Search for MSSM topologies at LEP and lower limit on LSP mass

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ALEPH

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BARI

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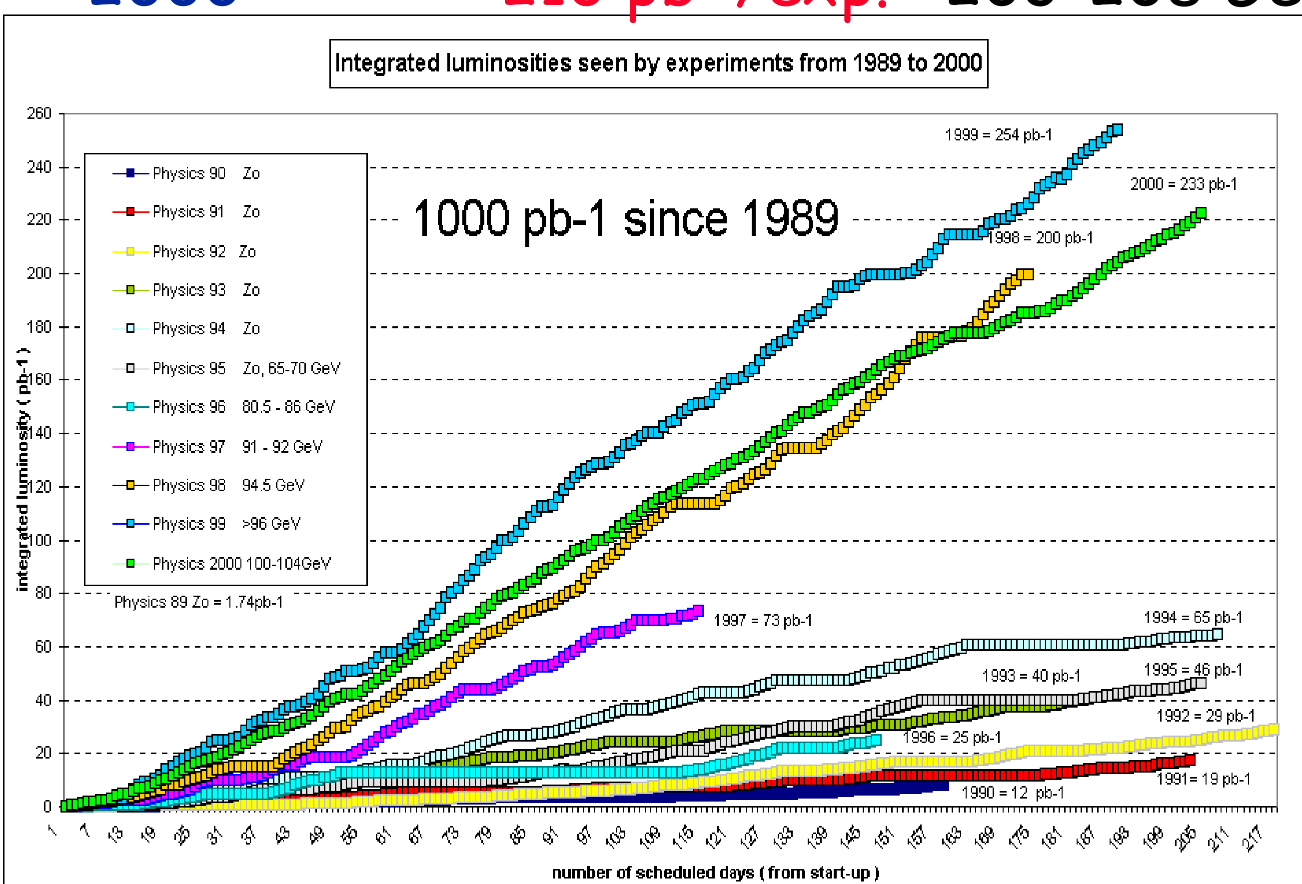
LEP performances

	$\int L dt$	$\sqrt{s}$
LEP 1	$\approx$ 175 pb^{-1}/exp.	Z peak
LEP 1.5	$\approx$ 6 pb^{-1}/exp.	130-136 GeV
1996	$\approx$ 22 pb^{-1}/exp.	161-172 GeV
1997	$\approx$ 56 pb^{-1}/exp.	183-184 GeV
1998	$\approx$ 170 pb^{-1}/exp.	189 GeV
1999	$\approx$ 240 pb^{-1}/exp.	192-202 GeV
2000	$\approx$ 210 pb^{-1}/exp.	203-208 GeV



Supersymmetry

Highly motivated theory beyond the Standard Model

The low energy formulation of SUSY can:

- Solve the hierarchy problem
- Unify the forces
- Introduce gravity

Fermion ⟷ Boson

~~SUSY~~ at Λsusy : $\Lambda_{susy} \approx 10^{11}$ GeV in MSSM

$\Lambda_{susy} \approx 100 - 1000$ TeV in GMSB

NEW particles are visible at low energy (< 1 TeV)

Minimal particle content

$\Rightarrow$ $h^0, A^0, H^{\pm}$ et H^0

$\Rightarrow$ $\tilde{l}$ (sleptons)

$\Rightarrow$ $\tilde{q}$ (squarks)

$\Rightarrow$ $\tilde{g}$ (gluino)

$\Rightarrow$ $\tilde{G}$ (gravitino)

$\tilde{W}^{\pm}$, $\tilde{H}^{\pm}$ mixing $\Rightarrow$ $\tilde{\chi}^{\pm}{}_{1-2}$ (charginos)

$\tilde{W}^0$, $\tilde{B}^0$, $\tilde{H}^0_1$, $\tilde{H}^0_2$ mixing $\Rightarrow$ $\tilde{\chi}^0{}_{1-4}$ (neutralinos)

SM couplings ➡ Sizeable x-sections at LEP

MSSM parameters

Gaugino masses M_1, M_2, M_3

Higgs mass μ

$\frac{\langle H_2^0 \rangle}{\langle H_1^0 \rangle}$ $\tan\beta$

Sfermion masses $m_{\tilde{q}R}$ $m_{\tilde{q}L}$ $m_{\tilde{l}_R}$ $m_{\tilde{l}_L}$

Trilinear couplings $A_{\tilde{l}}$ $A_{\tilde{q}}$

Mass of CP-odd Higgs m_A

CMSSM

Gaugino masses unification @ GUT $m_{1/2}$

$M_1:M_2:M_3=\alpha_1:\alpha_2:\alpha_3$

Scalar masses unification but the Higgs@ GUT m_0

$$m_{\tilde{l}R}^2 = m_0^2 + 0.15 \cdot m_{1/2}^2 + \ldots$$
$$m_{\tilde{l}_L,\tilde{\nu}R}^2 = m_0^2 + 0.5 \cdot m_{1/2}^2 + \ldots$$
$$m_{\tilde{q}}^2 = m_0^2 + 6 \cdot m_{1/2}^2 + \ldots$$

Scalar and gaugino mass related

Trilinear couplings unification @ GUT A_0

mSUGRA

All scalar masses unification — m_A not free param

Dynamic EWSB — $|\mu|$ fixed

Only 5 parameters left:

$m_{1/2}$ m_0 $|\mu|$ $\tan\beta$ A_0

$$R_p = (-1)^{3B+L+2S} \quad \begin{cases} +1 & \text{particle} \\ -1 & \text{sparticle} \end{cases}$$

3 natural terms in the SUSY Lagrangian can broken Rp

$$\lambda\ ijk\ L_iL_jE_k + \lambda'\ ijk\ L_iQ_jD_k + \lambda''\ ijkU_iD_jD_k$$

L(Q) = LEPTON (QUARK) LEFT

E(U,D) = LEPTON (QUARK) RIGHT

If λ' and λ'' both present ⇒ Fast proton decay

λ, λ' and $\lambda'' = 0$ ⟶ Rp conserved

Standard MSSM scenario

Only one coupling $\lambda,\lambda',\lambda''$ dominates ⟶ Rp violated

Phenomenology depends on:

- R parity

Rp conserved scenario (RPC) :

- $\tilde{p}$ produced by pairs
- LSP stable and neutral → $\not{E}$ signature
- NLSP → LSP + S.M particle

Rp violated scenario (RPV): **Not covered here!**

- produced singly or by pairs
- LSP unstable

  Many experimental signatures
- **LSP → SM particles**

- Lightest SUSY particle (LSP):

  lightest neutralino χ_1^0

- Selected MSSM parameters

which can affect the productions and decays.
Generally only a subset of them is relevant for specific search.

$$M_2 \approx 0.8 m_{1/2}, M_1 \approx 0.5 M_2$$

$$m_{\tilde{f}(m_0, M_2, \tan\beta)},\ m_{\tilde{\chi}_1^\pm}(M_2, \mu, \tan\beta),\ m_{\tilde{\chi}_j^0}(M_1, M_2, \mu, \tan\beta)$$

BUT full LEP MSSM parameters needed for results on LSP

Sfermions production

Mass eigenstates come from diagonalisation of L-R matrix

$$\mathbf{m}^2_{\tilde f} = \begin{pmatrix} m^2_{\tilde f_L} & \Delta_{\tilde f}\, m_f \\ \Delta_{\tilde f}\, m_f & m^2_{\tilde f_R} \end{pmatrix}$$

Large mass splitting between two mass eigenstates for 3rd generation $(\tilde t, \tilde b, \tilde \tau)$

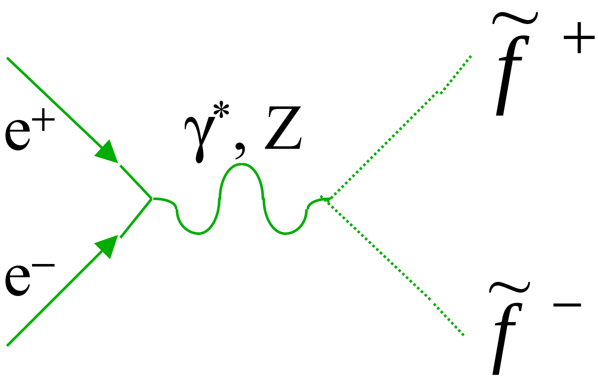
$$\Delta_{\tilde f} = \begin{cases} A_f - \mu \cot\beta & f = u\text{-type} \\ A_f - \mu \tan\beta & f = d, e\text{-type} \end{cases}$$

Parametrization

$$\begin{pmatrix} \tilde f_1 \\ \tilde f_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_{\tilde f} & \sin\theta_{\tilde f} \\ -\sin\theta_{\tilde f} & \cos\theta_{\tilde f} \end{pmatrix} \begin{pmatrix} \tilde f_L \\ \tilde f_R \end{pmatrix}$$

$$m_{\tilde\tau_1} < m_{\tilde\tau_2}$$
$$m_{\tilde b_1} < m_{\tilde b_2}$$
$$m_{\tilde t_1} < m_{\tilde t_2}$$

