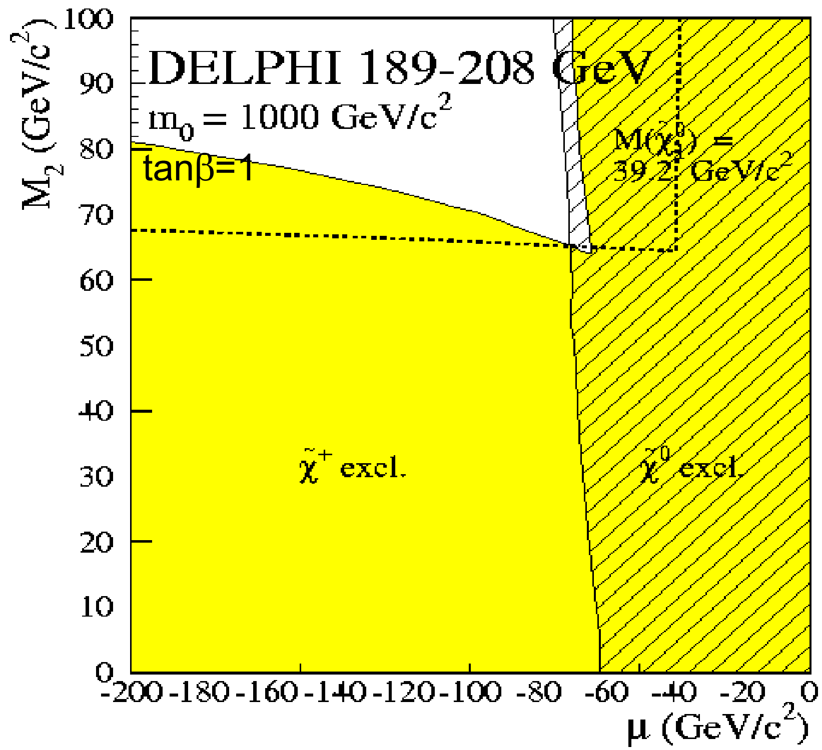
Cascades:

$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \gamma$ => Cover topologies with γ's in chargino/neutralino searches (low M_2 & μ)

$\tilde{\chi}_3^0 \tilde{\chi}_2^0, \tilde{\chi}_4^0 \tilde{\chi}_2^0$ => Allow to go slightly beyond chargino kinematic limit (M_2<120)

Neutralino cascades with photons





(B) LSP mass limit in CMSSM – Higgs

Low tanβ covered by Higgs exclusions if included

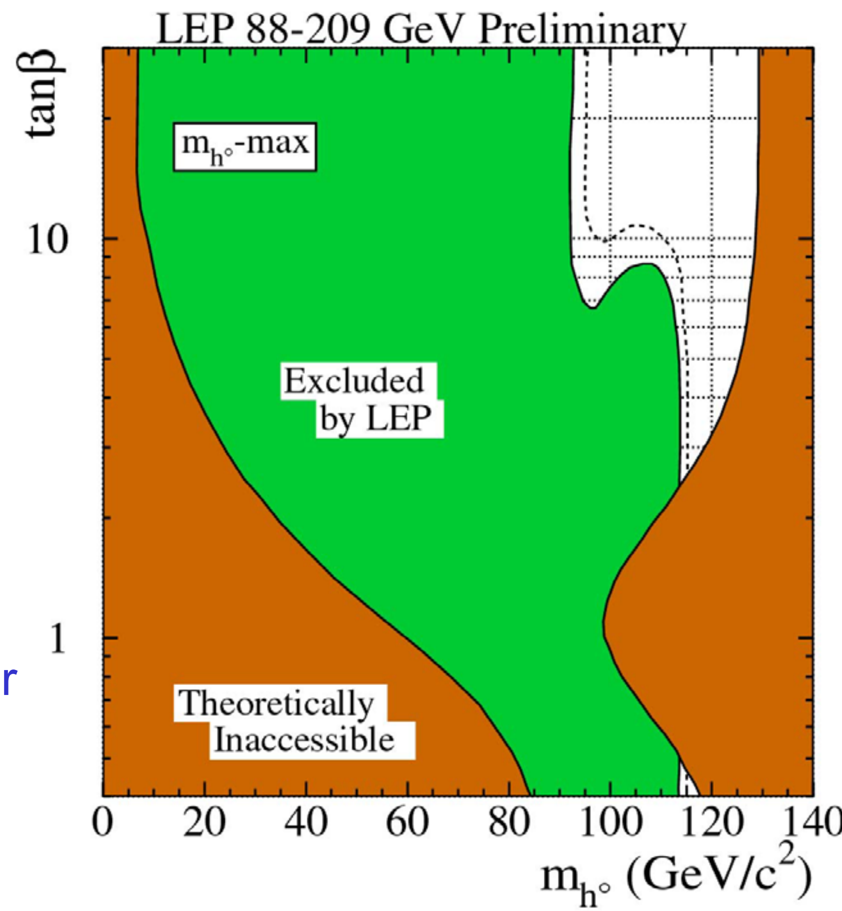
$0.54 < \tan\beta < 2.36$ ($M_{top}=174.3$ GeV/c²)

