New particle searches

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Outline :

- Introduction
- Exotic particles
- SUSY particles
- Higgs bosons
- Conclusions

Introduction

This review covers a few selected topics from :

- Tevatron (CDF/DØ):

  run I $\mathbf{p\bar{p}}$ data at $\sqrt{S}$=1.8 TeV ('87/'95)

  $\sim$ 110 pb^{-1} / expt

- HERA (H1/ZEUS):

  $\mathbf{e^+p}$ data at $\sqrt{s}$= 300 GeV ('94/'97) $\sim$ 40 pb^{-1} / expt

  $\mathbf{e^-p}$ data at $\sqrt{s}$= 318 GeV ('98/'99) $\sim$ 15 pb^{-1} / expt

  Now taking $\mathbf{e^+p}$ data again

- LEP2 (ALEPH/DELPHI/L3/OPAL):

  $\mathbf{e^+e^-}$ data ('95/'99):

'95/'97:	$\sqrt{s}$= 130 $\cdots$ 183 GeV	$\sim$ 90 pb^{-1} / expt
'98:	$\sqrt{s}$= 189 GeV	$\sim$ 170 pb^{-1} / expt
'99:	$\sqrt{s}$= 192/196 GeV	$\sim$ 105 pb^{-1} / expt

Now running at 200 GeV (since August 2) !!

LEP results come mostly from data up to 189 GeV with some updates from '99 data. Combined results from the LEP experiments are denoted ADLO.

Apologies for the results not shown here

All limits are at 95% C.L.
and MOST results are PRELIMINARY

Exotic particles

- **Technicolor**
  - Disfavored by fits to EW data
  - Direct searches pursued (CDF, D0, L3)

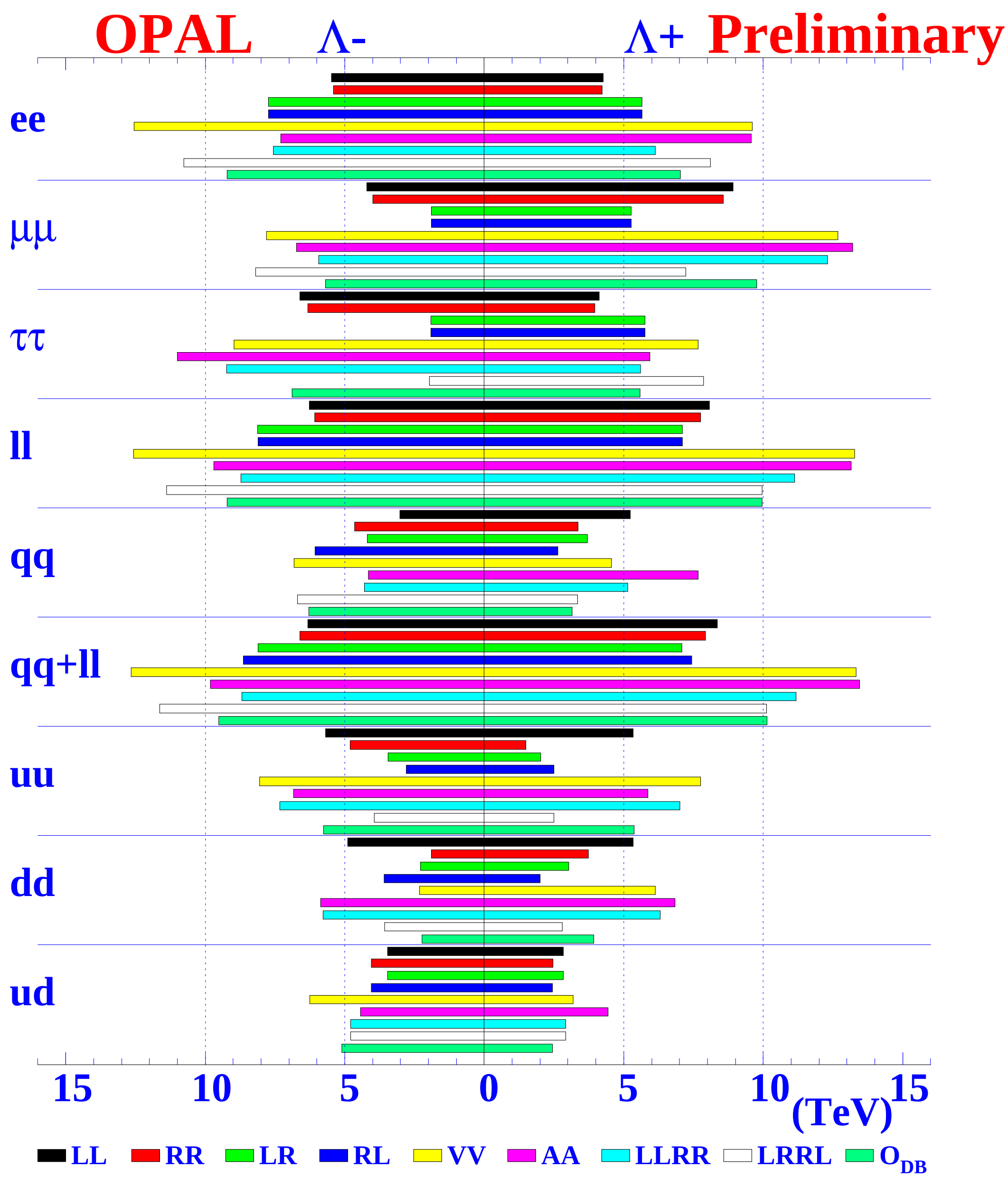
- **New Z' bosons**
  - Direct searches (Tevatron)
  - Indirect constraints (LEP)

$\Rightarrow$ $\boxed{\mathbf{M_{Z'}^{SSM} > 1\ TeV \qquad M_{Z'}^{E6,LR} > 600\ GeV}}$

- **Four fermion contact interactions**
  - Indirect constraints (HERA, LEP, Tevatron)

$\Rightarrow$Scales between **2 and 15 TeV** have been probed (depending on the fermion flavour and the helicity model)

Contact interactions, an example: OPAL 196 GeV



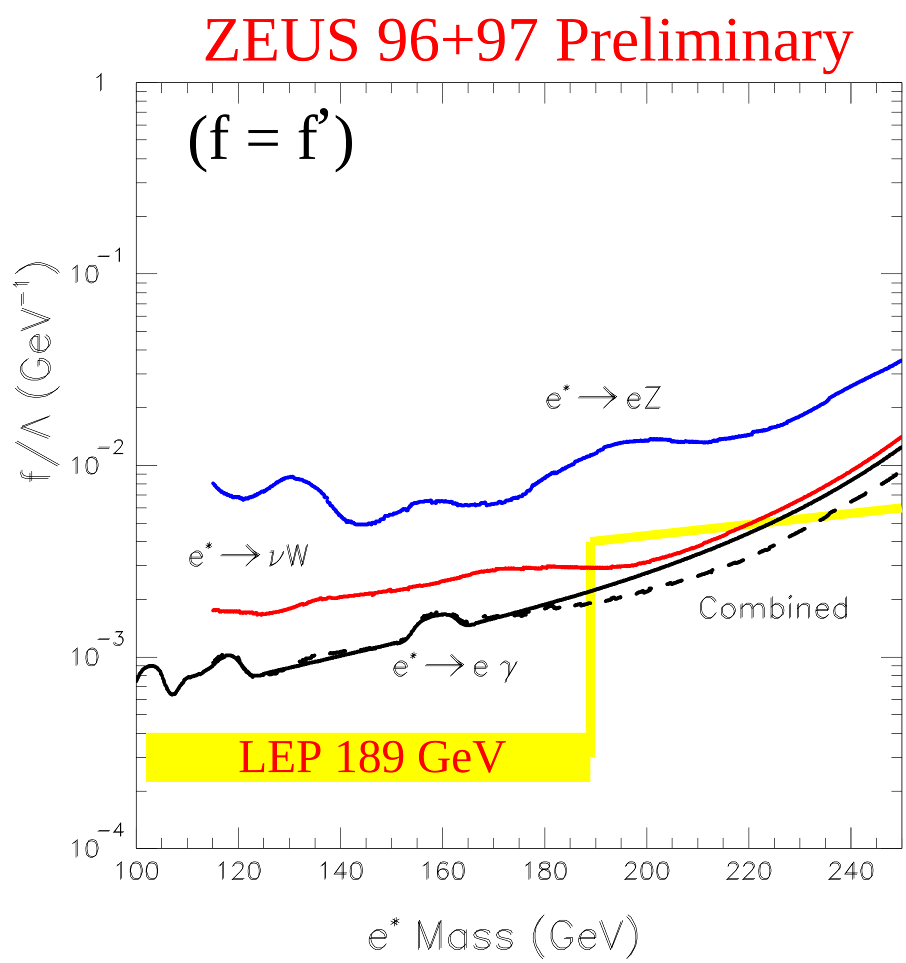
- **Excited/new/exotic fermions**
  - Indirect constraints (LEP)
  - Direct searches (HERA, LEP, Tevatron)

$\Rightarrow$eg. excited fermions :

Pair production at Tevatron : $\mathbf{M_{q^*} > 700\ GeV}$

Pair production at LEP : $\mathbf{M_{l^*,\nu^*} > 84/97\ GeV}$

Single production at LEP and HERA :



- **Leptoquarks**
  - indirect constraints (LEP)
  - direct searches (HERA, LEP, Tevatron)

$\Rightarrow$will be detailed for HERA

Leptoquarks

- expected in many theories (GUT, E6, compositeness, TC)
- carry **l** and **q** quantum numbers (colour triplet, L and B, fractional Q)
- Scalars or Vectors, F = 0 (eg. e^+q) or |F| = 2 (eg. e^-q)
- parameters :

  $\boldsymbol{\lambda_{lq}}$: LQ coupling to l,q generations

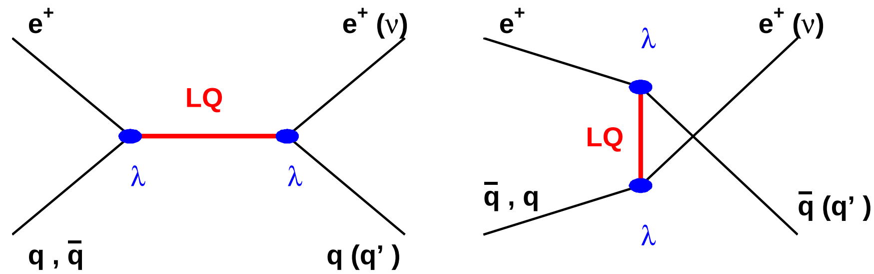
  $\boldsymbol{\beta_l}$: BR(LQ→ lq)

  $\mathbf{M_{LQ}}$: LQ mass

- phenomenological framework :
  - BRW (Buchmüller et al.) model : constrained
    ⇒ 10 LQ isospin multiplets
    ⇒ couplings to a single generation
    ⇒ $\boldsymbol{\beta_l}$ is fixed (1 or 0.5) ⇒ $\boldsymbol{\lambda}$, $\mathbf{M_{LQ}}$ as free parameters