At large tanβ



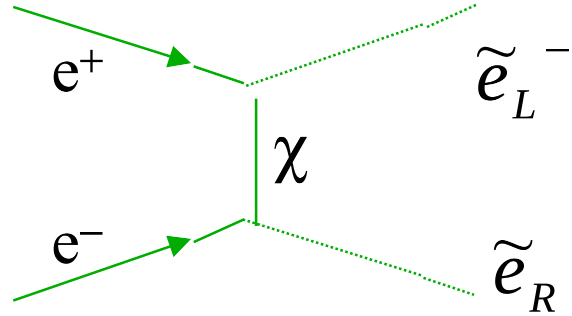
Z coupling depends on mixing and could vanish

X-sect depends on sfermion mass and mixing angle

$$m_{\tilde f_R} < m_{\tilde f_L}, \quad \sigma_{\tilde f_R} < \sigma_{\tilde f_L}$$

For the s-electron also t-channel exchange

$$\sigma = \sigma(\mathrm{M}_2, \mu, \tan\beta)$$



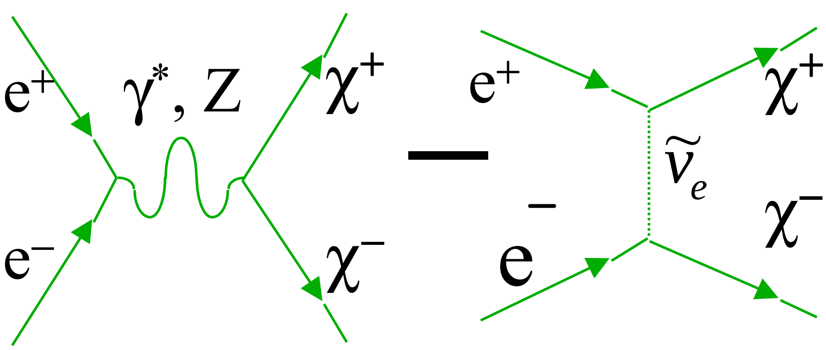
Gauginos production

·Charginos

$$\sigma = \sigma\left(M_2, \mu, m_{\tilde{\nu}}, \tan\beta\right)$$

$$\text{Higgsino like}: M_2 << |\mu|$$

$$\text{Gaugino like}: M_2 >> |\mu|$$



t-chan.

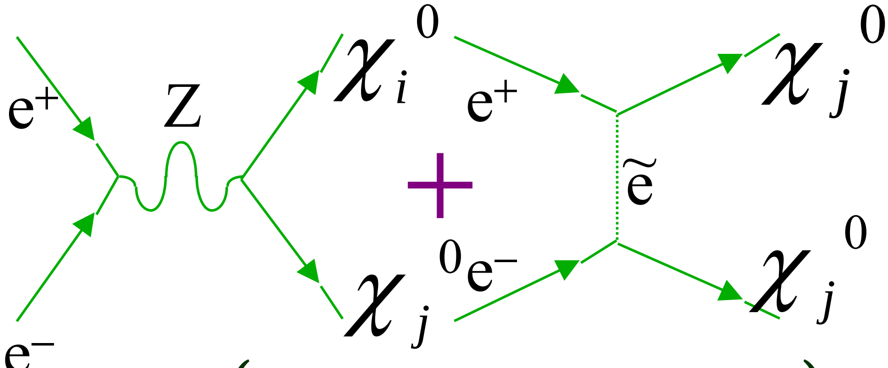
No contribution if higgsino like

reduced x-sect. if gaugino like and low m_0

·Neutralinos

$$\chi_i^0 = \underbrace{\delta_{1i}\tilde{\gamma} + \delta_{2i}\tilde{z}}_{gaugino} + \underbrace{\delta_{3i}\tilde{h}_1^0 + \delta_{4i}\tilde{h}_2^0}_{higgsino}$$

$$m_{\chi_1^0} \propto \min(|\mu|, M_2)$$



t-chan.

No contribution if higgsino like

enhanced x-sect. if gaugino like and low m_0

$$\sigma = \sigma\left(M_2, \mu, m_{\tilde{e}}, \tan\beta\right)$$

Decay topologies

$\chi^{\pm}$

$\chi^{\pm} \rightarrow W^* \chi_1^0$; $\chi^{\pm} \rightarrow \tilde{\nu} l^{\pm}, \tilde{l}^{\pm} \nu$

- 4 JETS + $\not{E}$
- 2 JETS + LEPTONS + $\not{E}$
- 2 LEPTONS + $\not{E}$

$\chi^0{}_j$

$\chi^0{}_j \rightarrow Z^* \chi^0{}_1$; $\chi^0{}_j \rightarrow \tilde{\nu}\nu, \tilde{l}^{\pm} l^{\mp}$

- 2 JETS + $\not{E}$
- 2 LEPTONS + $\not{E}$

$\tilde{l}$

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

- 2 LEPTONS + $\not{E}$

$\tilde{t}_1$

$\tilde{t}_1 \rightarrow c\, \chi^0{}_1$

- 2 JETS + $\not{E}$

$\tilde{t}_1 \rightarrow l\, \tilde{\nu}\, b$

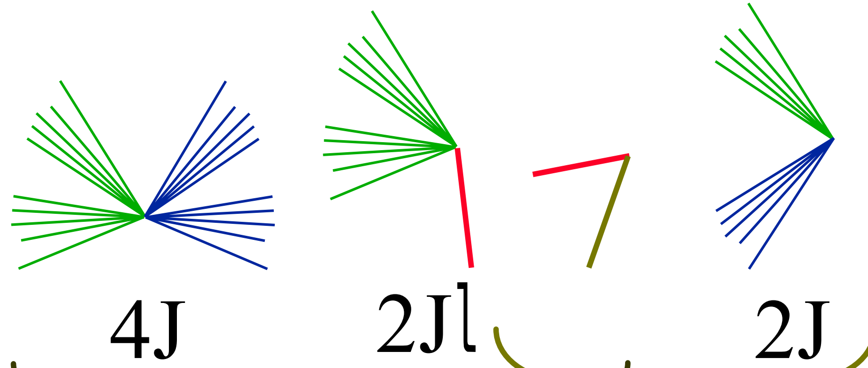
- 2 JETS + 2 LEPTONS + $\not{E}$

$\tilde{b}_1$

$\tilde{b}_1 \rightarrow b \chi^0{}_1$

- 2 JETS + $\not{E}$

$\not{E}$ signature +



$2\,\chi$ LSP's

$\chi^{\pm}$

$\tilde{\tau}$ χ^{0}_{j} $\tilde{q}$

$\not{M}$, $\not{P}$

beam axis not favorite direction → Acoplanar leptons/jets acollinearity, $\not{P}_t$

The event properties depend on

- Final states: jets, e μ, τ; N_{jets}, $N_{leptons}$
- Visible energy, which depends on

$$M_{\tilde{p}} \quad \Delta M = M_{\tilde{p}} - M_{LSP} \quad \sqrt{s}$$

BUT $E_{vis} < 3$ GeV for $\Delta M < 3$ GeV → Standard trigger efficiency too low