MSSM Higgs search in maximal M_{h0} scenario:

$M_A \leq 1000$ GeV/c², $A_t - \mu/\tan\beta = \sqrt{6}$ TeV/c²

$A_t - \mu/\tan\beta \Rightarrow M_{h0}$ maximal

M_{h0} maximised by tuning mixing in the stop sector



Dependence on m_{top}

$0.6 < \tan\beta < 2.0$ ($M_{top}=179$ GeV/c²)

(C) LSP mass limit in CMSSM – Low m_0

Light Sleptons:

Effect on chargino cross-section

(OK down to m_0~ 200 GeV/c^2)

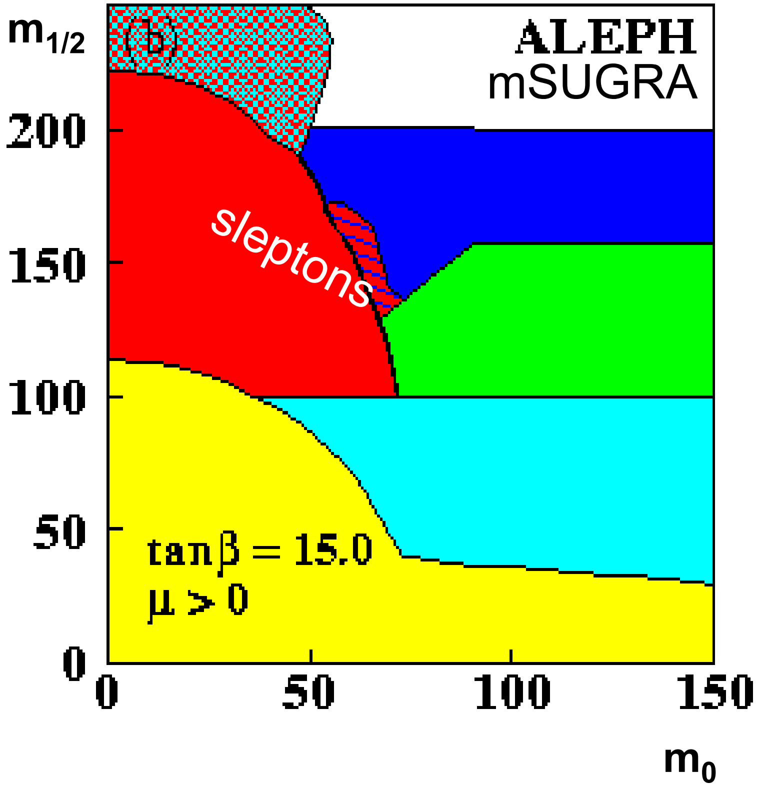
=> Increased neutralino cross-section!

Chargino invisible decays:

$$\tilde{\chi}_1^{\pm} \rightarrow \tilde{\nu}\ell^{\pm} \quad \text{with} \quad m(\tilde{\chi}_1^{\pm}) \approx m(\tilde{\nu})$$

=> Charginos cannot exclude

=> Use sleptons direct search:



GUT scale unification:

$$m_{\tilde{f}} \equiv m_{\tilde{f}}(\tan\beta, m_0, M_2)$$

$$\tilde{e} \text{ search} \Rightarrow m_{\tilde{e}} \text{ limit} \Rightarrow m_{\tilde{\nu}} \text{ limit} \Rightarrow m_{\tilde{\chi}_1^{\pm}} \text{ limit} \Rightarrow m_{LSP} \text{ limit}$$

Neutralinos can play a role in low cross-section (chargino or selectron) areas

(D) LSP mass limit in CMSSM – Mixing

$\tilde{\tau}_R, \tilde{\tau}_L \xrightarrow{\text{mixing}} \tilde{\tau}_1, \tilde{\tau}_2$

3^{rd} family L-R mixing can give light $\tilde{\tau}_1, \tilde{b}_1, \tilde{t}_1$

Mass splitting $\propto$ $A_\tau - \mu \tan\beta$, $A_b - \mu \tan\beta$ } Large $\tan\beta$

$A_t - \mu / \tan\beta$

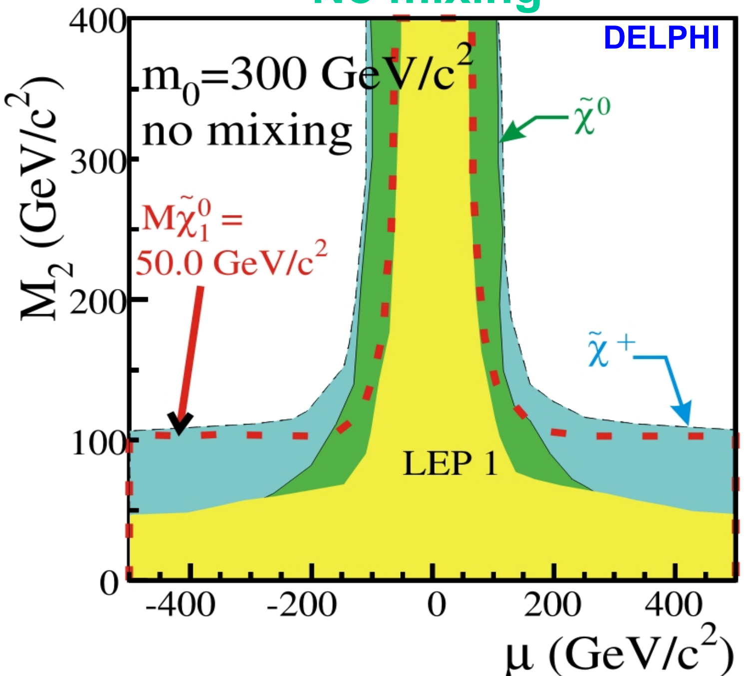
More studied cases:

- No mixing
- A=0

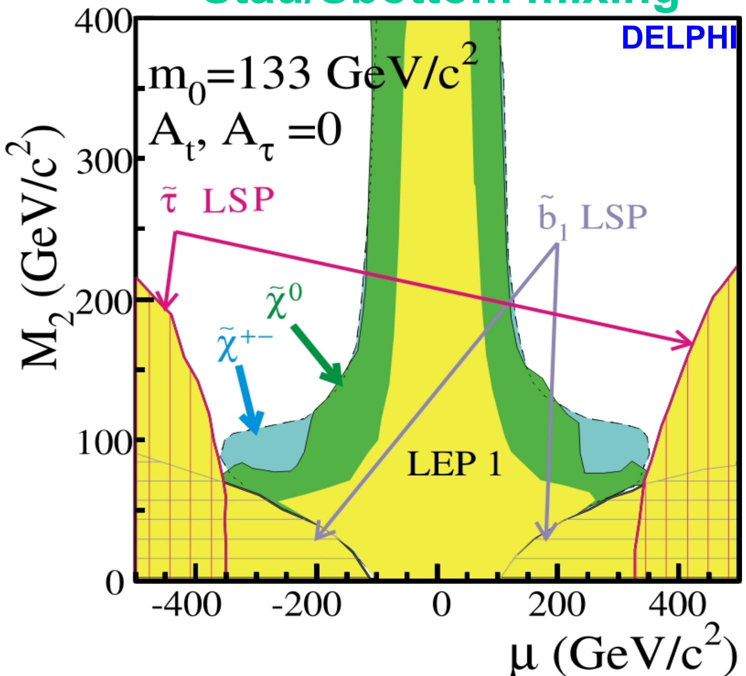
then study variation with mixing

Example:
($\tan\beta = 35$)

No mixing



Stau/Sbottom mixing

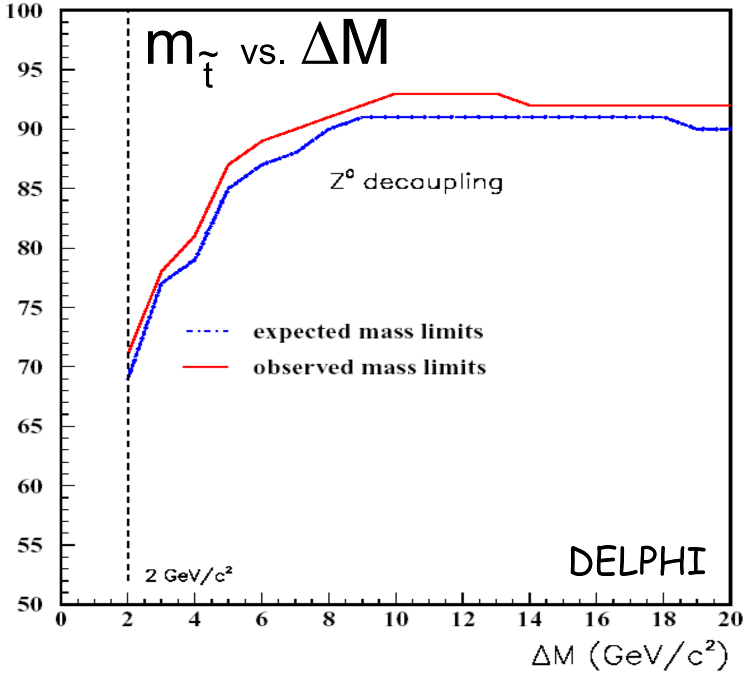


LSP mass limit in CMSSM – Mixing

Light squarks

direct squark search...