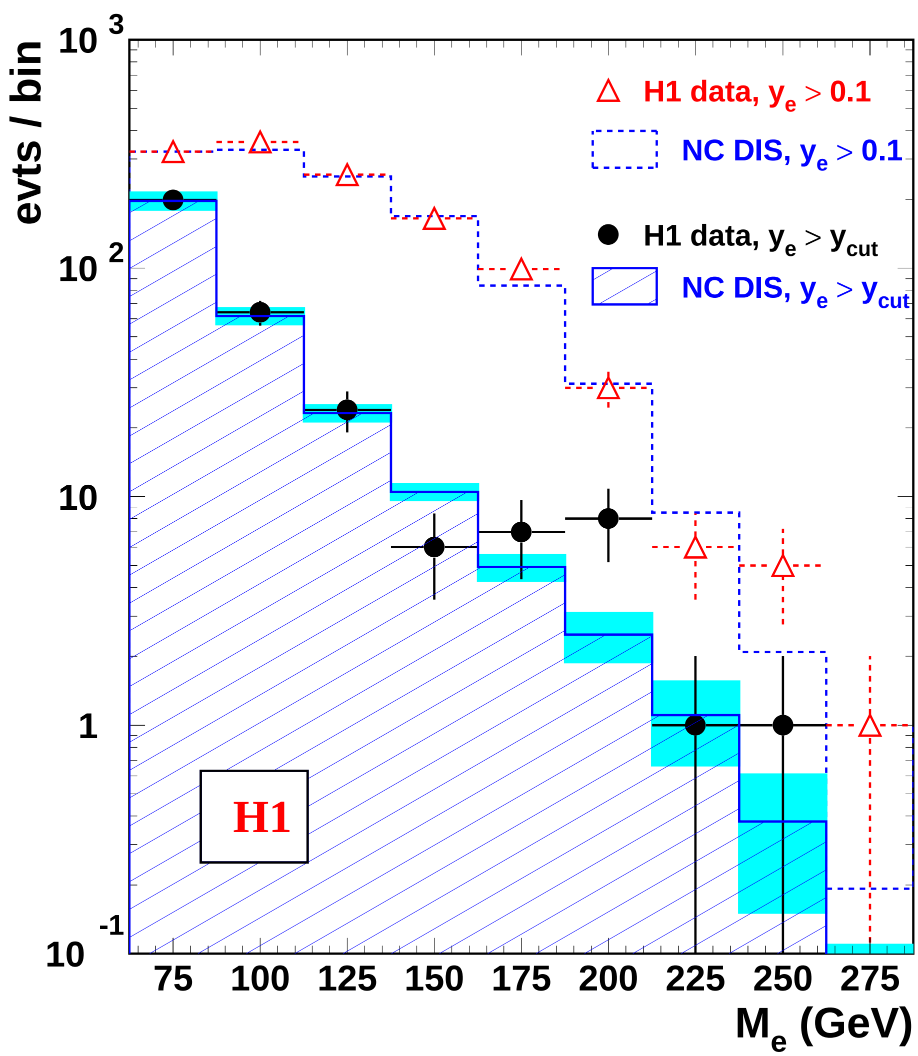
  - generic models : some assumptions relaxed
    ⇒ variable $\boldsymbol{\beta_l}$
    ⇒ LQ with mixed couplings

Ex. 1: first generation LQ at HERA



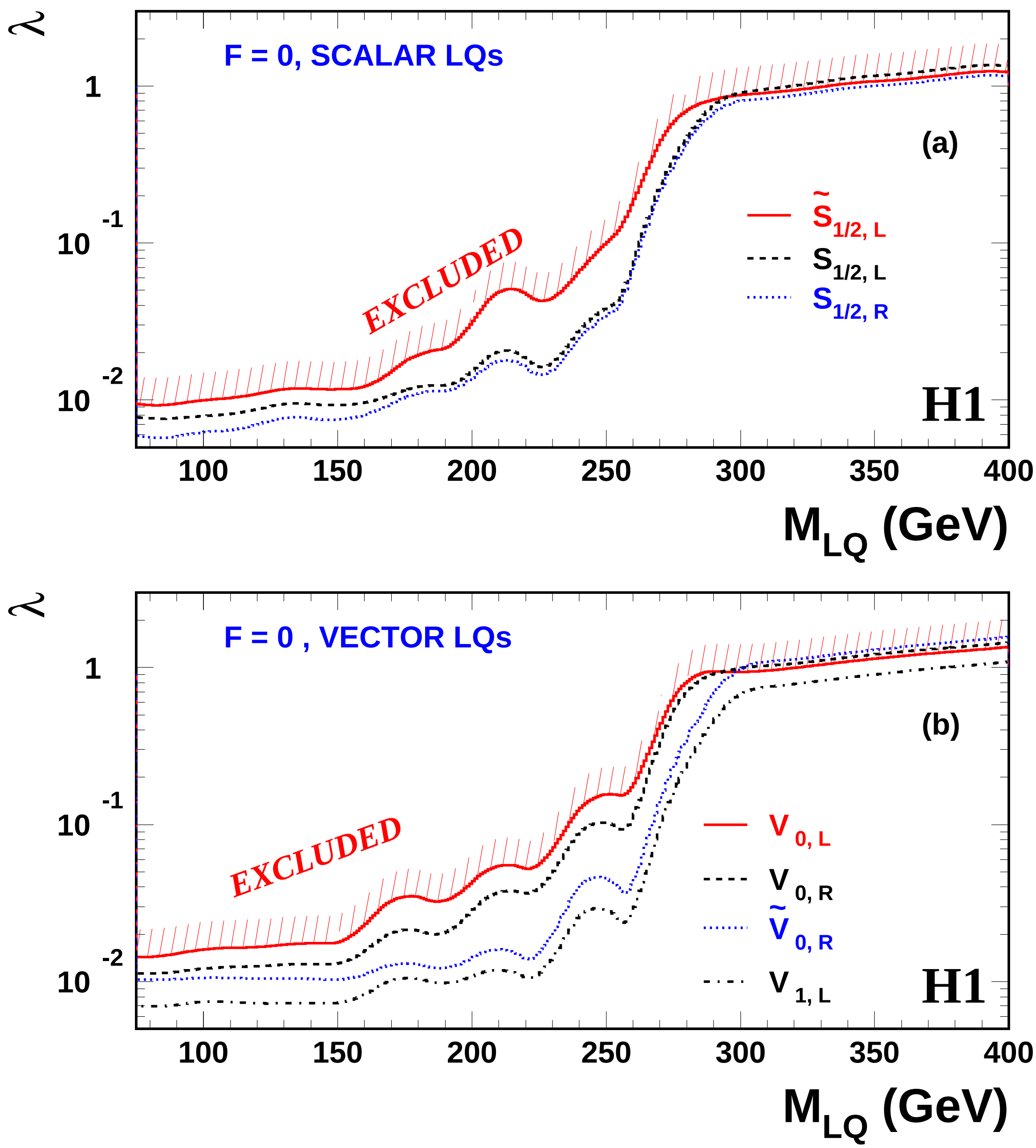
⇒s and u channels interfere with DIS (NC and CC)

⇒DIS selections + specific cuts if needed, eg for NC events:



$\mathbf{y}_{\rm cut}$: LQ mass dependent $\mathbf{y}_e$ cut (here for a F=0, scalar LQ)

Ex.1, 1st generation LQ at HERA: BRW models (β_e=0.5,1)



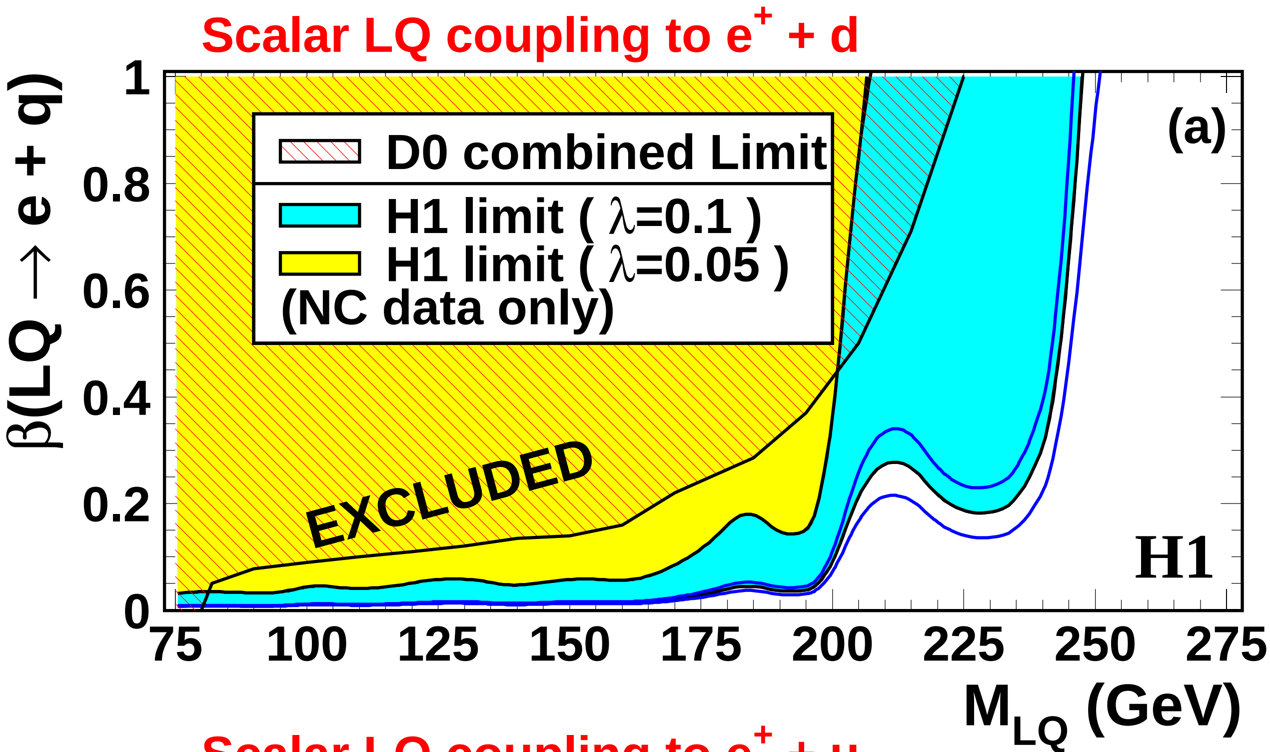
$\Rightarrow$ For $\boldsymbol{\lambda_{11} = \lambda_{em}}$ (~ 0.3): $\mathbf{M_{LQ} > 265}$ **GeV**