Detector requirements

Large acceptance

Good energy resolution

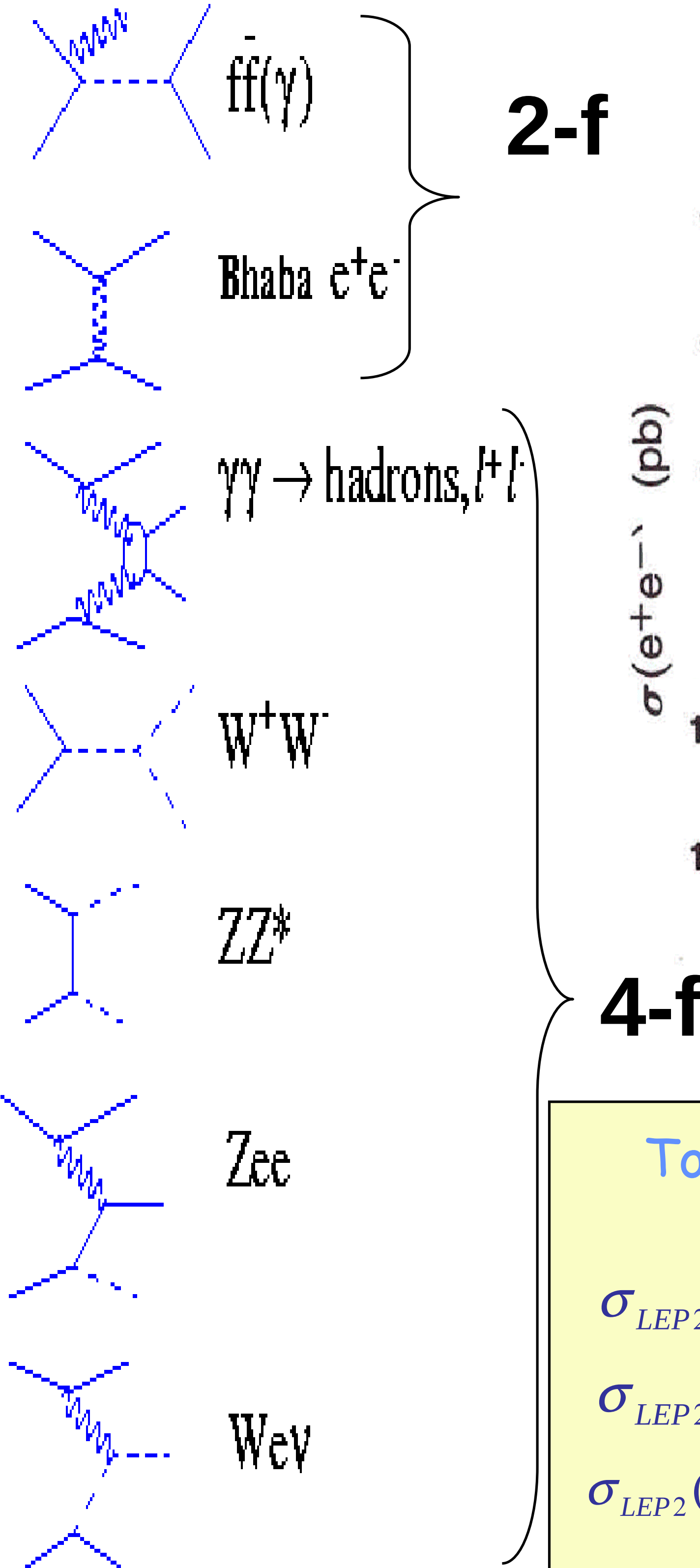
Good (θ, ϕ) resolution

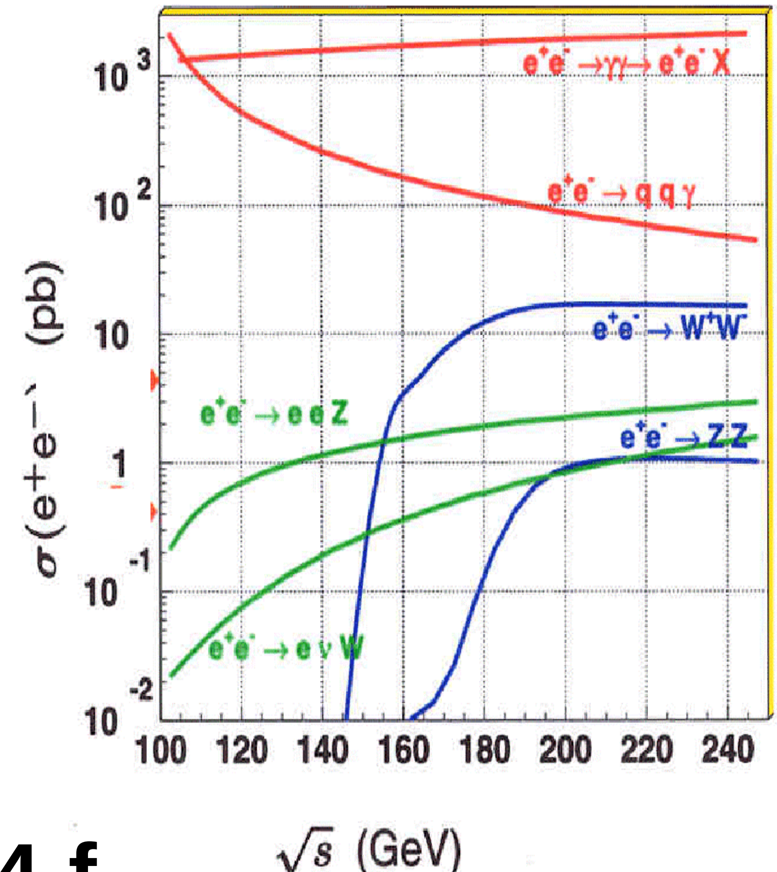
E_{vis}, M_{mis}

$P_t \approx E_{vis}$

acopl, acol

SM background





To be compared with tipical signal x-section

$$\sigma_{LEP2}(e^+e^- \to \chi^+\chi^-) \approx (2-25)\beta \;\; (pb)$$

$$\sigma_{LEP2}(e^+e^- \to \chi^0_i\chi^0_j) \approx (1-10)\beta \;\; (pb).$$

$$\sigma_{LEP2}(e^+e^- \to \tilde{\ell}^+\tilde{\ell}^-, \tilde{q}\tilde{\bar{q}}) \approx (0.5-5)\beta^3 \; (pb)$$

$$\beta = \sqrt{1 - \frac{4m^2}{s}}$$

Bkg | σ | Signatures | ΔM | $\not{E}$

Zee
Weν
ZZ
<5 pb

M_{LSP}small

Large M_{vis} and E_{vis}, energetic lepton and large Mult. low acopl

85

70

W^+W^-
<20 pb

$M_{LSP} = \frac{1}{2} M_P$

Large M_{vis} and E_{vis}, large mult., large acol, Thrust, not isolated lepton and P_{miss}

40

$f\bar{f}(\gamma)$
<100 pb

20

$M_{LSP} \sim M_P$

"γγ"

Small E_{vis}, M_{vis} efficiency low

Small Pt, small Acop, small Mult. , 2-phot kinematic cut.

Huge x-sect.
~ nb

5

Beam gas, cosmics

stable and long-lived particles : kinks and anomalous ionization

Analysis strategies

Each experiment realizes different analyses for different ΔM ranges and topologies.

Large number of selections optimized using bkg and signal MC vs ΔM and [N_{lepton} ,N_{jet} ,...]

For each selection the best combination of cuts which maximize signal/bkg ratio is used to give the highest sensitivity

LEP combination: ADLO

The analyses for each experiment have been combined by using the **Likelihood Ratio** method .
A **confidence level** is derived by comparing the two hypothesis:

- the observed events are due to signal+bkg
- the observed events are due to bkg only.

The unsubtractable bkg (with high systematic uncertainty) is not used in Confidence Level evaluation

Results

Number of candidates in agreement with the expected number of SM processes

Derive model independent upper limit on the production X-section at 95% C.L.

Plots in $(M_{\tilde{p}}, M_{LSP})$ plane

Calculate the theoretical cross section (including B.R.) as a function of CMSSM parameters and compare to experimental result.

If the theoretical x-section is higher then the upper limit then that mass point is excluded

Model dependent results :

constraints on SUSY parameters

The limits on the parameter of the model allow INDIRECT lower limit on **LSP**

Sleptons

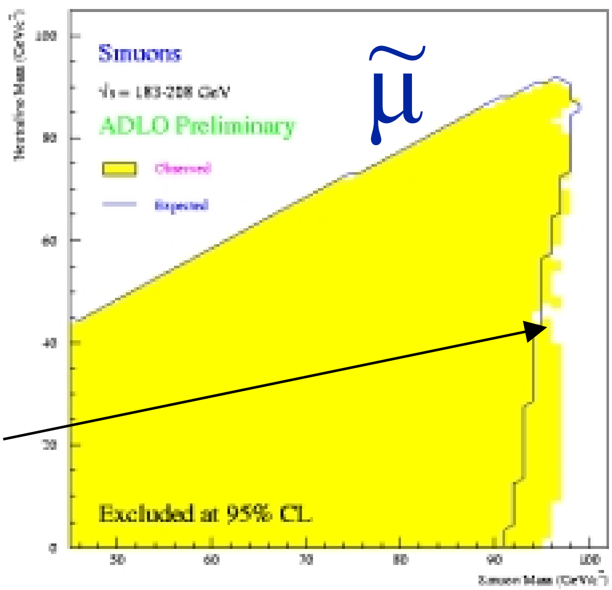
Exp. and obs. exclusion domains in the $(M_{\tilde{p}}, M_{\chi})$ plane.
The unification of gaugino masses is assumed.

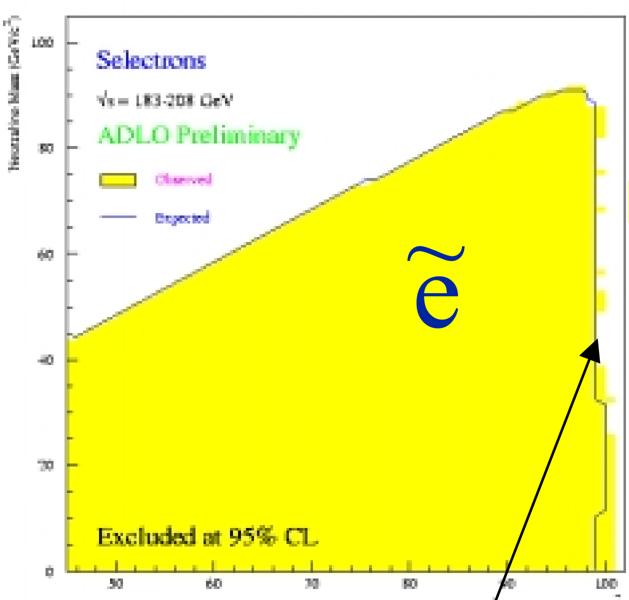
Observed mass limit exceeds the expected one because of deficit of candidates

B.R.100% $\tilde{l}_R \Rightarrow l\chi$

$m_{\tilde{\mu}} > 96.4\ \mathrm{GeV/c^2}$

M_{LSP}=40 GeV/c²





M_{LSP}=40 GeV/c²

$m_{\tilde{e}} > 99.4\ \mathrm{GeV/c^2}$

Fixed μ=-200 GeV/c² and tanβ=1.5 (small selectron cross section).

Aleph

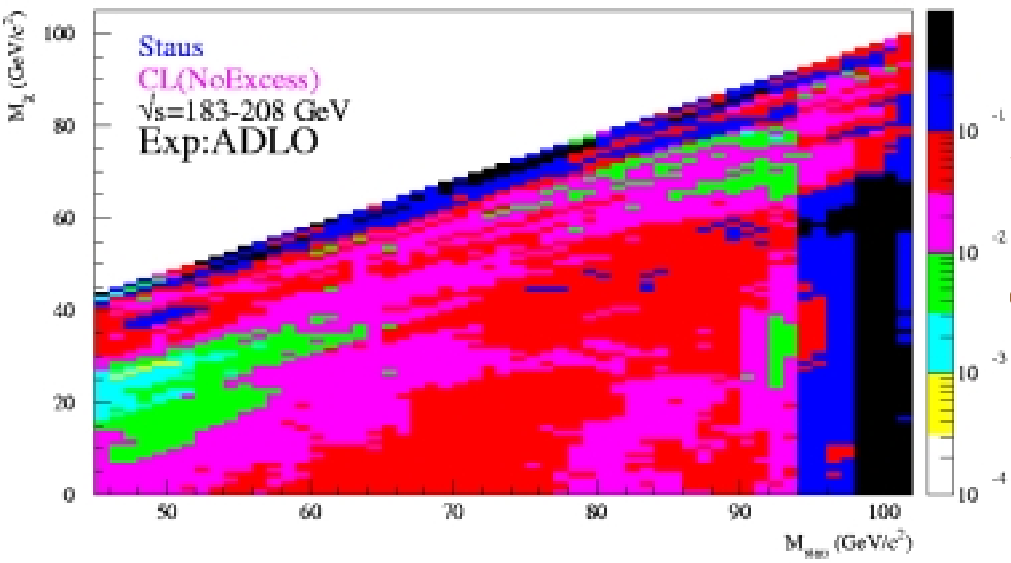
$\tilde{e}_L \tilde{e}_R$ in low ΔM analysis

The search for a pair of one high and one low momentum electrons.

$m_{\tilde{e}} > 75\ \mathrm{GeV/c^2}$ for $\tan\beta = 2$

$\mu = -200\ \mathrm{GeV/c^2}$ for any Δm

The excess in the $\widetilde{\tau}$ channel (3σ in large ΔM region) observed in the data collected at energies of 189-202 GeV has not been confirmed in last year data.