... down to low ΔM

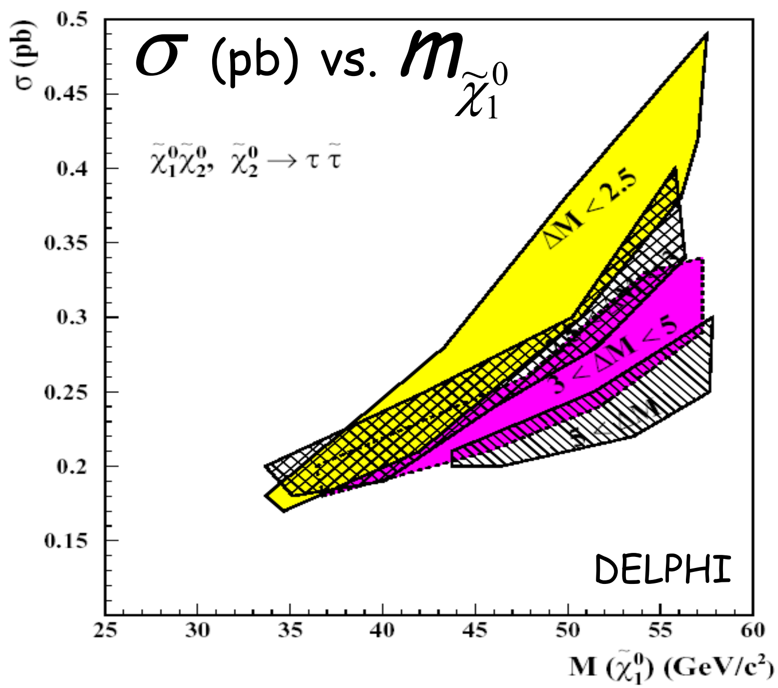


Light stau => blind spot in $\tilde{\chi}_1^{\pm}$ search

$$\tilde{\chi}_1^{\pm} \rightarrow \tilde{\tau}_1 \nu \rightarrow \tilde{\chi}_1^0 \tau \nu, \quad m(\tilde{\tau}_1) \approx m(\tilde{\chi}_1^0)$$

Only visible channels:

$\tilde{\chi}_1^0 \tilde{\chi}_2^0, \tilde{\chi}_2^0 \tilde{\chi}_2^0$ with $\tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1 \tau$



Obtained limit (set by squarks and stau cascades) robust with mixing

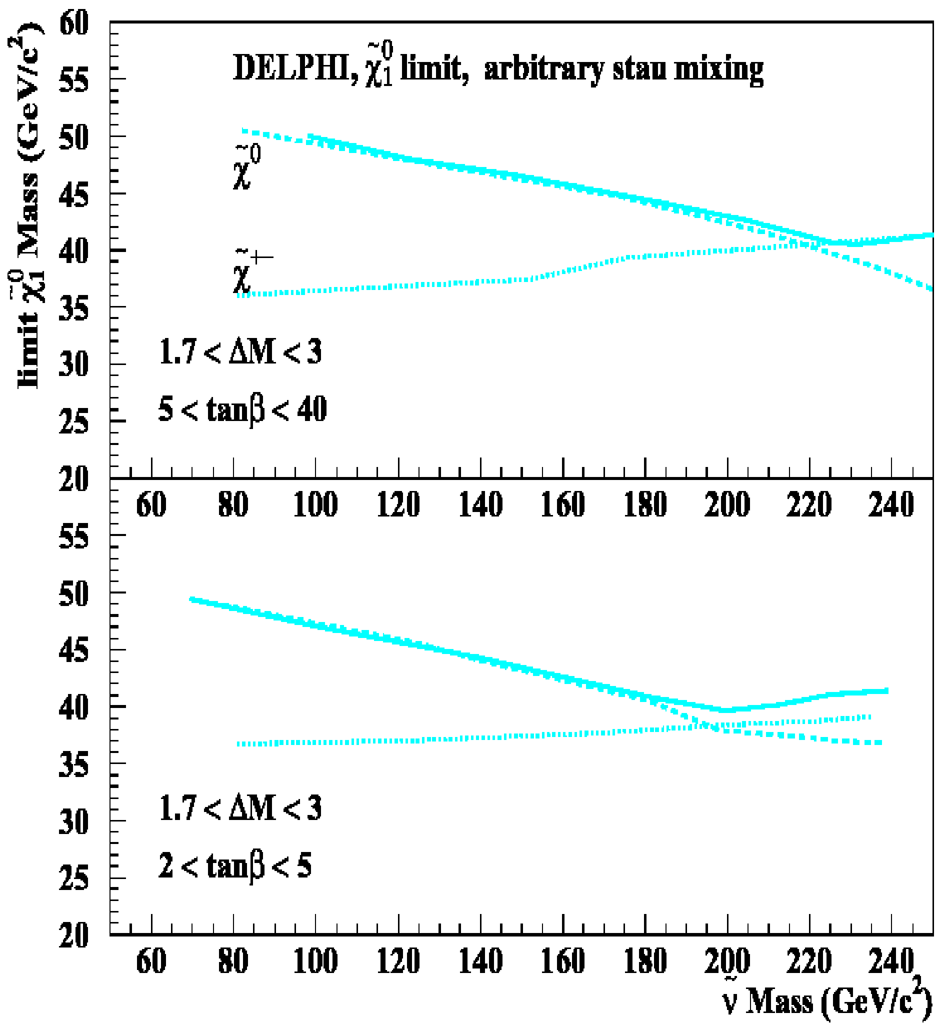
Invisible higgs search can exclude some points but not for any mixing