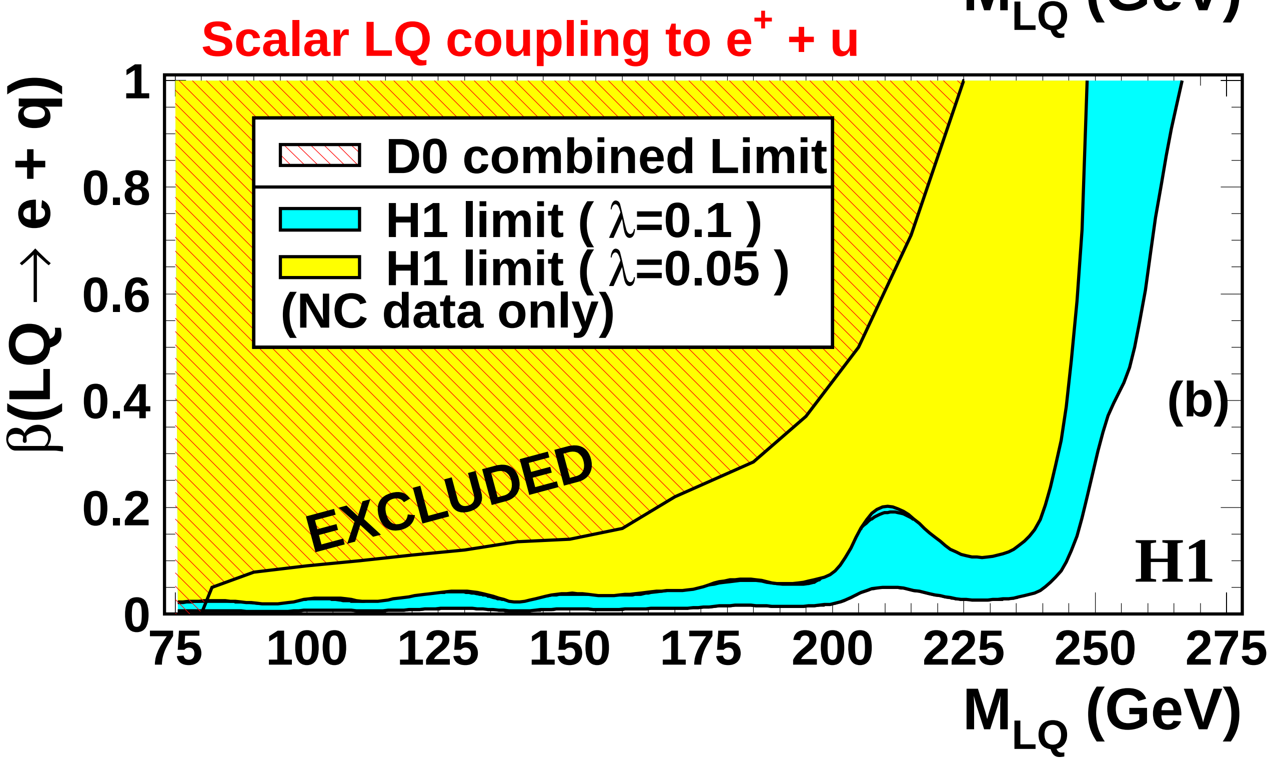
NB: LEP results for $\boldsymbol{\lambda_{11} = \lambda_{em}}$:

indirect limits : better in some cases, eg. $\mathbf{M_{V_{1,L}} > 590}$ **GeV**

direct searches : reach kinematical limit $(\sim 189$ GeV$)$ at best

Ex.1, second result: in generic models (β_e variable)





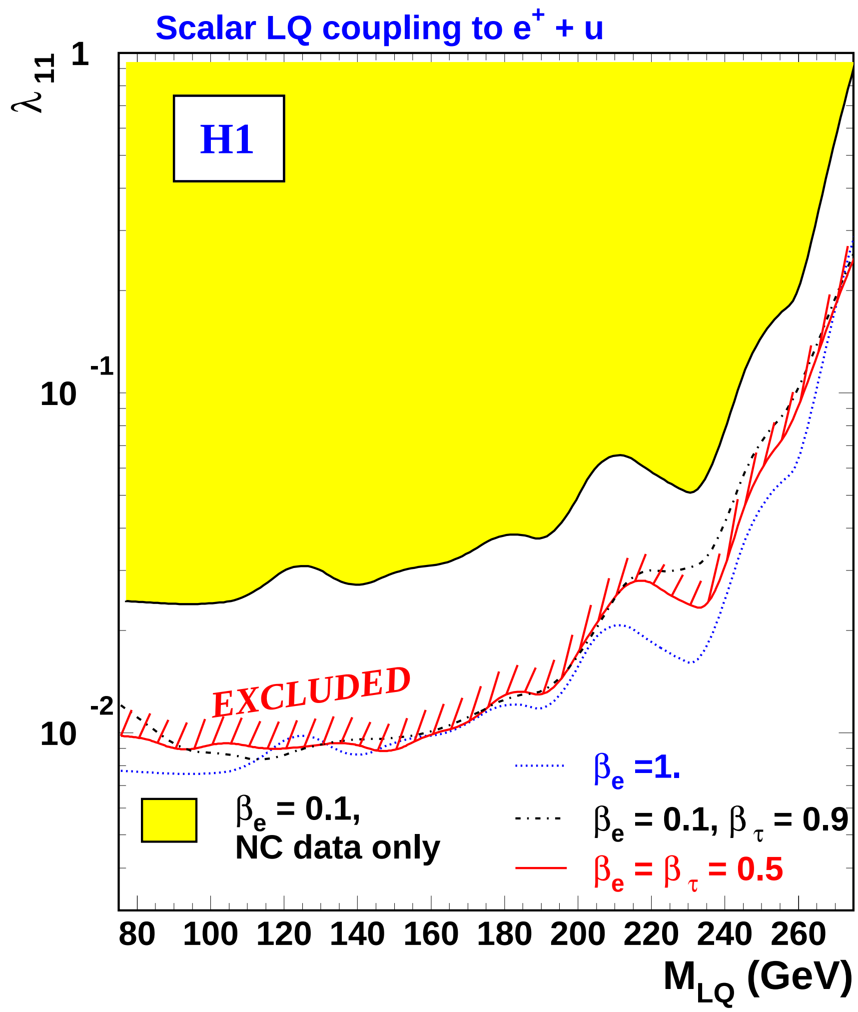
⇒HERA sensitivity extends down to small $\boldsymbol{\beta_e}$ even for small $\boldsymbol{\lambda_{11}}$, eg:

for $\boldsymbol{\beta_e}\sim$ 10% and $\boldsymbol{\lambda_{11}}\sim$ 0.05: $\mathbf{M_{LQ} > 200}$ **GeV**

Ex. 2: LQ with LFV couplings at HERA

direct search for $\mathbf{e\ q \to LQ \to \tau\ q}$ $\mathbf{e\ q \to LQ \to \mu\ q}$

•low mass LFV LQ: τ channel



if $\beta_e + \beta_\tau \sim 1$, same sensitivity as if $\beta_e = 1$

Reminder: Tevatron results for third generation LQ (no LFV):
with $\beta_\tau = 1$: $\mathbf{M_{LQ} > 99\ GeV}$, with $\beta_{\nu_\tau} = 1$: $\mathbf{M_{LQ} > 149\ GeV}$

•very high mass LFV LQ: τ and μ channels
Constraints on $\lambda_{1i}\lambda_{2j}$ / M^2_{LQ} and on $\lambda_{1i}\lambda_{3j}$ / M^2_{LQ} have been updated and in many cases compete well with or supersede indirect constraints from low energy experiments.

Supersymmetric particles

- **Constrained MSSM**
  - Direct searches (LEP, Tevatron)

- **R-parity breaking**
  - Indirect constraints (LEP)
  - Direct searches (LEP, Tevatron)

- **Gauge mediated Supersymmetry breaking (GMSB)**
  - Direct searches (LEP, Tevatron)

Constrained MSSM

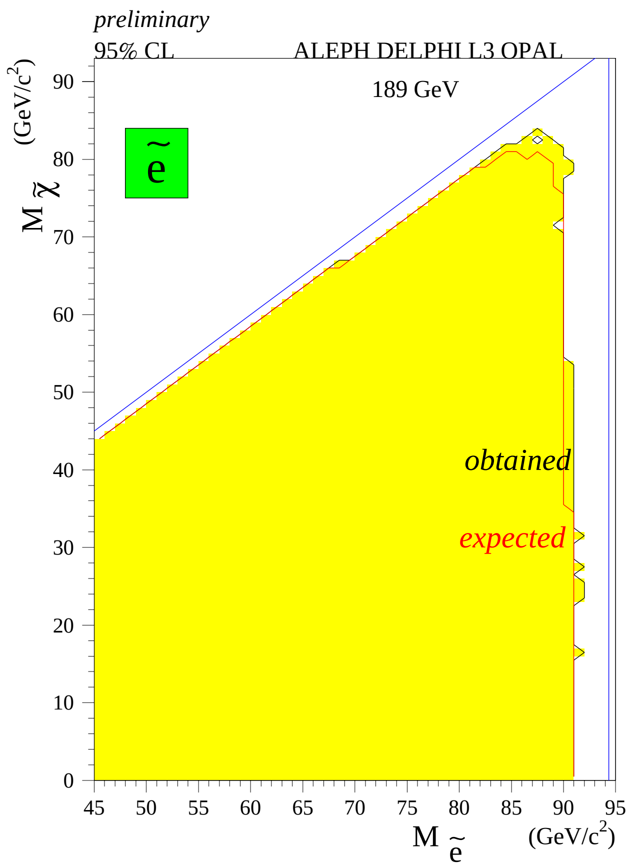
- Framework
  MSSM, Rp conserved
  + soft SUSY breaking mediated by gravity
  ⇒soft breaking terms unified at high scale
- Parameters
  - $\mathbf{m_0}$: common sfermion mass term @ GUT scale
  - $\mathbf{m_{1/2}}$: common gaugino mass term @ GUT scale
  - $\mathbf{A}$: common trilinear coupling @ GUT scale
  - $\boldsymbol{\mu}$: Higgs mixing parameter
  - $\mathbf{tan\beta}$: ratio of Higgs doublet v.e.v.
- Phenomenology at EW scale
  - particle spectrum derived from RGE

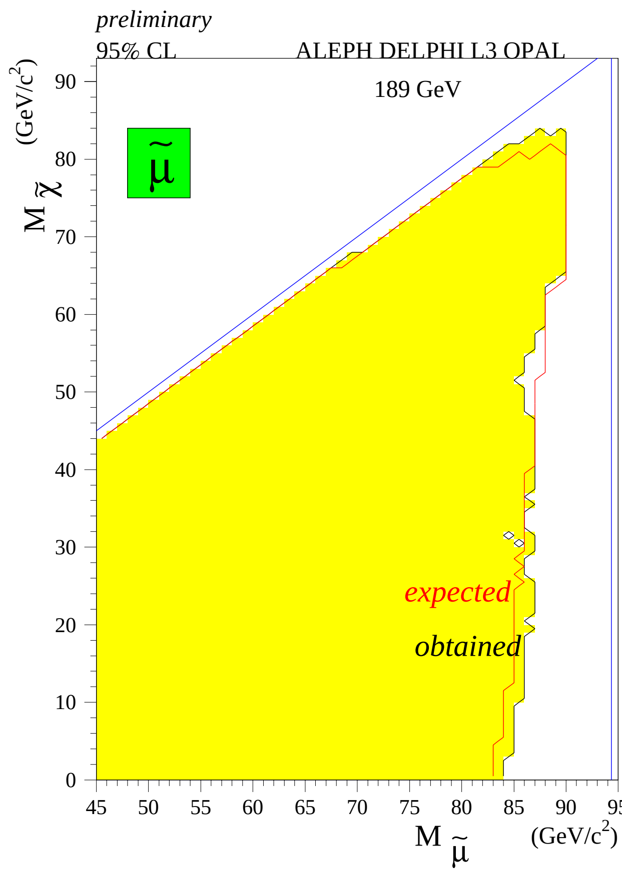
    $$\boxed{\mathrm{LSP} = \tilde{\chi}^0_1} \quad \text{(usually)}$$