Probability of data to come from bkg only calculated for all mass points

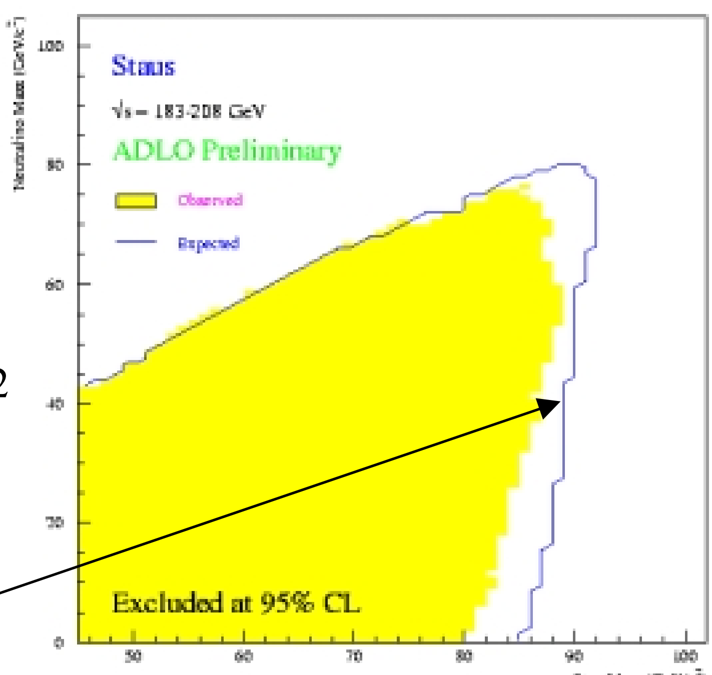
Conservative results obtained assuming no mixing
In case of mixing, conservative limits are set for θ=52⁰ (τ-Z decuples)

The observed exclusion mass limit < expected one because of the excess

Exp. $m_{\tilde{\tau}} > 89.3\,\mathrm{GeV/c^2}$

M_{LSP}=40 GeV/c²

$m_{\tilde{\tau}} > 87.1\,\mathrm{GeV/c^2}$



Squark

X-section depends on the mass and mixing

$\tilde{t}$ could be the lightest sparticle

$\vartheta_1 : 56^0$ $\tilde{t}$ - Z decoupling

$\vartheta_1 = 0 \Rightarrow$ pure $\tilde{t}_L$

Dominant decay process

$$\tilde{t} \rightarrow c\,\chi_1^0$$

(FCNC) mediated by loop diagram

$$\Gamma(\tilde{t} \rightarrow c\,\chi) = (0.3-3)\,10^{-10}\ M_{\tilde{t}}\ (1 - M^2{}_\chi / M^2{}_{\tilde{t}})^2$$

Depends on ΔM

Different topologies

ΔM> 3 GeV/c²

- Negligible stop lifetime
  acoplanar jets

<u>Standard search</u>

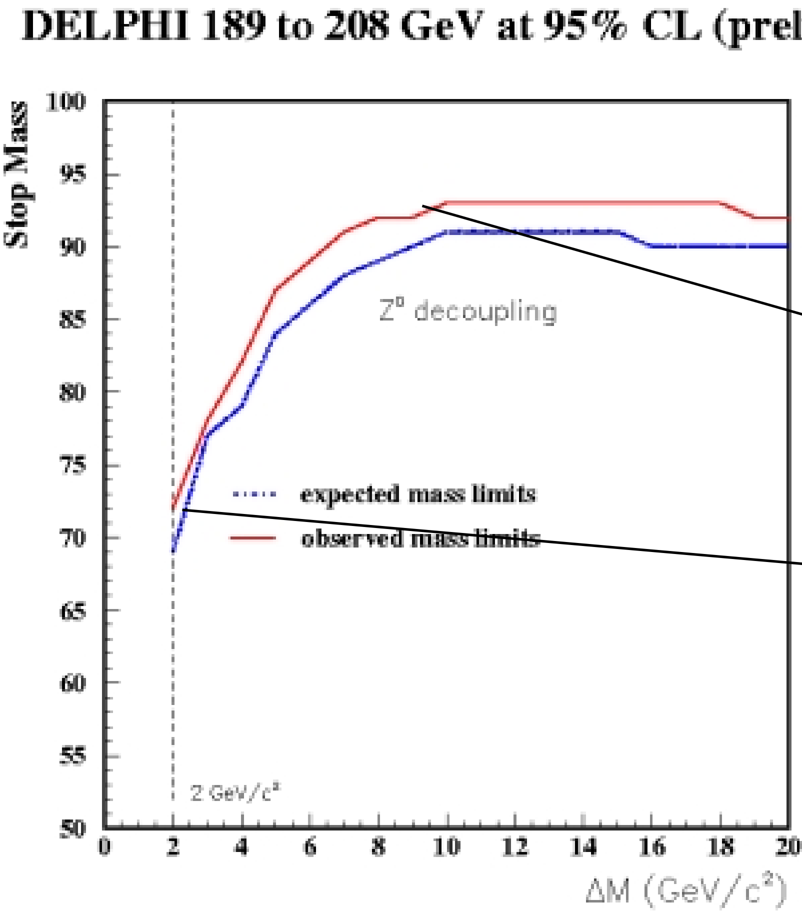
ΔM< 3 GeV/c²

- Intermediate lifetime
  stop decay within the detector
  Heavy neutralino, small E_{vis}, soft charge tracks

<u>Impact parameter</u>

- Large lifetime: decay lenght > detector size
  Heavy stable particle topology

<u>Anomalous ionization</u>



Standard search
conservative result
minimal x-section

For $\Delta M > 10$ GeV/c²

$m_{\tilde{t}} > 92$ GeV/c²

For $\Delta M > 2$ GeV/c²

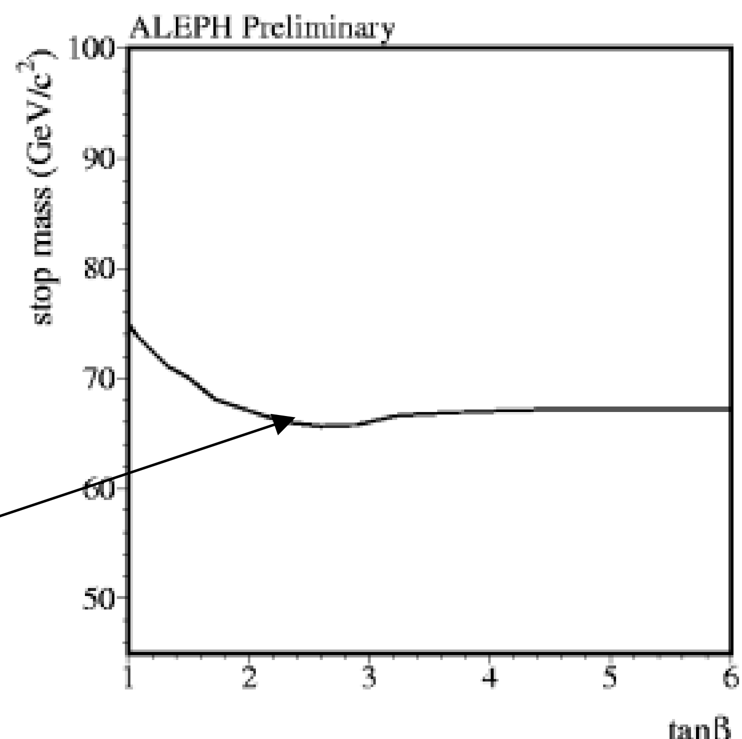
$m_{\tilde{t}} > 72$ GeV/c²

Absolute mass lower limit

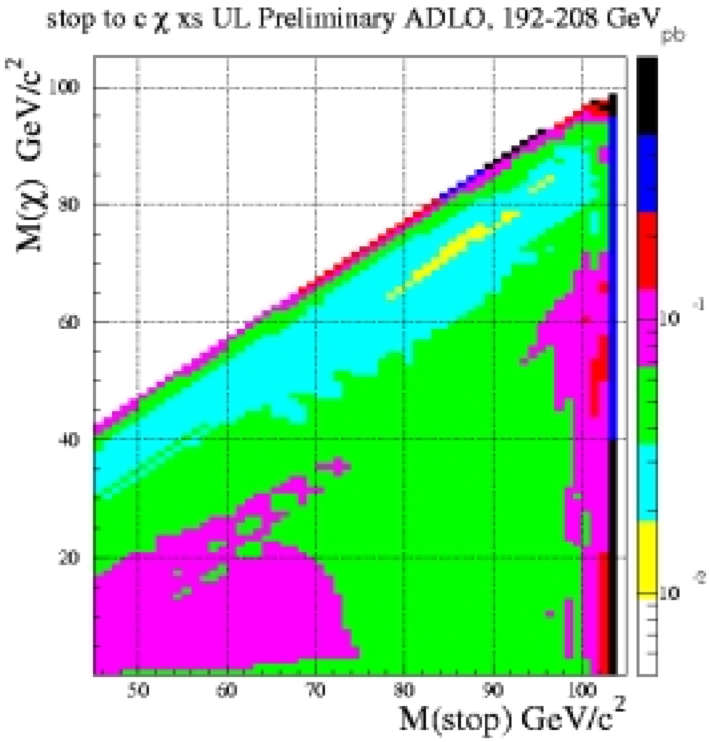
In low ΔM region mass lower limit as a function of $\tan\beta$, independent from other MSSM parameters