Stau mixing

A conservative limit on m_{lsp} valid for any $\tilde{\tau}$ mixing

model with mixing only
in the stau sector

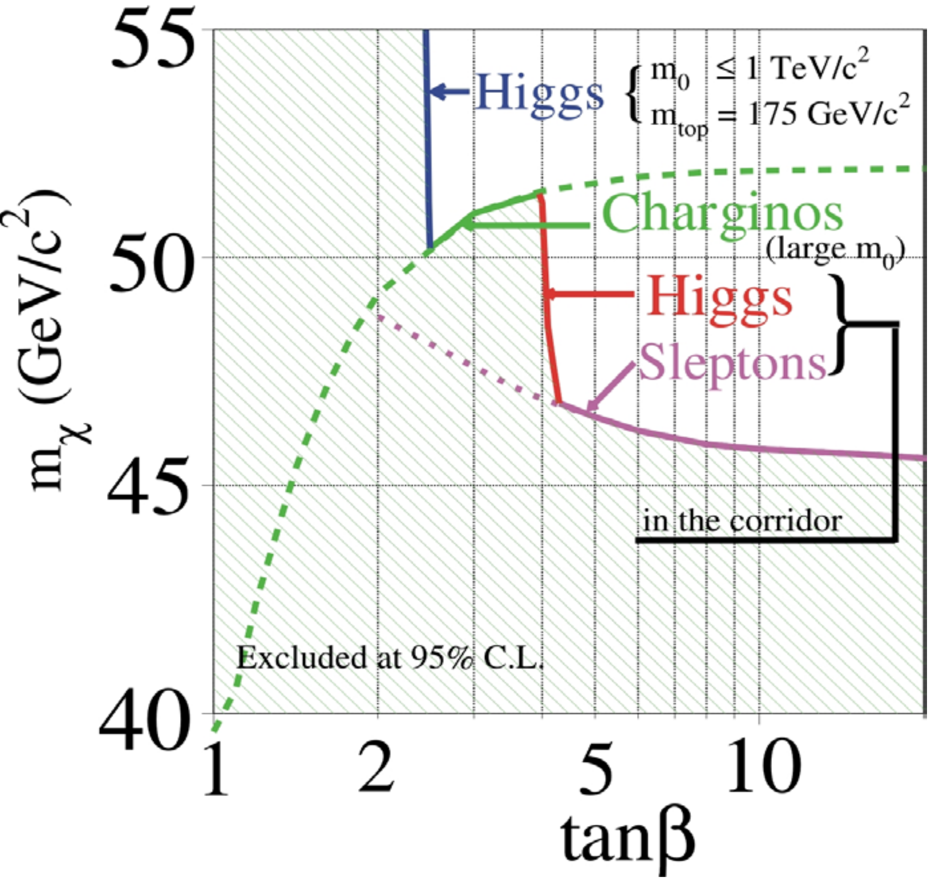
=> maximises (LSP, stau)
degeneracy region