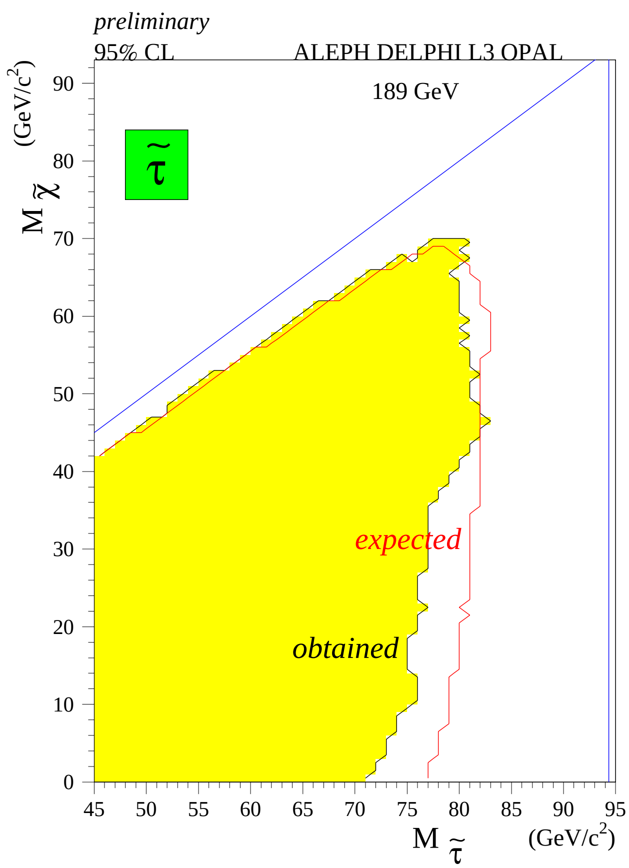
  - Rp conserved
    ⇒sparticles are pair produced
    ⇒sparticles decay in SM partner + a sparticle
    ⇒LSP stable ⇒missing energy signature

- NB: there are several constrained models with more/less assumptions, among which is :
  minimal supergravity model (mSUGRA)
  = Constrained MSSM
  with common scalar mass term $\mathbf{m_0}$ @ GUT scale
  + radiative EW symmetry breaking (⇒$|\boldsymbol{\mu}|$ fixed)

Sleptons (LEP): $e^+e^- \to \tilde{l}^+ \, \tilde{l}^-, \; \tilde{l}^\pm \to l^\pm \; \tilde{\chi}^0_1$







ADLO 189 GeV:

For $|M_{\tilde{l}} - M_{\tilde{\chi}^0_1}| > 15$ GeV:

$M_{\tilde{e}} > $ **89 GeV (exp. 90 GeV)**

$M_{\tilde{\mu}} > $ **84 GeV (exp. 83 GeV)**

$M_{\tilde{\tau}} > $ **71 GeV (exp. 77 GeV)**

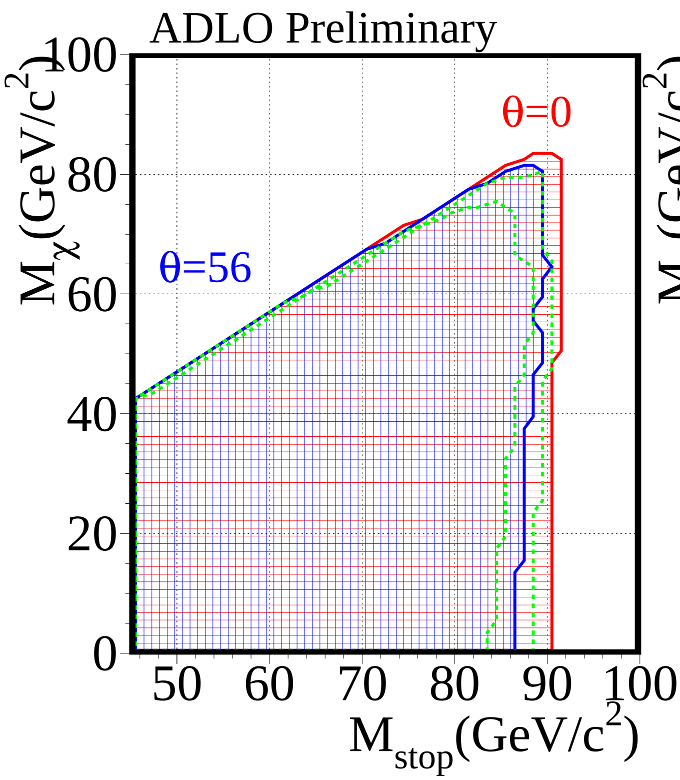
NB: minimal $\tilde{l}_R$ production σ assumed

DELPHI 196 GeV:

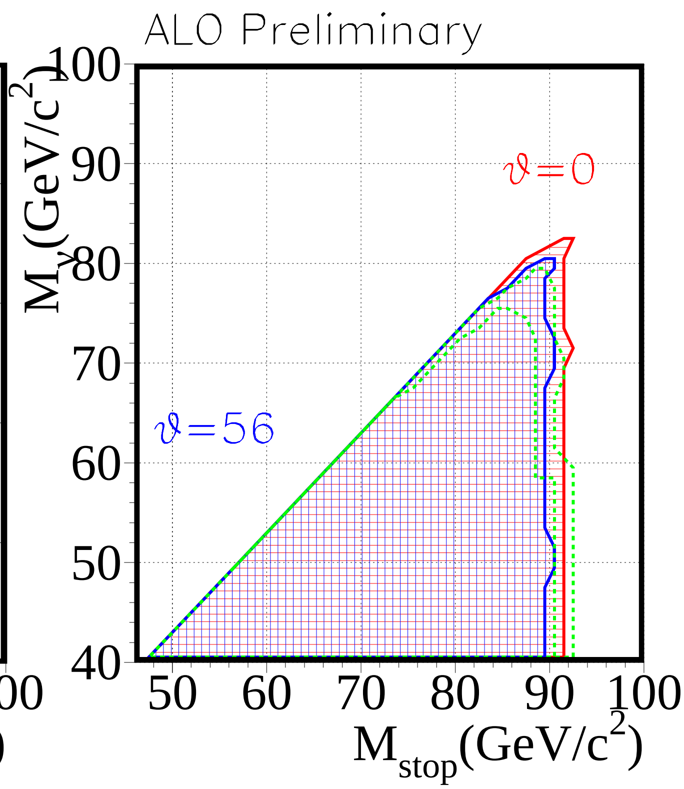
$|\Delta M| > 15$ GeV: $M_{\tilde{e},\tilde{\mu},\tilde{\tau}} > 88,80,77$ GeV

Light squarks at LEP: $e^+e^- \to \tilde{t}\tilde{t}$ and $e^+e^- \to \tilde{b}\tilde{b}$

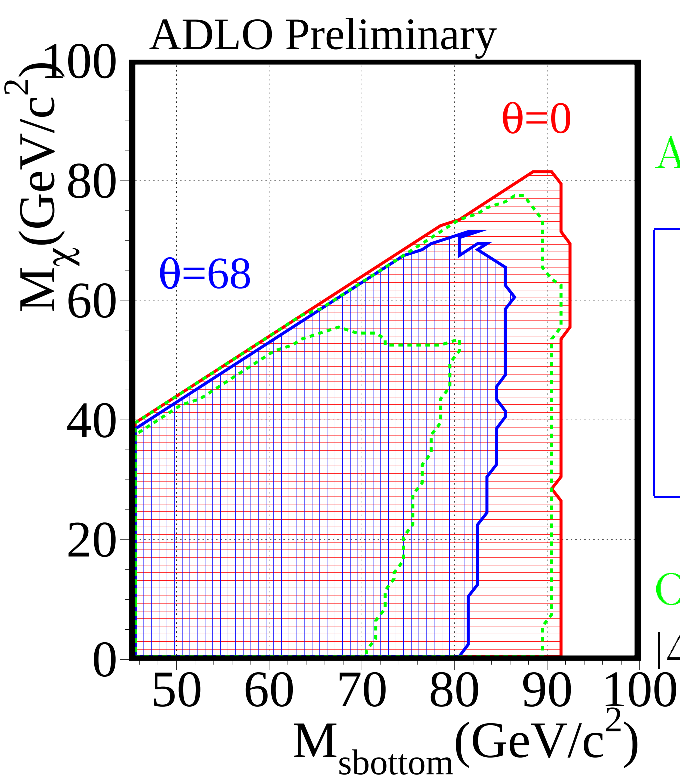
$\tilde{t} \to c\ \tilde{\chi}^0_1$:



$\tilde{t} \to b\ l\ \tilde{\nu}$:



$\tilde{b} \to b\ \tilde{\chi}^0_1$:



ADLO 189 GeV:

For $|\Delta M| > 20$ GeV, minimal σ:

$M_{\tilde{t}}^{c\tilde{\chi}} >$ **87 GeV (exp. 84 GeV)**

$M_{\tilde{t}}^{bl\tilde{\nu}} >$ **90 GeV (exp. 91 GeV)**

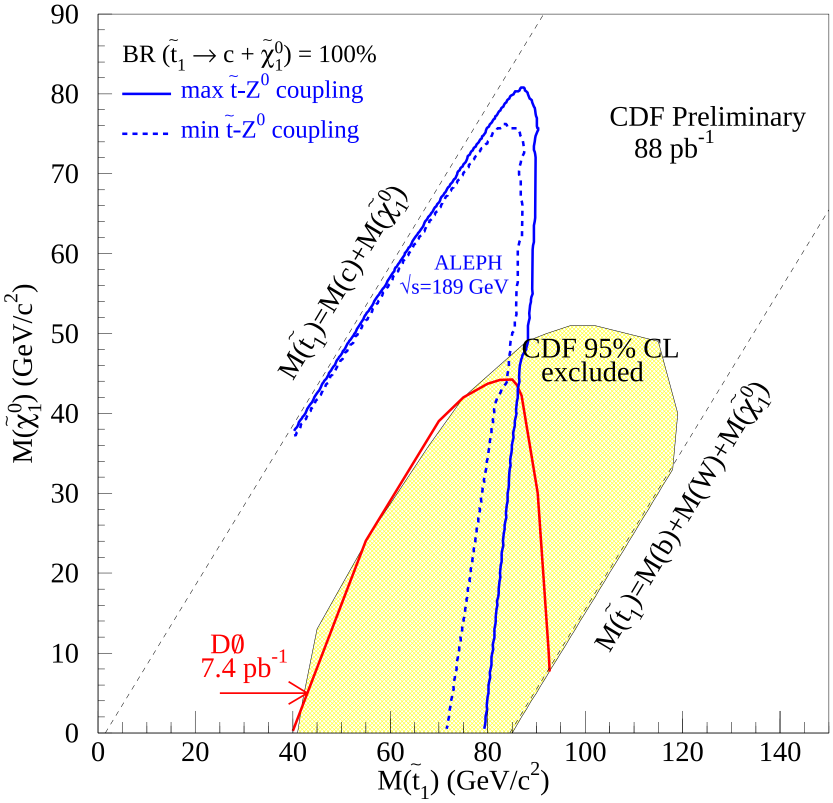
$M_{\tilde{b}} >$ **81 GeV (exp. 71 GeV)**