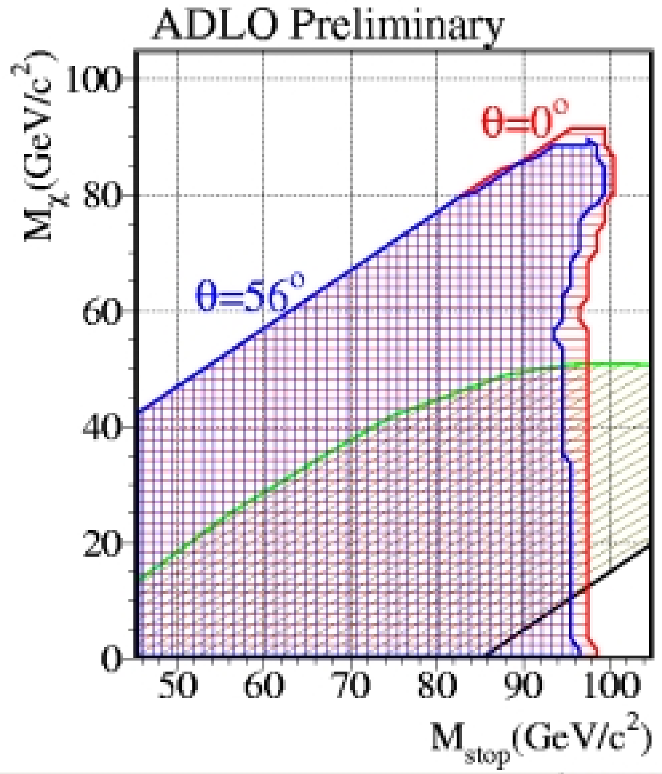
$m_{\tilde{t}} > 65$ GeV/c²

for $\tan\beta = 2.7$



Lep improves Tevatron limits for small ΔM





Excluded Stop masses < 96 GeV/c² for ΔM>20 GeV/c²

$$\tilde{t} \rightarrow b\, l\, \tilde{\nu}$$

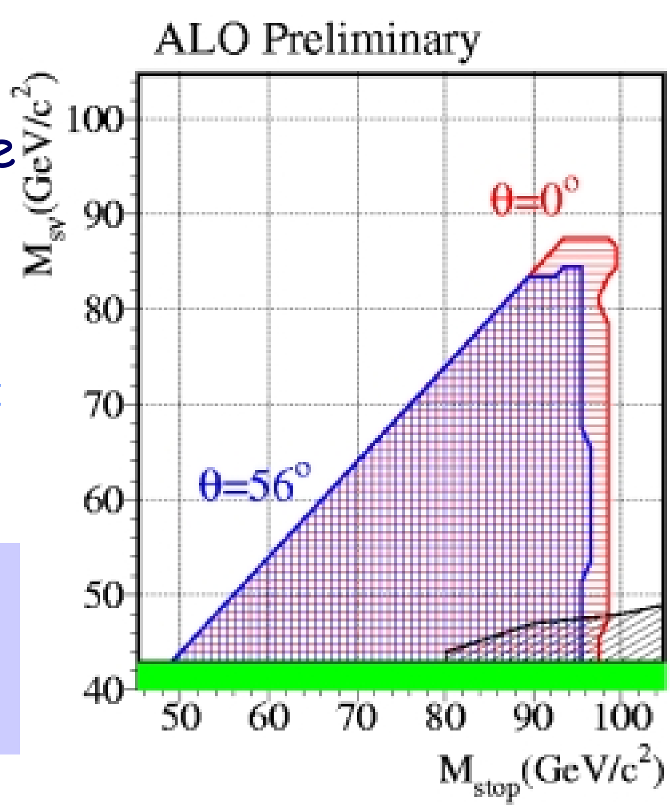
Via virtual chargino exchange

When allowed, dominates

l= e, μ, τ for gaugino like χ±

l= τ for higgsino like χ±

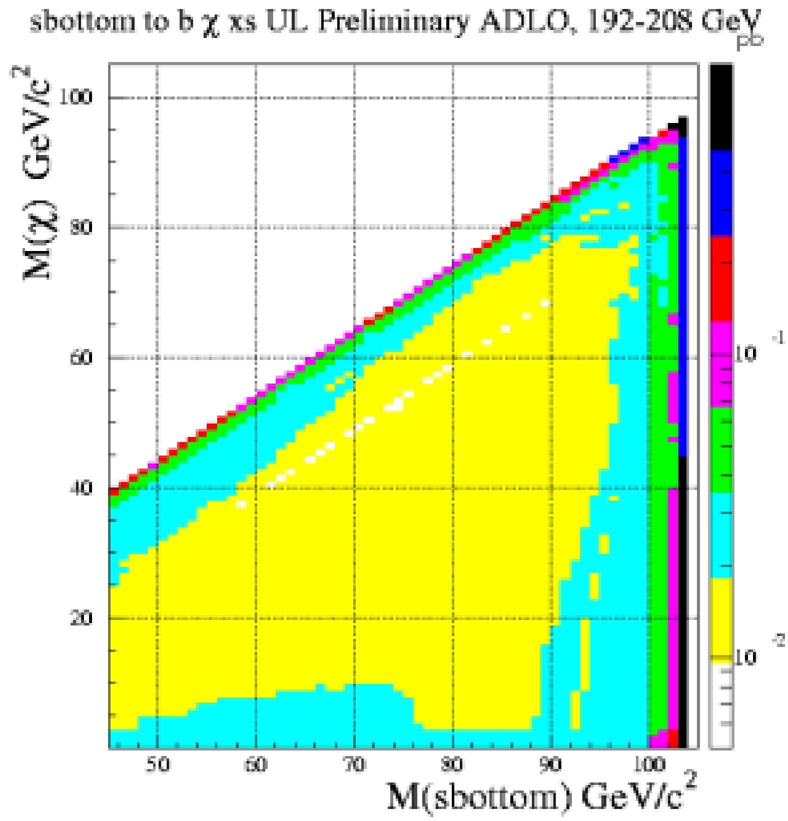
Excluded Stop masses below 96 GeV/c² for ΔM>20 GeV/c²

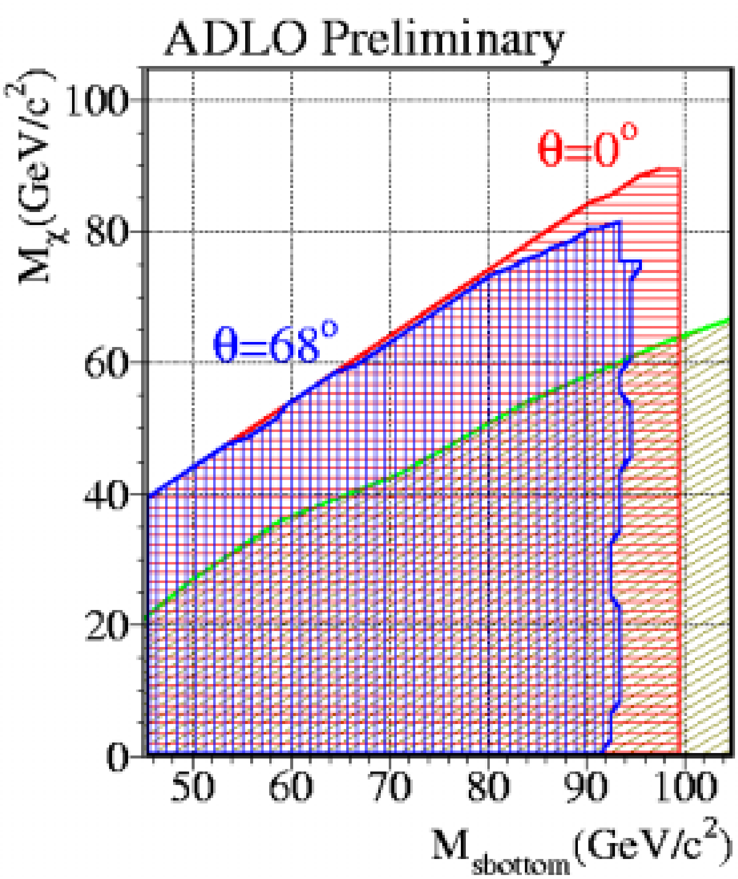


If tanβ>10, light sbottom could be accessible.

For a gaugino like neutralino, sbottom lifetime > hadronisation time

$$\tilde{b} \rightarrow b\chi_1^{\ 0}$$





$\vartheta_1 : 68^0$ $\tilde{b}$ - Z decoupling

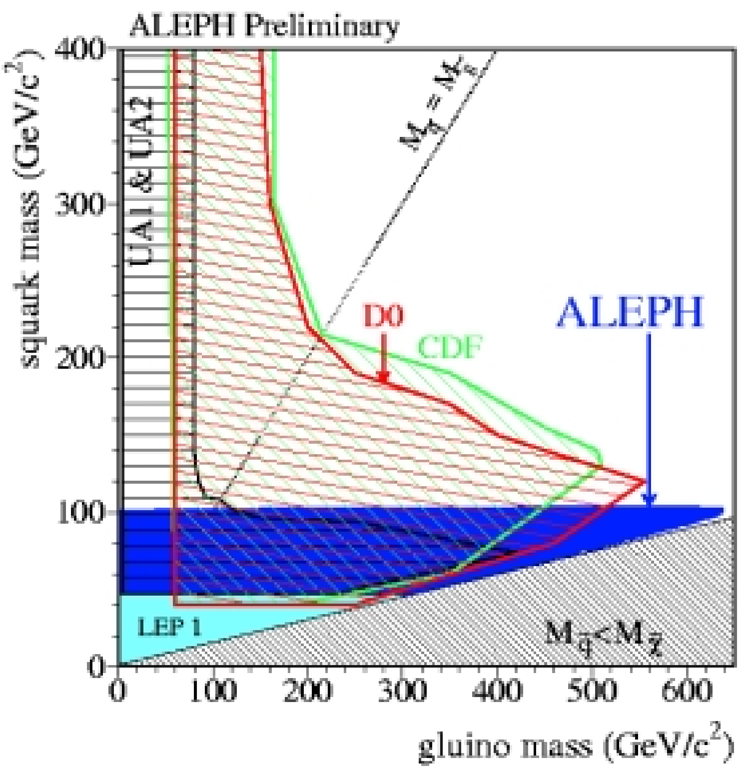
$\vartheta_1 = 0 \Rightarrow$ pure $\tilde{b}_L$

Excluded Sbottom masses < 95GeV/c² for ΔM>20 GeV/c²

Degenerate squarks

Partner of light quarks too heavy to be produced at LEP. But gluino loop can give large negative corrections to masses.

ALEPH set limits on degenerate u,d,s, b left and right handed squarks



Assumption:

GUT relation between the M_i, relating gluino and neutralino masses

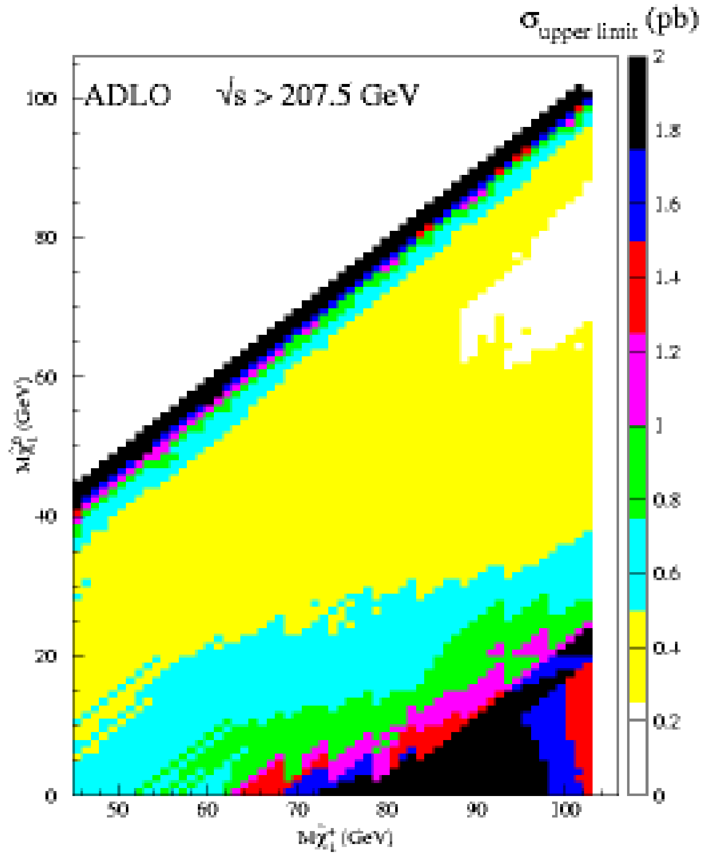
$\tan\beta = 4$,

$\mu = -400$ GeV/c^2

The result improves the Tevatron limits in low ΔM region

Gauginos m_0 large

In this scenario only chargino, neutralino and Higgs can be produced

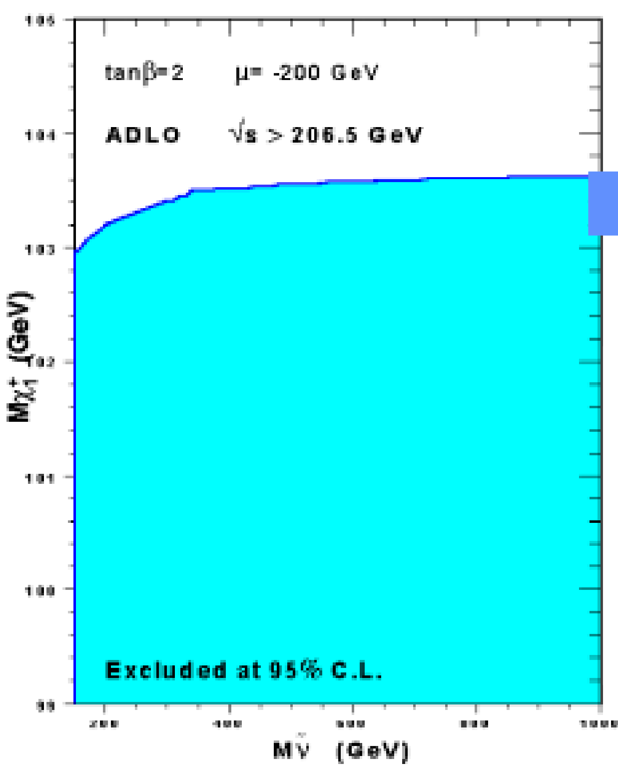


Decay mechanisms

$$\chi^\pm \to W^* \chi_1^0$$

$$\chi^0{}_j \to Z^* \chi^0{}_1$$

X-section upper limit in $(m_{\chi\pm}, m_{\chi^0{}_1})$ plane



ADLO lower limit on $\chi^\pm$

as a function of sneutrino mass

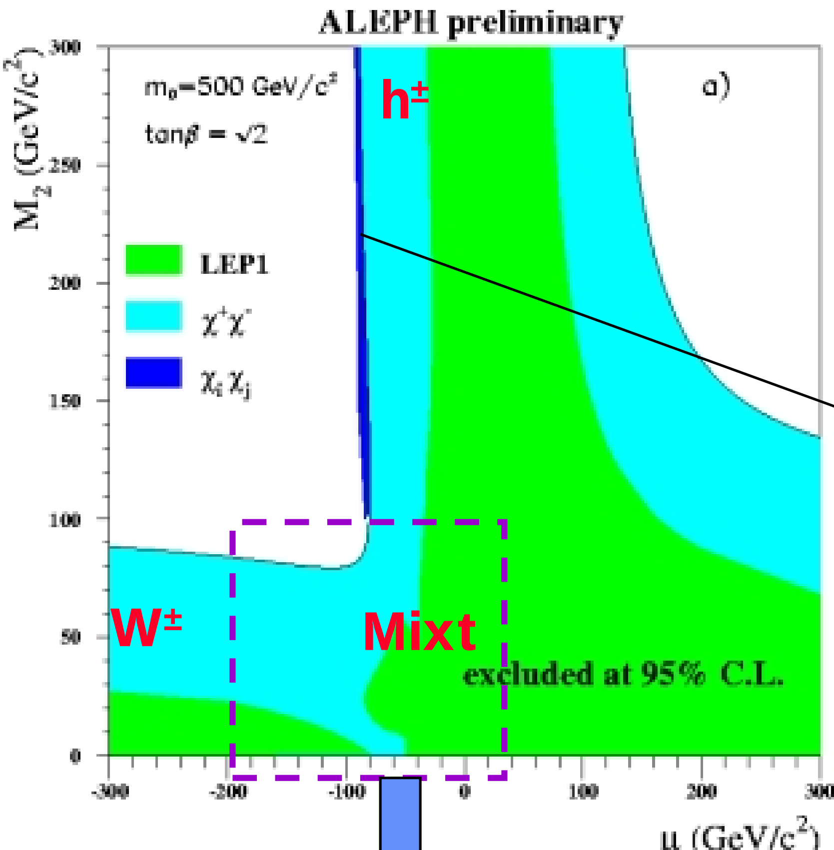
$m\chi^\pm$> 103.5 GeV/c²

for $m_{\tilde{\nu}}$ >300 GeV/c²

All masses, cross sections and decay BR's of charginos and neutralinos depend on the M_2 and μ for fixed $\tan\beta$

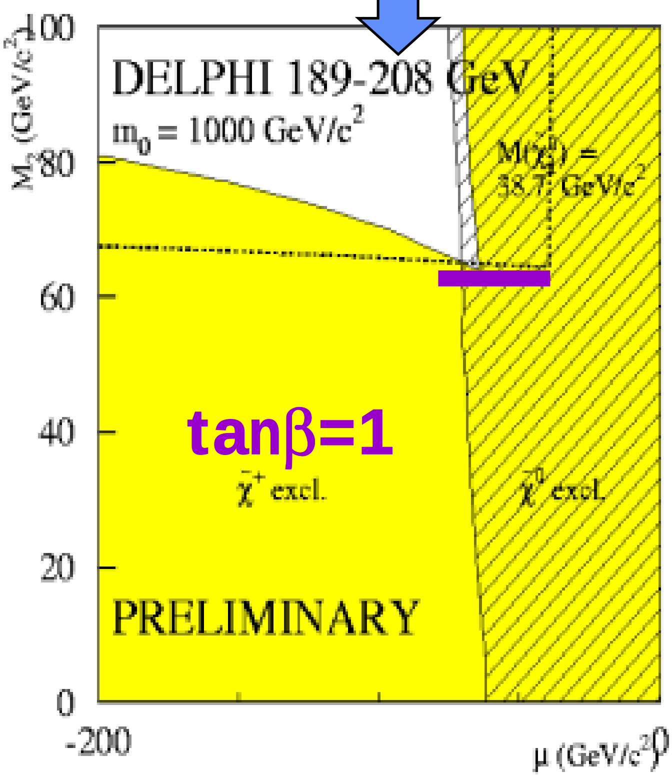
Exclusion in plane (M_2, μ)

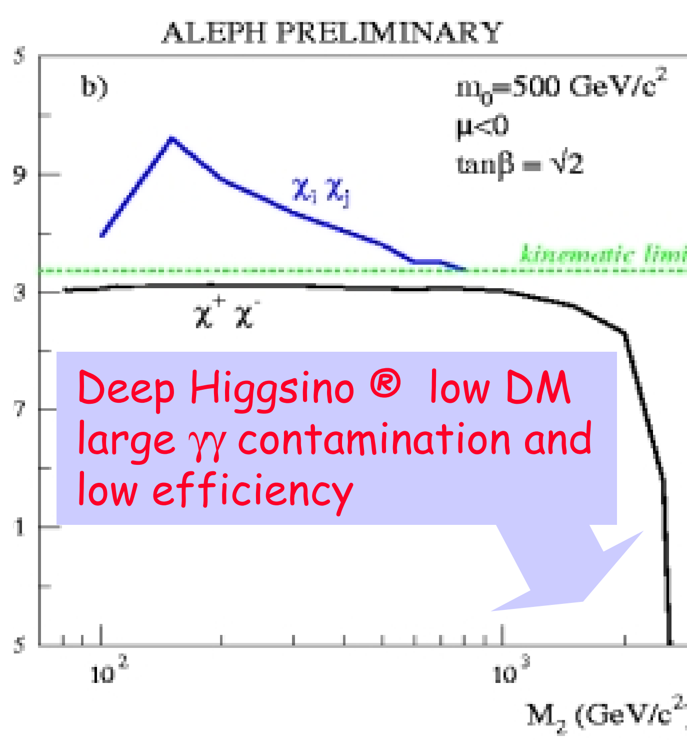
Gaugino unification @ GUT scale



Neutralino still helps at low $\tan\beta$ and in the higgsino region

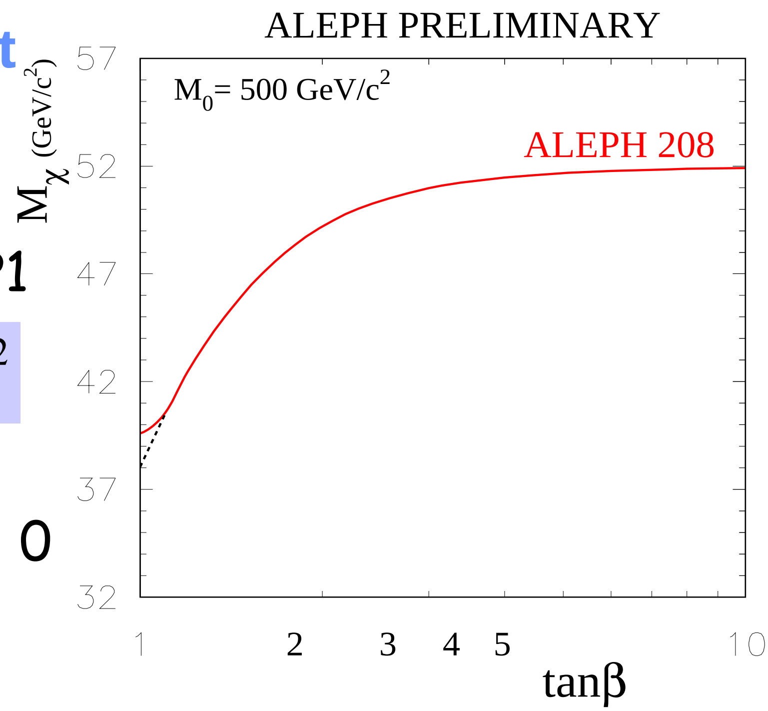
One can infer indirect chargino mass limit





Deep Higgsino ® low DM large $\gamma\gamma$ contamination and low efficiency

One can infer indirect neutralino mass limit



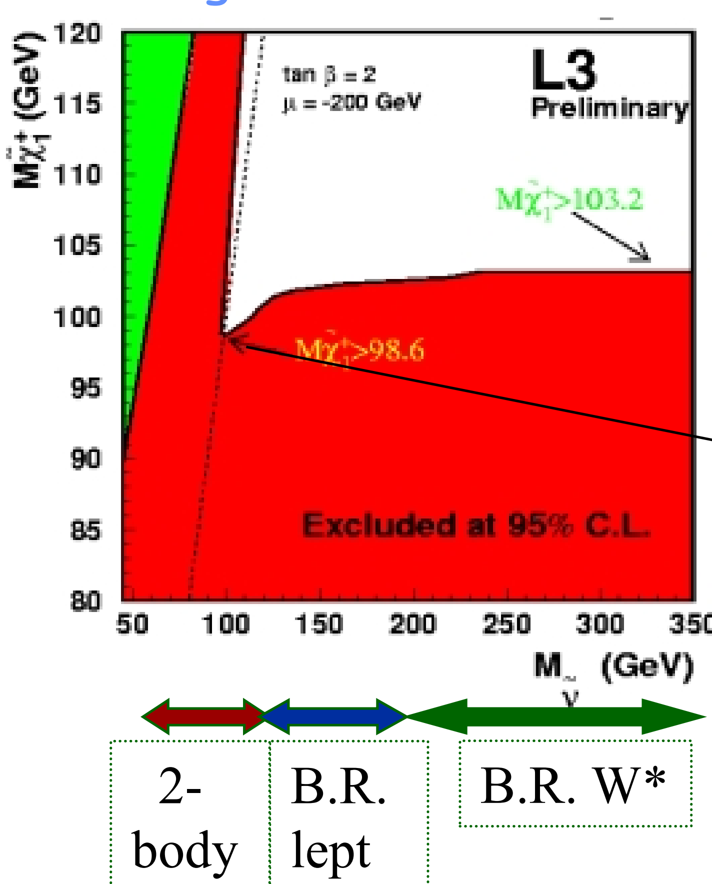
Combined limits chargino-neutralino-LEP1

$$m(\chi_1^0) > 39.6\ \mathrm{GeV/c^2}$$

Found for tanβ=1 in *mixted region* and μ < 0

m_0 low

- Neutralino X-section enhanced due t-channel
- Charginos X-section reduced due to t-channel



$$m_{\tilde{\nu}} \geq m_{\chi^\pm}$$

leptonic B.R. enhanced

$$m_{\tilde{\nu}} < m_{\chi^\pm}\ \text{2-body decay}$$

For $m_{\tilde{\nu}} \approx m_{\chi^\pm}$ lepton too soft

Reduced sensitivity of the gaugino sector

Lepton search used

Chargino exclusion depends on $m_{\tilde{\nu}}$

Neutralino exclusion depends on $m_{\tilde{e}}$

Assuming the sfermion masses unification m_0 @ GUT:

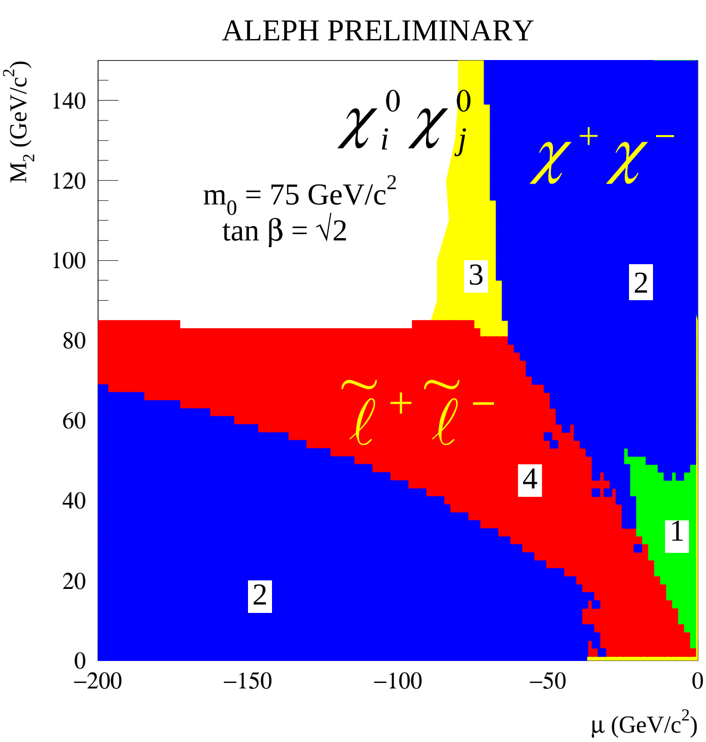
$$M^2_{\tilde{l}_R} = M_0^2 + 0.23 \cdot M_2^2 - \sin^2\vartheta_W M_Z^2 \cos(2\beta)$$

slepton mass limit can be turned into a limit on M_2, fixed tanβ and m_0

In slepton-sneutrino corridor:

Limit on $m_{\tilde{e}_R}$ → limit on $m_{\tilde{\nu}}$ → limit on $m_{\tilde{\chi}^\pm}$ and $m_{\chi^0_1}$

Limit from large m_0 and tanβ =1 still valid in mixted region at low m_0



$$m_0 = 75\ \mathrm{GeV/c^2}$$

$$\tan\beta = \sqrt{2}$$

At low m_0 the combined searches on chargino, neutralino and slepton are used to derive limit

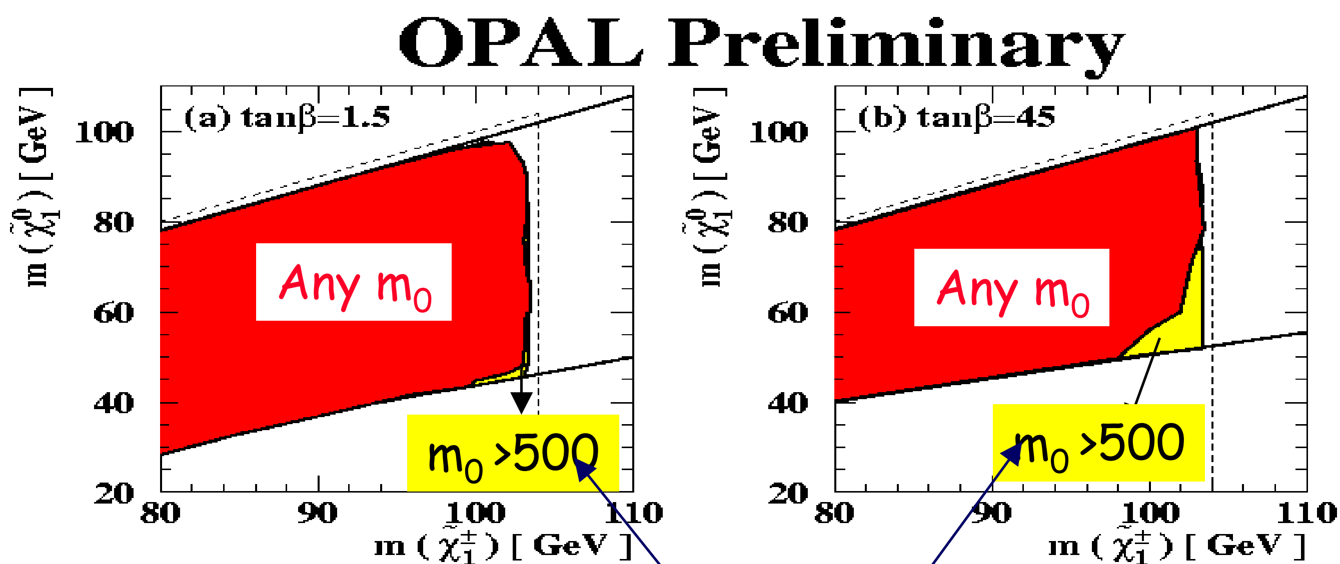
no mixing in stau sector

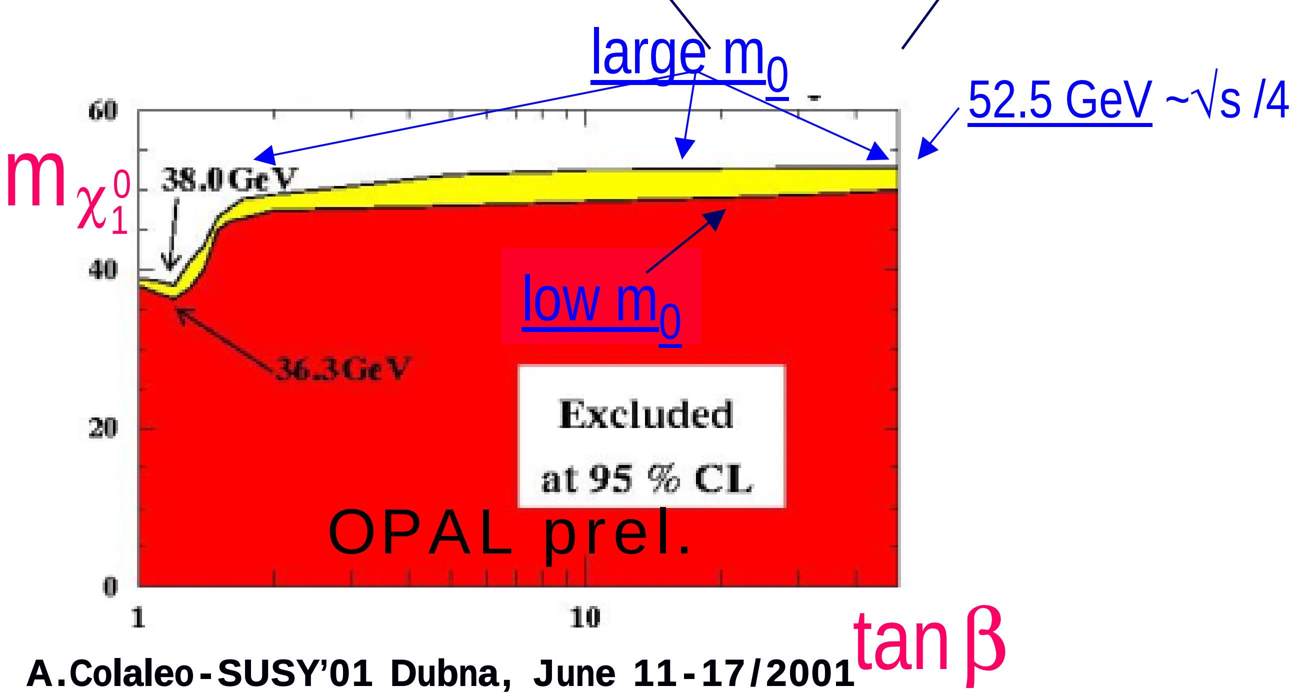
To derive the absolute limit on the mass of chargino and neutralino a scan is performed in MSSM parameter space

$$0 \le M_2 \le 2000 \text{ GeV/c}^2 \qquad m_0 \le 1000 \text{ GeV/c}^2$$

$$|\mu| \le 500 \text{ GeV/c}^2 \qquad \tan\beta < 60$$

The best m_0 ⇒ smaller number of expected chargino and neutralino events for each $(\mu, M_2, \tan\beta)$ ⇒ most conservative limit valid at **Any m_0**

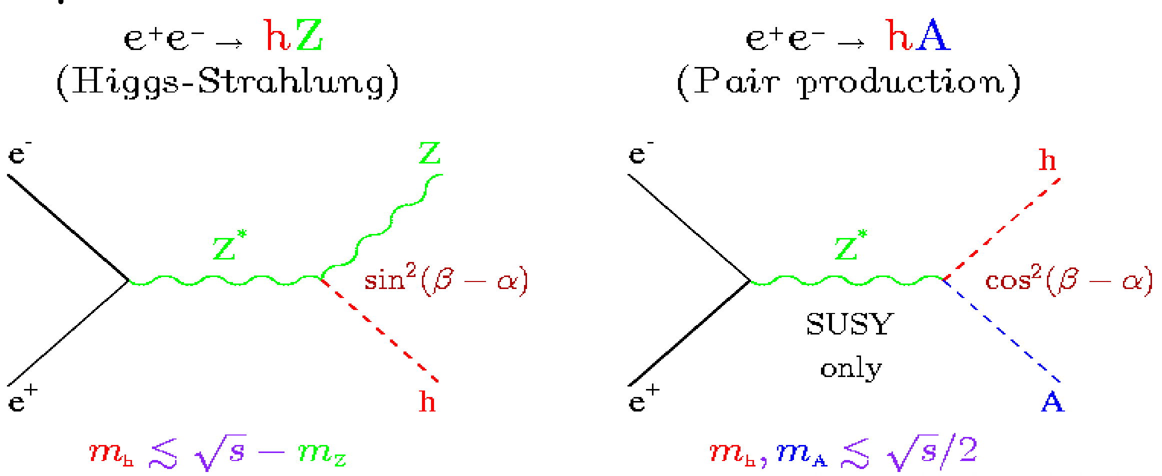




Contribution from Higgs search

The lighter scalar is SM-like with reduced coupling
$\xi_{SM} \bullet \cos(\alpha-\beta)$