$M_{LSP} > 39$ GeV/c^2

LSP mass limit – ADLO combinations

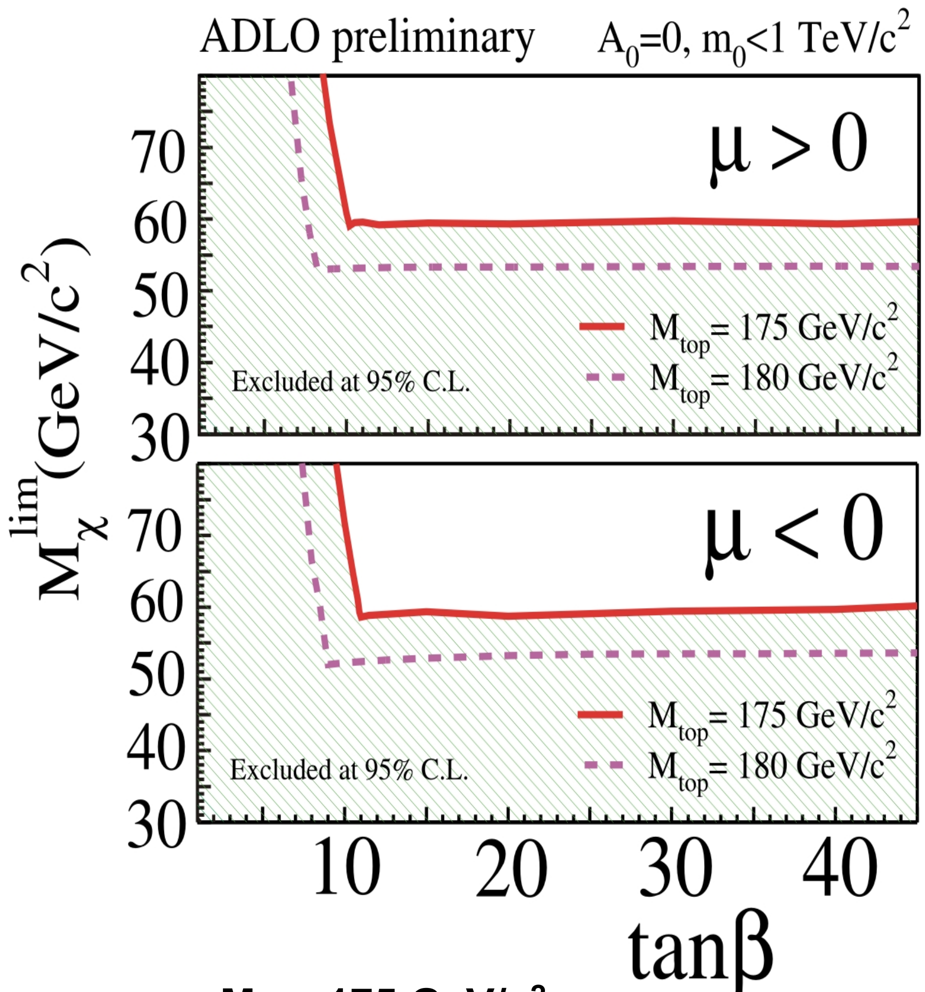
CMSSM



No stau mixing included

$M_{LSP} > 45$ GeV/c^2

mSUGRA



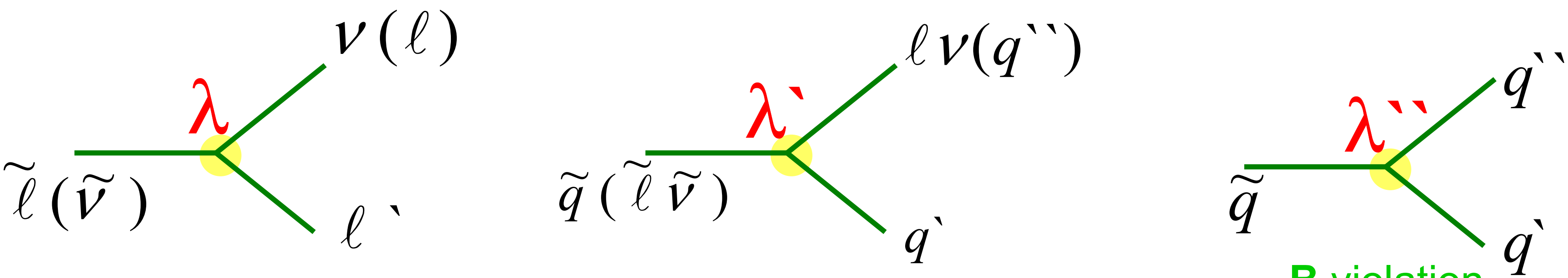
M_{top}=175 GeV/c^2:

$M_{LSP} > 59$ GeV/c^2

RpV

- Explicit RpV breaking trilinear superpotential terms:

$$\lambda_{ijk}\, L_L^i L_L^j \overline{E}_R^k + \lambda'_{ijk}\, L_L^i Q_L^j \overline{D}_R^k + \lambda''_{ijk}\, \overline{U}_R^i \overline{D}_R^j \overline{D}_R^k$$



L violation

9 couplings (i≠j)

27 couplings

B violation

9 couplings (i≠j)

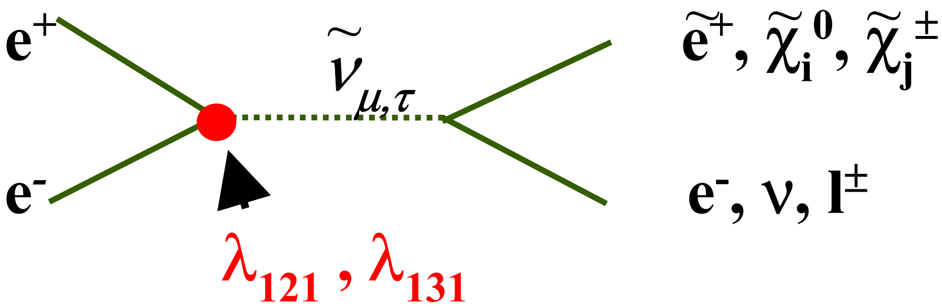
- Sfermions can decay directly into fermions
- SUSY particles can be singly produced
- The LSP is no longer stable

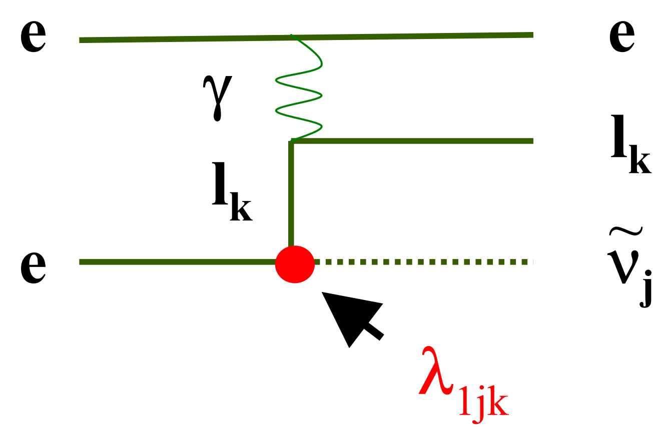
- **Only one** λ-coupling non-negligible at a time
- **Prompt decay** of sparticles (L<1 cm)