OPAL 196 GeV:

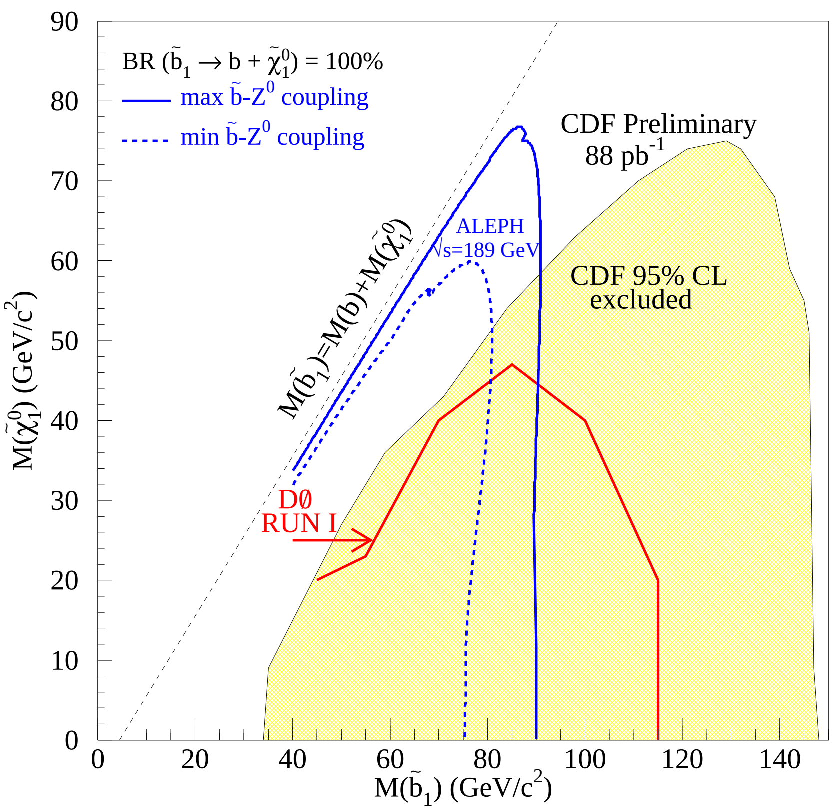
$|\Delta M| > 10$ GeV: $M_{\tilde{t}^c, \tilde{t}^b, \tilde{b}} > 90, 89, 81$ GeV

Light squarks at Tevatron: $p\bar{p} \to \tilde{t}\tilde{t}$ and $p\bar{p} \to \tilde{b}\tilde{b}$

$\tilde{t} \to c\ \tilde{\chi}^0_1$:



$\tilde{b} \to b\ \tilde{\chi}^0_1$:

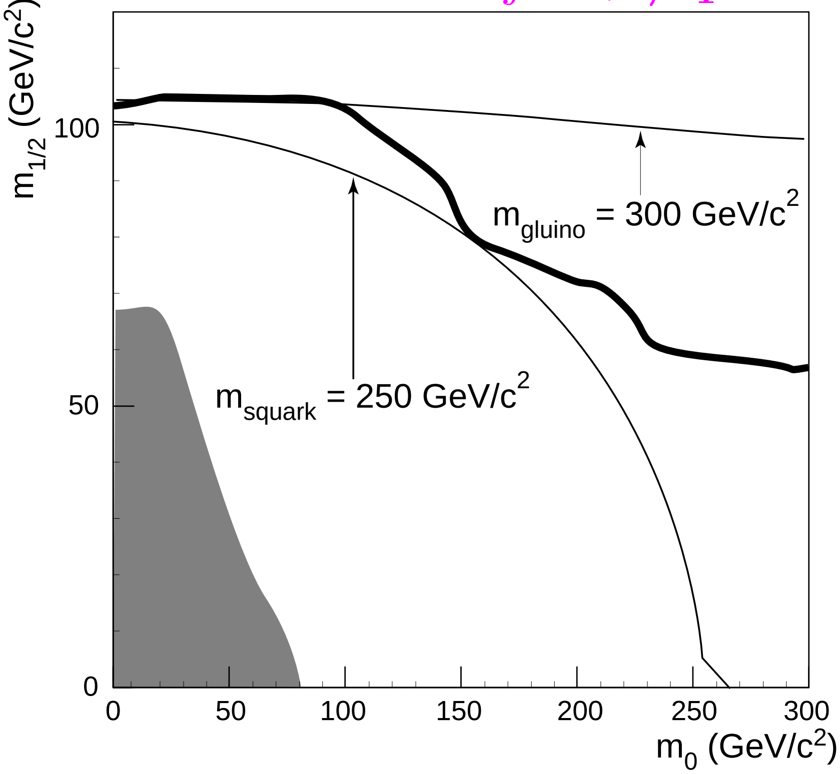


Squarks and gluinos (Tevatron): $p\bar{p} \rightarrow \tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{q}\tilde{g}$

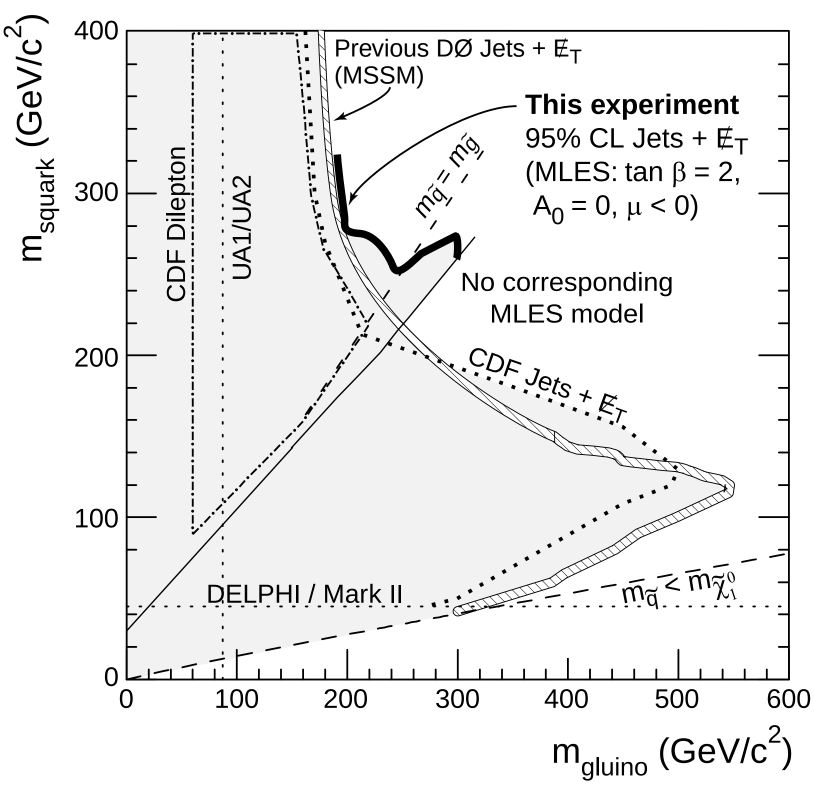
$\tilde{q}$ and $\tilde{g}$ undergo cascade decays to **LSP + q, g, $W^{\pm}$** and **Z**

$\Rightarrow$two channels : jets + $\not{E}_T$ or **l l j j** + $\not{E}_T$

Ex: DØ final result in the jets + $\not{E}_T$ channel



Analysis optimized
for
mSUGRA
and
A = 0
tanβ = 2
μ < 0



$M_{\tilde{q}}, M_{\tilde{g}} \sim 250$ GeV
probed

$\tilde{\chi}^{\pm}_1$ and $\tilde{\chi}^0_i$ at LEP: $e^+e^- \rightarrow \tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^0_2\tilde{\chi}^0_1$, $\tilde{\chi}^0_2\tilde{\chi}^0_2$

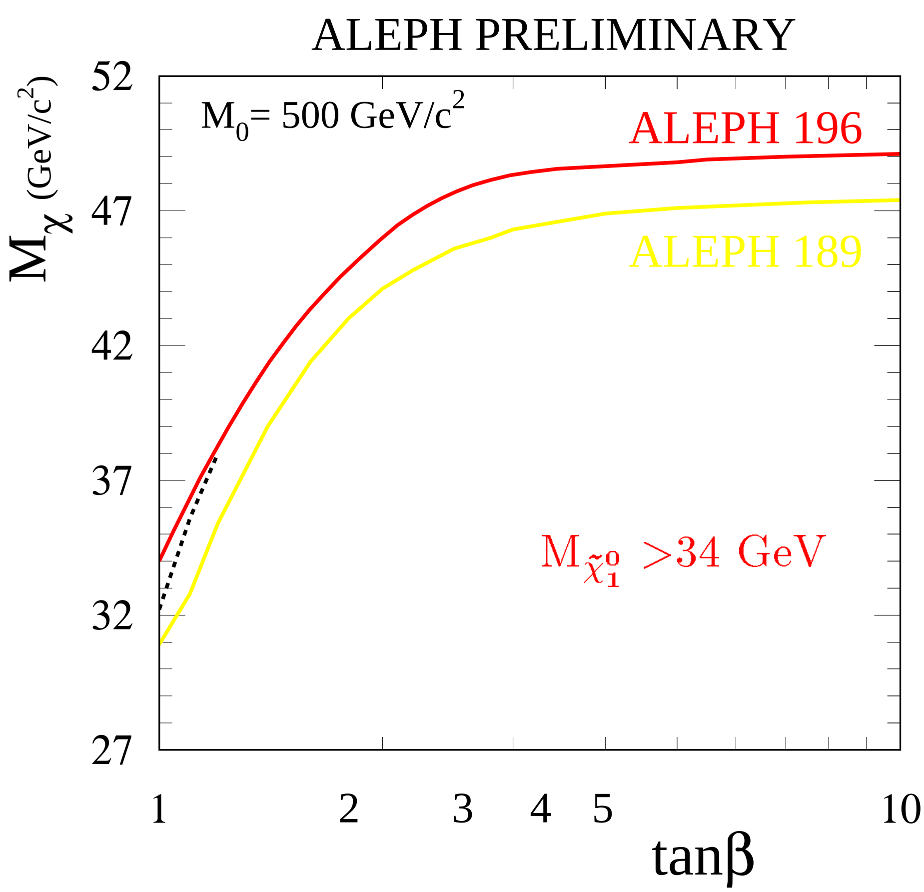
• Limits on $M_{\tilde{\chi}^{\pm}_1}$ from $\tilde{\chi}^{\pm}_1$searches (+ LEP1 constraints):

close to kinematical limit in most of the parameter space eg:

OPAL 196 GeV, $|\Delta M| > 10$ GeV, large m_0: $M_{\tilde{\chi}^{\pm}_1} > 97.6$ GeV