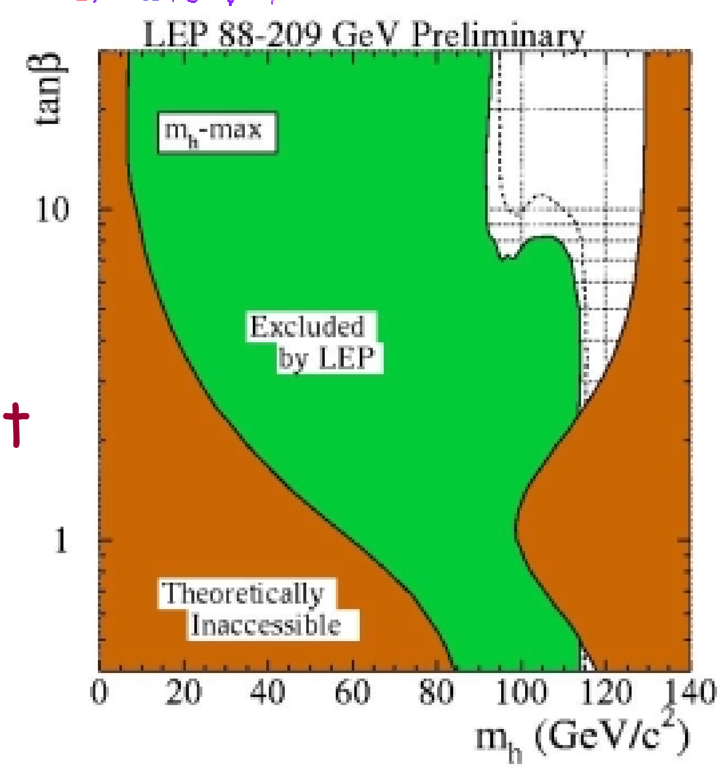
Important channels $e^+e^- \rightarrow hZ, hA$



- At the tree level:

$$M_h < m_Z |\cos 2\beta|$$

m_h limit ➡ $\tan\beta$ limit



- Radiative correction:

$$\Delta m_h^2 \sim \frac{m_t^2}{\sin^2\beta} \cdot \ln\left(\frac{m_{\tilde{t}_1} \cdot m_{\tilde{t}_2}}{m_t^2}\right)$$

m_h limit ➡ $m_{\tilde{t}}$ limit

$m_h > 113$ GeV/c^2
$\cos(\alpha-\beta)=1$

Lower limit on m_h could be converted in limit on (m_0, M_2) o $(m_0, m_{1/2})$

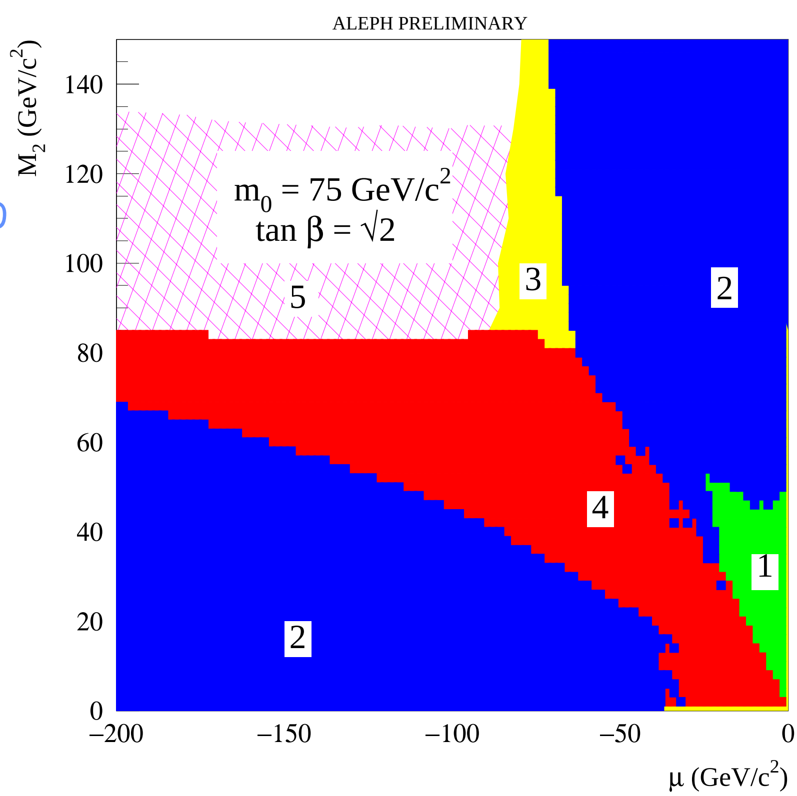
$$\text{(e.g. } m^2_{\tilde{t}_R} \cong m_0^2 + 6.1 \cdot m_{1/2}^2 \text{)}$$

$$m_0, \tan\beta \text{ fixed, } m_{\tilde{t}} \text{ increases with } M_2$$

$$\text{With } m_t \approx 175\,\text{GeV}, \; m_h \text{ increase with } M_2$$

$$\text{Then limit on } m_h \Rightarrow \text{lower limit on } M_2$$

GUT scale sfermion masses unification m_0 needed



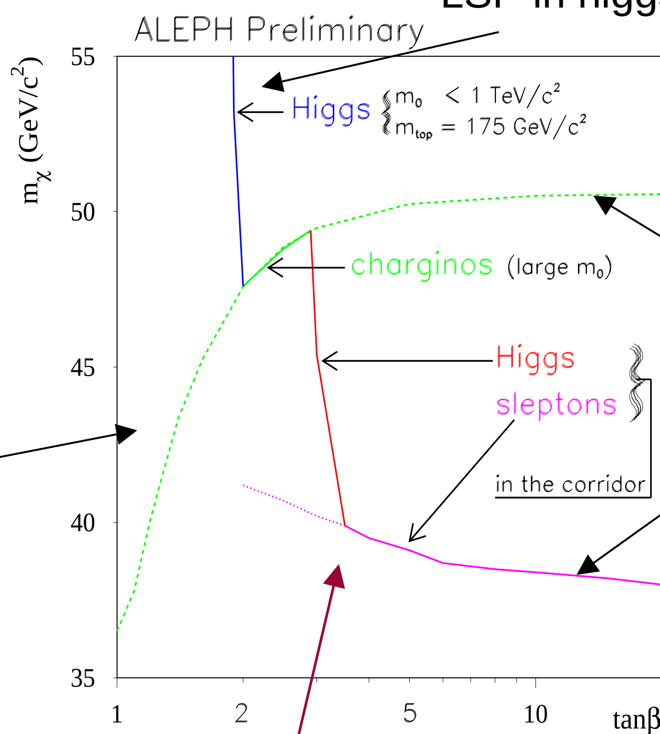
But Higgs results depend on m_A, A_t

Max M_h ⟺ $A_t - \mu / \tan\beta$ ⟺ high M_A and tuning the mixing in stop sector

Constraints from Higgs search move the lower limit on LSP in the corridor in the gaugino region at large tanβ

LSP in higgsino region

LSP in mixted region



LSP in gaugino region

Very low tanβ values are excluded

Coverage of the corridor at low tanβ improved

Higgs no helps for large tanβ

But result depends on m_t and m_0

$$m_t = 180\,\mathrm{GeV/c^2} \text{ and } m_0 > 1\,\mathrm{TeV/c^2}$$

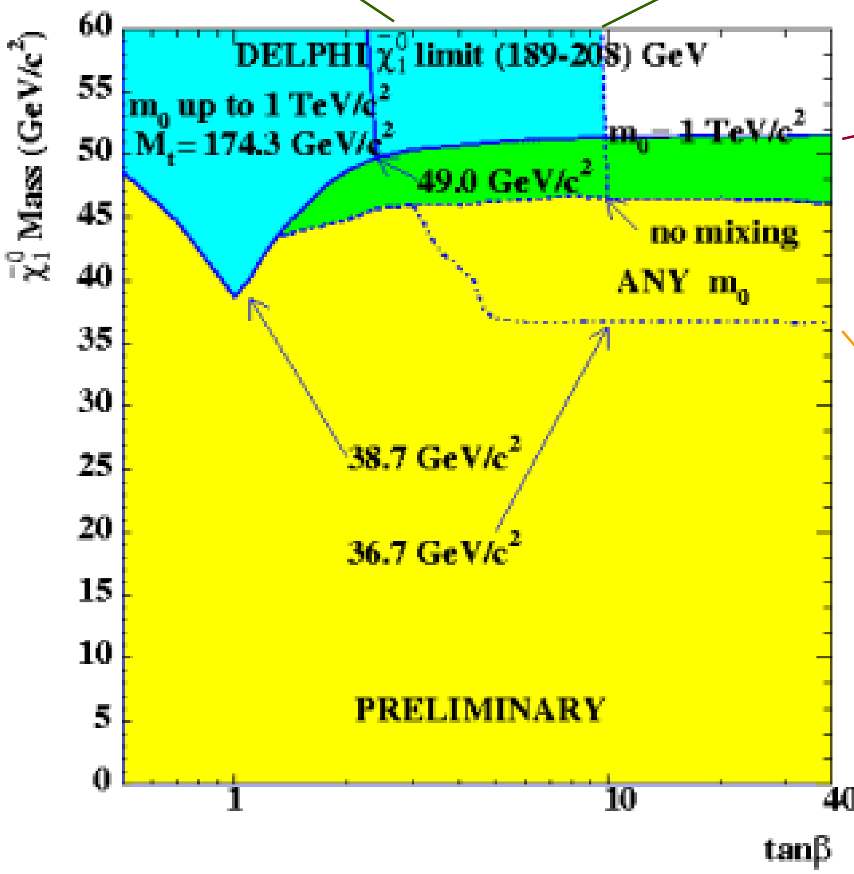
⇒ LSP limit back in mixted region at low tanβ

scan parameters for the more conservative limit

$m_t = 174.3\ \mathrm{GeV/c^2}$ and $m_0 < 1\ \mathrm{TeV/c^2}$

M_h max ➡ Tanβ > 2.36

M_h no mixing ⬇ Tanβ > 9.7



m_0 large

Any m_0 and no mixing in 3rd generation

Any m0 and mixing in 3rd generation

Higgs search $m_{\chi^0{}_1} > 49.0\ \mathrm{GeV/c^2}$ Tanβ > 2.36

"Any m_0" from chargino, neutralino, slepton searches - no mixin

$$m_{\chi^0{}_1} > 46.0\ \mathrm{GeV/c^2}$$ Tanβ > 1

"Any m_0" stop, sbottom and neutralino searches - mixing

$$m_{\chi^0{}_1} > 36.7\ \mathrm{GeV/c^2}$$ Tanβ > 3

Conclusions

•MSSM signals have been searched at LEP at Ecm < 209 GeV

•Number and topologies of the selected events are in agreement with the Standard Model expectation

⇓

new limits set

•Constraints are put on model parameters and on the masses of the sfermions and gauginos in CMSSM framework

•Lower limits on LSP have been derived indirectly from the search of other MSSM particles and Higgs bosons

$$m(\chi_1^0) \approx 40\,\mathrm{GeV/c^2}$$ $\tan\beta>1$ any m_0