RpV

... At production

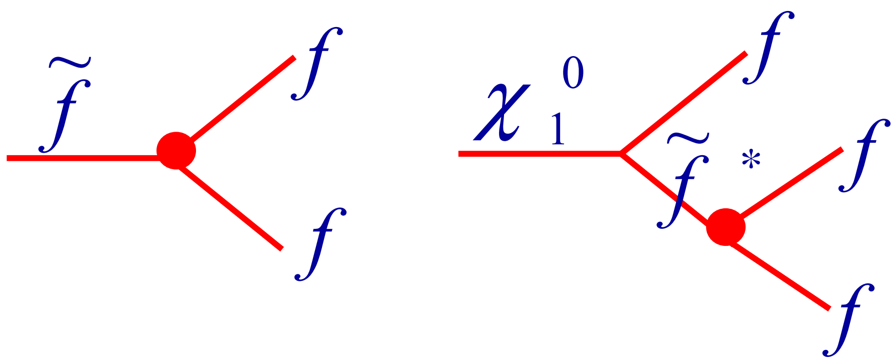
Resonant and non-resonant sneutrino production



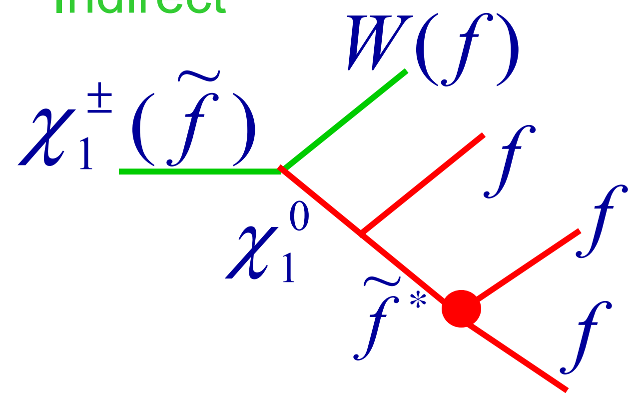


... At decay

Direct...



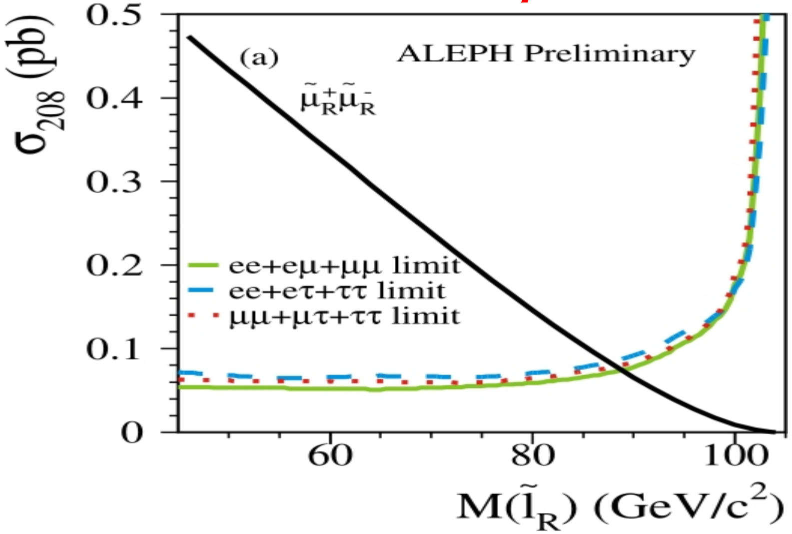
Indirect

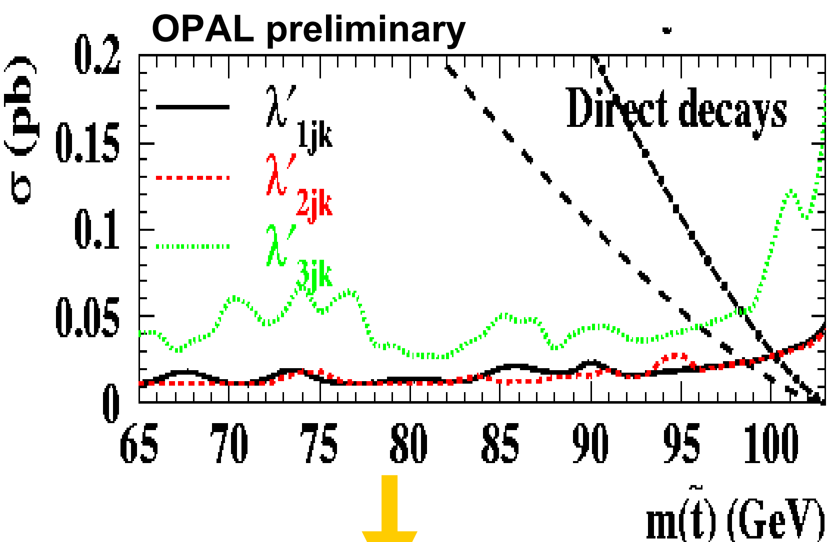


Different channels and couplings => many possible final state topologies !!