• Limit on $M_{\tilde{\chi}^0_1}$ from $\tilde{\chi}^0_i$and $\tilde{\chi}^{\pm}_1$searches (+ LEP1 constraints):

valid for large m_0 (whatever the other parameters), eg:



• NB: Small $m_0 \Leftrightarrow$ light $\tilde{\nu}$

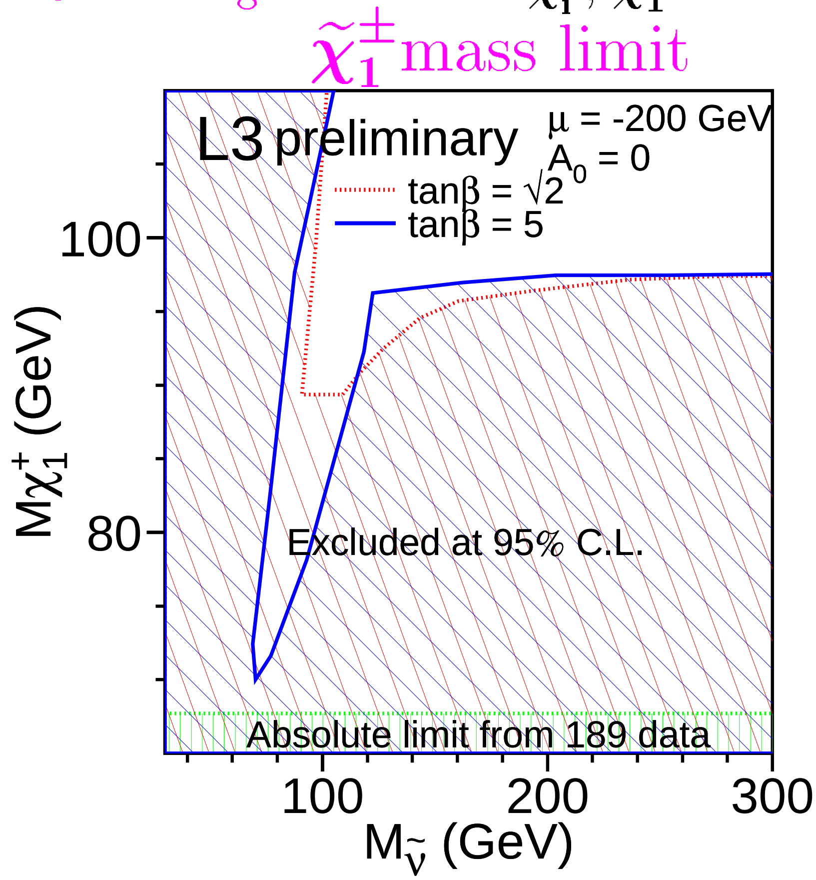
$\Rightarrow \sigma_{\tilde{\chi}^{\pm}_1}$ drops, $\tilde{\chi}^{\pm}_1 \rightarrow l\,\tilde{\nu}$ enhanced and invisible if $M_{\tilde{\chi}^{\pm}} \sim M_{\tilde{\nu}}$

$\Rightarrow \sigma_{\tilde{\chi}^0_i}$ increases but $\tilde{\chi}^0_i \rightarrow \nu\,\tilde{\nu}$ opens and can be invisible

$\Rightarrow$light $\tilde{e}$ $\Rightarrow$slepton searches can help a lot

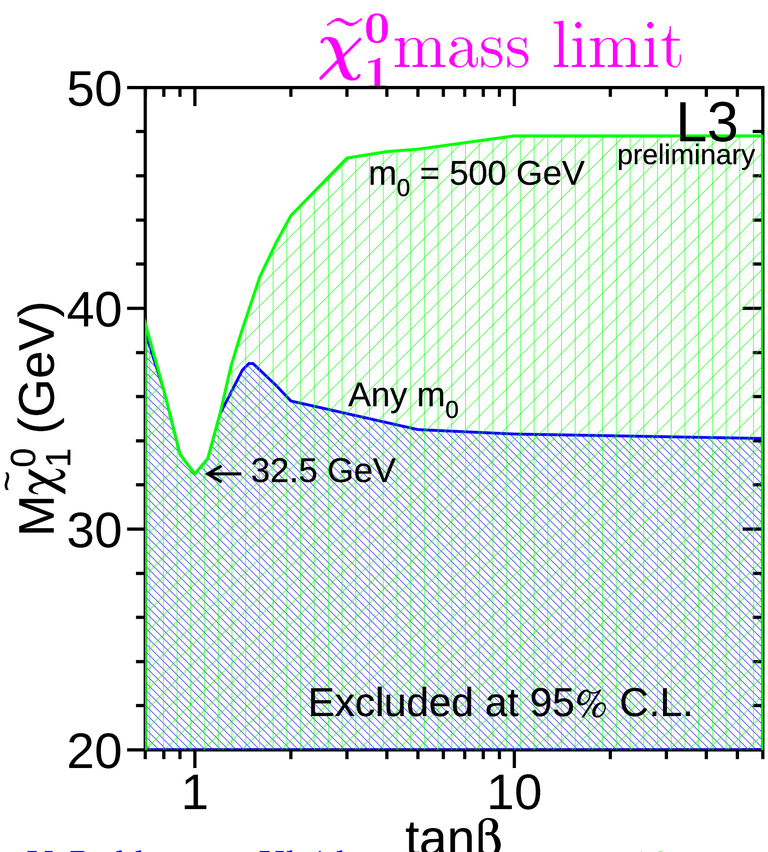
Absolute limits on $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ masses:

Combining results from $\tilde{\chi}_i^0$, $\tilde{\chi}_1^\pm$ and slepton searches:



L3 189 GeV:

$M_{\tilde{\chi}^\pm} > 67.7$ GeV



LEP 189 GeV:

$M_{\tilde{\chi}_1^0}$ limits (GeV)

A	D
32.3	31.2
L	O
32.5	31.6

Rp breaking

- Framework

  MSSM, soft SUSY breaking mediated by gravity

  $\bigoplus$ R-parity broken:

$$\mathcal{W} = \underbrace{\lambda_{ijk}\; L_i L_j \bar{E}_k + \lambda'_{ijk}\; L_i Q_j \bar{D}_k}_{L\ violation} + \underbrace{\lambda''_{ijk}\; \bar{U}_i \bar{D}_j \bar{D}_k}_{B\ violation}$$

- Parameters

  CMSSM parameters ($\mathbf{m_0}$, $\mathbf{m_{1/2}}$, A, $\boldsymbol{\mu}$, tan$\boldsymbol{\beta}$)

  $\bigoplus$ 45 new couplings (9 $\boldsymbol{\lambda}$, 27 $\boldsymbol{\lambda}'$, 9 $\boldsymbol{\lambda}''$)

- Phenomenology at EW scale

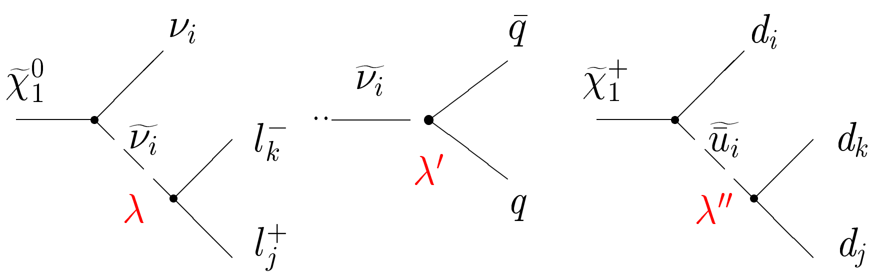
  R_p broken

  ⇒single sparticle production is possible

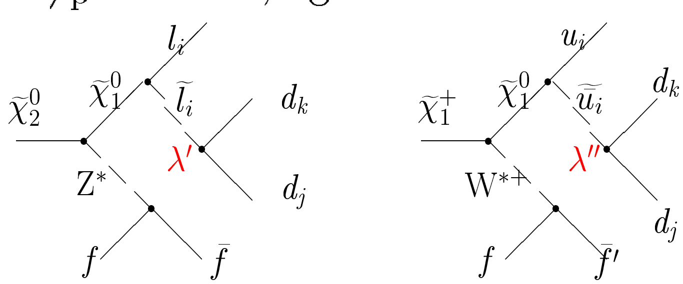
  ⇒LSP (= $\tilde{\chi}^0_1$ as in CMSSM) no longer stable

  ⇒sparticle decays are :

  - direct in SM particles through $\not{R}_p$ vertices, eg:



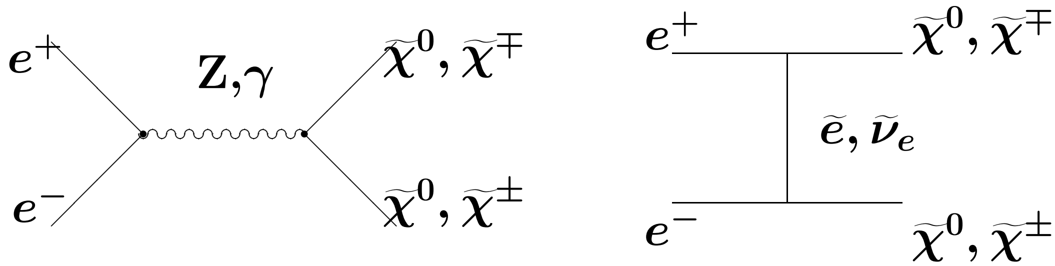
  - indirect ie cascade decays to SM particles through R_p conserved and $\not{R}_p$ vertices, eg:



⇒Many final states, with multileptons and/or multijets (+ $\not{E}$)

$\not{R}_p$: $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_i^0$ at LEP: $e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^0\tilde{\chi}_1^0$, $\tilde{\chi}_2^0\tilde{\chi}_1^0$...

- Production: as in R_p conserved mode



- Decay: completely new wrt R_p conserved mode:
  - $\tilde{\chi}_1^0\tilde{\chi}_1^0$ is visible
  - Many final-states to look at, eg:

	$\tilde{\chi}_1^0\tilde{\chi}_1^0$ direct decay	$\tilde{\chi}_1^+\tilde{\chi}_1^-$ indirect decay	$\tilde{\chi}_1^0\tilde{\chi}_2^0$ indirect decay
λ	$4l + \not{E}$	$6l + \not{E}$ $4l + 4j + \not{E}$ $5l + 2j + \not{E}$	$4(6)l + \not{E}$ $4l + 2j + \not{E}$
λ'	$4j + \not{E}$ $2l + 4j$	$2l + 4j + \not{E}$ $3l + 6j + \not{E}$ $l + 6j + \not{E}$	$4l + 4j$ $2l + 4j + \not{E}$ $2l + 6j$ $4(6)j + \not{E}$
λ''	$6j$	$2l + 6j + \not{E}$ $l + 8j + \not{E}$ $10j$	$2l + 6j$ $6j + \not{E}$ $8j$

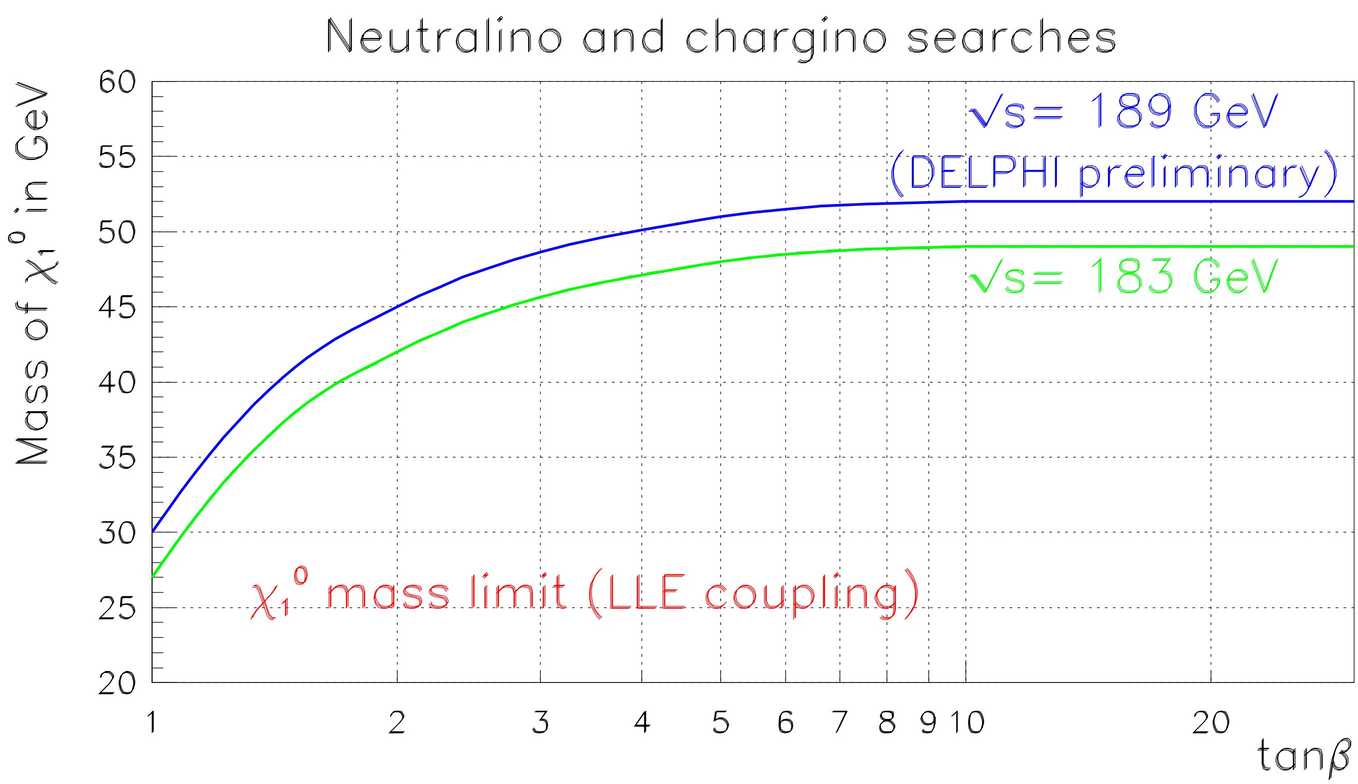
$\Rightarrow$ a lot of striking signatures

$\Rightarrow$ more stringent constraints on SUSY parameters (ie small m_0 is no more a problem)

$R\!\!\!/_p$: absolute limits on $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_i^0$ masses:

From $\tilde{\chi}_i^0$ and $\tilde{\chi}_1^\pm$ searches only:

- Exemple of result: limit on $M_{\tilde{\chi}_1^0}$ for λ couplings:



- Comprehensive study from L3 (189 GeV):

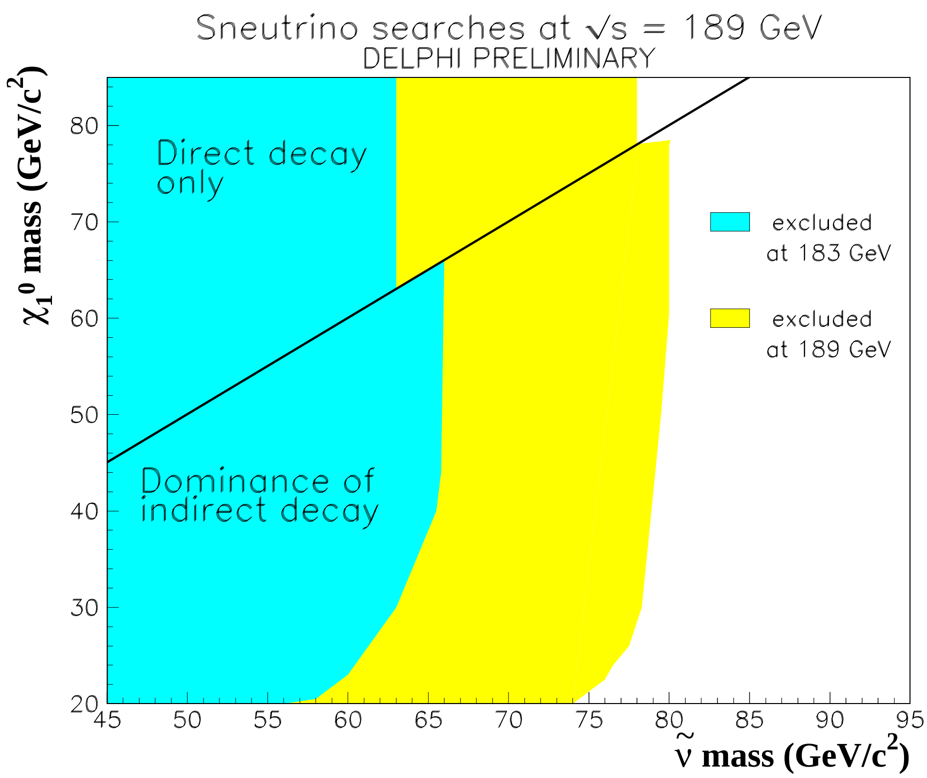
	$M_{\tilde{\chi}_1^0} >$	$M_{\tilde{\chi}_2^0} >$	$M_{\tilde{\chi}_1^\pm} >$
λ, λ':	30 GeV	50 GeV	94 GeV
λ'':	32 GeV	67 GeV	94 GeV

$\not{R}_p$: sneutrinos (LEP)

New wrt R_p conserving mode: $\tilde{\nu}$ is visible

- Double production: $e^+e^- \to \tilde{\nu}\tilde{\nu}$
  All final states (from direct or indirect decays and all types of couplings) investigated

Exemple of result: limit on $M_{\tilde{\nu}}$ for λ_{133} coupling:



•direct decays more difficult
•for any ν flavour and any λ coupling ($\bigoplus M_{\tilde{\chi}^0_1}$ limit):

$M_{\tilde{\nu}} > 78$ GeV

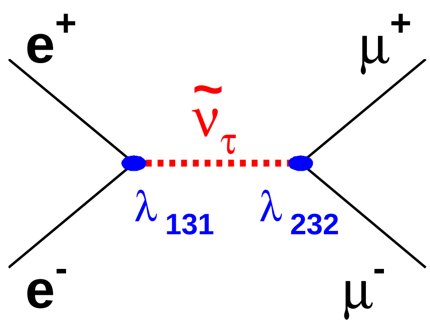
Other couplings: results from ALEPH 189 GeV

- λ': **$M_{\tilde{\nu}} > 56$ GeV** (any ν flavour)
- λ'': **$M_{\tilde{\nu}_e} > 77$ GeV** (no constraint on μ and τ sneutrinos)

$\not R_p$: sneutrinos (LEP), cont'd:

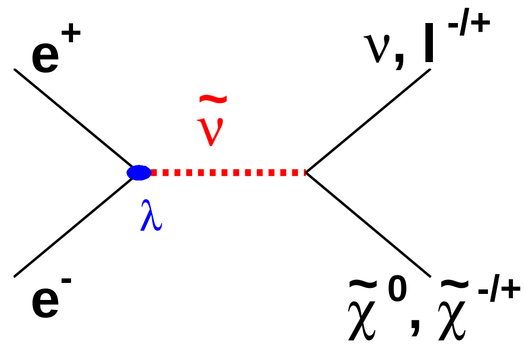
- Single production: $\tilde{\nu}_\tau$, $\tilde{\nu}_\mu$, $\boldsymbol{\lambda}$ couplings only

Direct decays, eg:
($\tilde{\nu}$ exchange)



deviations / SM

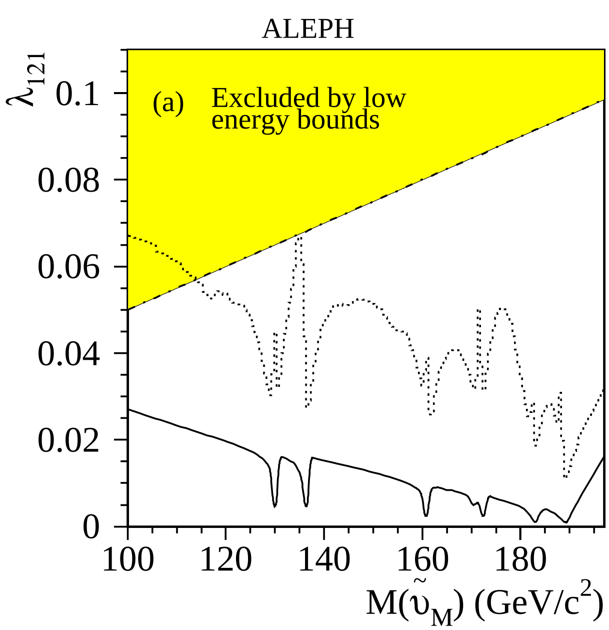
Indirect decays, eg:
($\tilde{\nu}$ resonance)

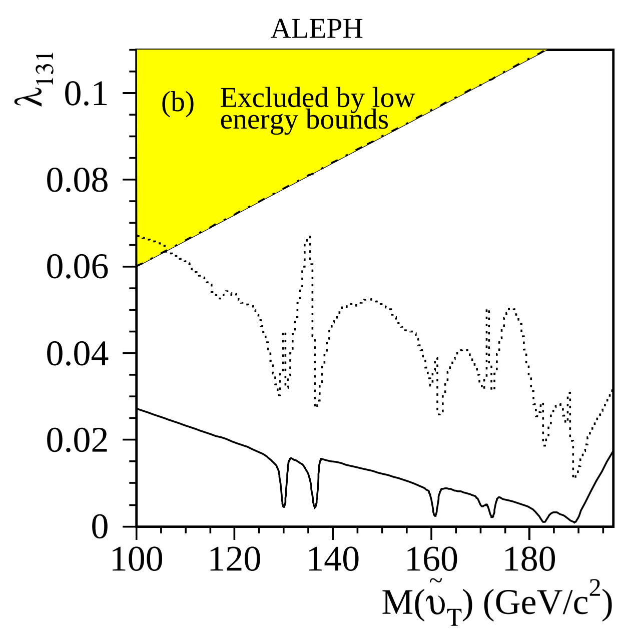


direct searches

Single vs double production
$\Rightarrow$higher masses accessible ($\sim$ 100/200 GeV)
$\Rightarrow$constraints in $\boldsymbol{\lambda}$ vs $M_{\tilde{\nu}}$ plane

Exemple of result from ALEPH 189 GeV:





$\boldsymbol{\lambda}_{121}, \boldsymbol{\lambda}_{131}$ > **a few 10^{-2}**

$\not{R}_p$: Charged sleptons and squarks:

- Charged sleptons and light squarks (LEP):

  Coverage of all final states (direct or indirect decays, any type of coupling): not yet complete.