RpV - examples

Direct Decays

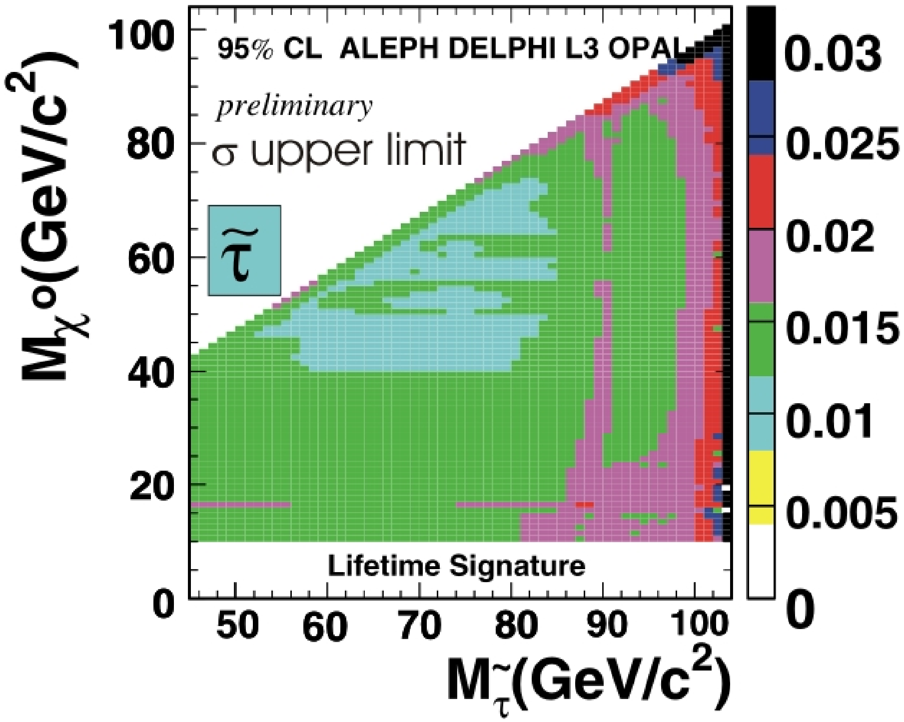




Limits on RpV couplings

λ, λ', λ''

Indirect Decays (ADLO)



Limits on masses and parameter space regions

Indirect decays tend to dominate, when kinematically allowed

SUSY at LEP - Summary

... Many analyses, scenarios, **results**!

- Cross-section limits: ≈ model-independent
- Mass limits => Assumptions (BR, ΔM, m, ...)
- Exclusion of parameter space regions

More constrained scenarios:
Need to increase predictive power...
Still trying to cover most realistic scenarios

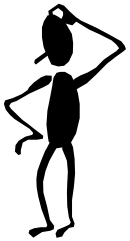
In general:

- Excluded ranges comparable in different scenarios
  - » SUSY limits proved to be robust
  - » Chargino: close to kinematic limit
  - » LSP: ~ 40 GeV/c^2
- General exclusions not easy to set

Sparticle mass limits (GeV/c^2)		
$\tilde{\chi}^{\pm}$	103.5	SUGRA, large m_0, ΔM>3
	92	CMSSM
	96	RpV “CMSSM”
	96	GMSB
	68	AMSB
$\tilde{\chi}^{0}$	45	CMSSM
	38	RpV “CMSSM”
	89	GMSB
	68	AMSB
$\tilde{\nu}$	85	RpV
	98	GMSB, slepton NSLP
$\tilde{\tau}$	85	SUGRA ΔM>15
	96	RpV (LLE), ΔM>3, $m_{\chi^0}>10$
	87	GMSB, slepton NLSP
$\tilde{b},\tilde{t}$	76	SUGRA, ΔM>7
	77	RpV (LLE), ΔM>5

Searches at LEP - Perspective

No signal in any of the channels...



Final results are currently being prepared

70% of Beyond the SM session ICHEP 2002 contributed papers

What matters now? What did Searches at LEP leave to us?

Many constraints

- Complete interpretations in the frame of models
- Complete model-independent results in case of new ideas

Important to keep LEP data accessible

Analysis experience

- Methods for sensitivy improvement
- Statistical treatment
- Generators

Searches at LEP - Perspective

LEP did a great job for the last 12 years!

...Great opportunities for searches at next colliders

Tevatron	LHC	Linear collider

Tevatron: the next step - the future is already here!

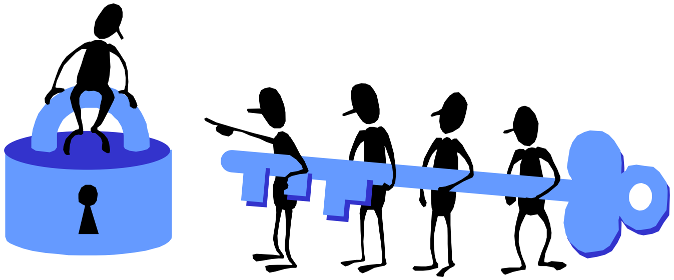
LHC: Acessing yet unexplored regions... First observations of SUSY?

LC: detailed map of SUSY

High precision measurement (masses, cross-section, couplings, mixings)

Extrapolation to GUT, Planck => origin of SUSY breaking

Most scenarios involve rich new physics at E ~ 1 TeV



In the next decade, we hope to find a key...
... At least the one leading us to the next puzzle!