  Some results (from ALEPH and OPAL 189 GeV):

  λ couplings: $M_{\tilde{e}_R} > 84$ GeV and $M_{\tilde{\tau}_R}, M_{\tilde{\mu}_R} > 60$ GeV

  $\lambda^{'}$ couplings: $M_{\tilde{t}_1} > 84$ GeV for any mixing

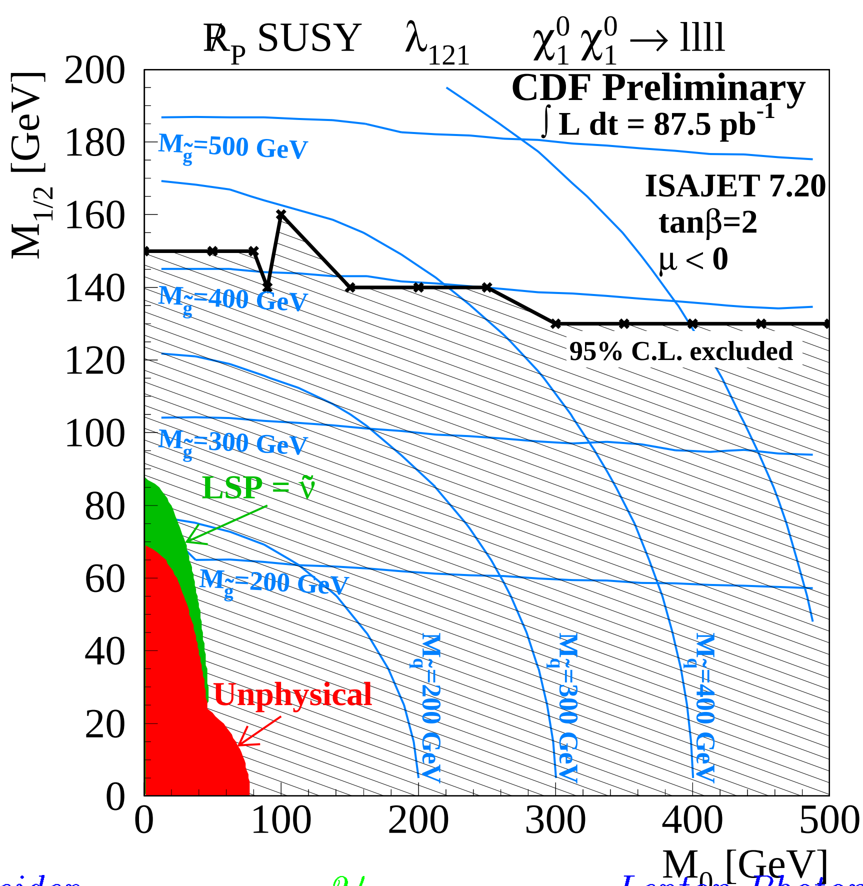
  $\lambda^{''}$ couplings: $M_{\tilde{t}_1} > 79$ GeV for any mixing

- Heavy squarks (LEP, HERA, Tevatron):

  HERA (LEP) set constraints in the $\lambda^{'}_{1j1}$ ($\lambda^{'}_{1jk}$) vs $M_{\tilde{q}}$ plane. An example of result:

$$\lambda^{'}_{1j1} = \lambda_{em}: M_{\tilde{q}} > 240 \text{ GeV (H1)}$$

  Tevatron performs $\not{R}_p$ searches for particular λ and $\lambda^{'}$ couplings. Results are model-dependent, eg:



GMSB

- Framework

  MSSM, Rp conserved

  $\bigoplus$ soft SUSY breaking mediated by gauge interactions

- Parameters: usually, six basic parameters

  $\sqrt{\mathbf{F}}$: SUSY breaking scale

  $\mathbf{\Lambda}$: universal mass scale of SUSY particles

  $\mathbf{M_s}$: messenger mass scale

  $\mathbf{n}$: number of messenger generations

  $\boldsymbol{\mu}$: Higgs mixing parameter

  $\mathbf{tan}\boldsymbol{\beta}$: ratio of Higgs doublet v.e.v.

- Phenomenology at EW scale

  - Rp conserved

    ⇒pair production

    ⇒decay into SM partner + sparticle

    ⇒stable LSP

  - Differences wrt gravity mediated breaking:

    • LSP = $\widetilde{\mathbf{G}}$ expected to be light:

    $$\mathrm{M}_{\widetilde{\mathbf{G}}}(\mathrm{eV}) \sim 1.5\ \mathbf{F}/(100\mathrm{TeV})^2 = 10^{-6}\ \mathrm{eV}\ ....\ \mathrm{keV}$$

    •NLSP = $\widetilde{\boldsymbol{\chi}}^{\mathbf{0}}_{\mathbf{1}}$ or $\widetilde{\boldsymbol{\tau}}_{\mathbf{1}}$ (or three degenerated $\widetilde{\mathbf{l}}$)

    •The NLSP lifetime can be non negligible :

    $$\mathbf{c}\boldsymbol{\tau} \propto (\mathbf{M}_{\widetilde{\mathbf{G}}})^{\mathbf{2}}$$

    ⇒wrt standard SUSY searches: new topologies to look at

...BUT

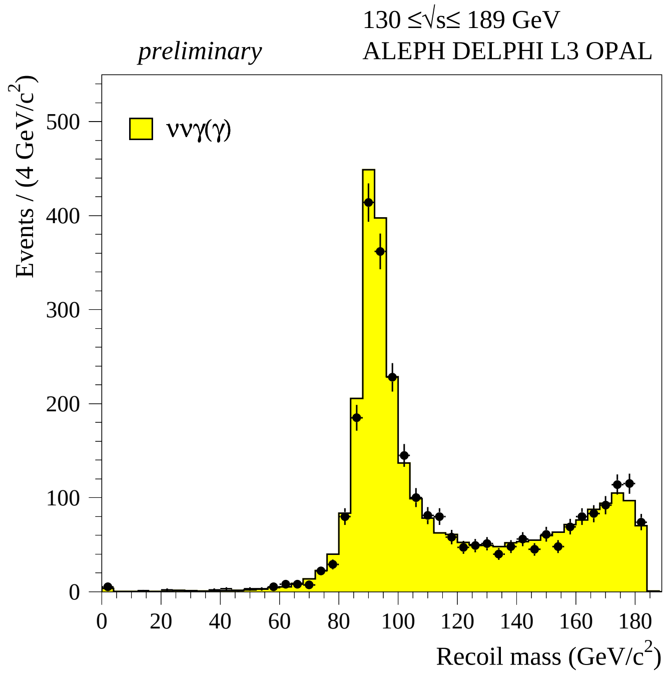
Re-interpretation of existing results in GMSB:

One example:

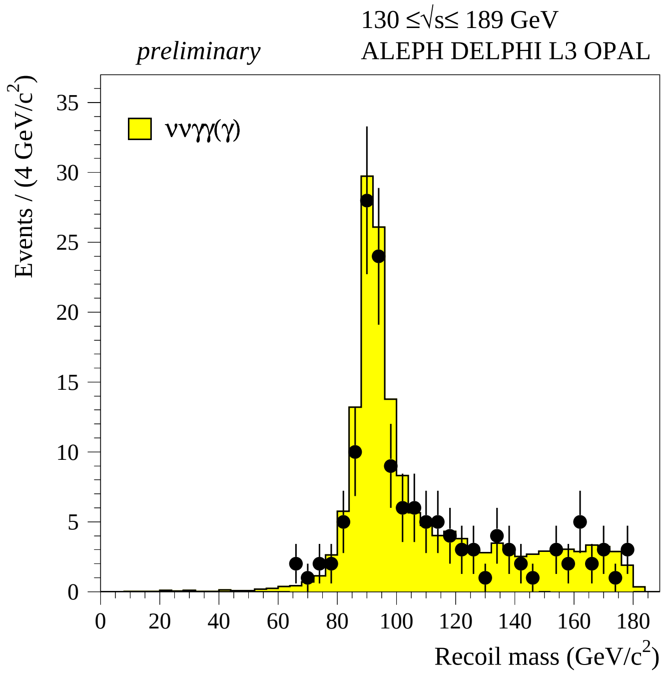
CMSSM: $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0\ \gamma \Leftrightarrow$ GMSB: NLSP$=\tilde{\chi}_1^0 \rightarrow \tilde{G}\ \gamma$ (for short $\tilde{\chi}_1^0$ $c\tau$)

Experimental results: eg, photon final states at LEP

Single γ: $e^+e^- \rightarrow \gamma$



Acoplanar $\gamma\gamma$: $e^+e^- \rightarrow \gamma\gamma$



$\Rightarrow$derive limits on σ vs $M_{X\rightarrow Y\gamma}$ and compare to predictions from specific models

NB: in a superlight $\tilde{G}$ scenario with all other SUSY particles above threshold (not strictly GMSB): limit on $\sigma \Leftrightarrow$ lower limit on $M_{\tilde{G}}$

D	L	A	CDF
$e^+e^- \rightarrow \tilde{G}\ \tilde{G}\ \gamma$			$p\bar{p} \rightarrow \tilde{G}\ \tilde{G}$ g or q
$8.9\,10^{-6}$ eV	$8.9\,10^{-6}$ eV	10^{-5} eV	$1.2\ 10^{-5}$ eV

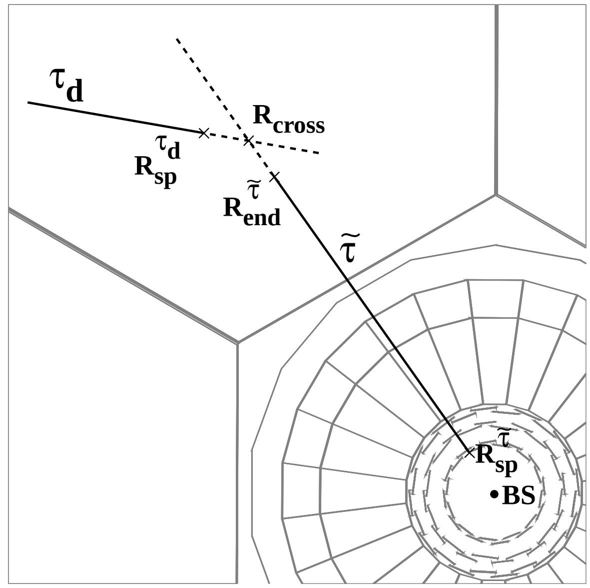
New analyses specific to GMSB models:

New toplogies arise if NLSP lifetime is non negligible, eg:

- NLSP=$\tilde{\chi}_1^0$: $\tilde{\chi}_1^0 \rightarrow \tilde{G}\ \gamma$ $\Rightarrow$non-pointing photons
- NLSP=$\tilde{l}$: $\tilde{l} \rightarrow \tilde{G}\ l$

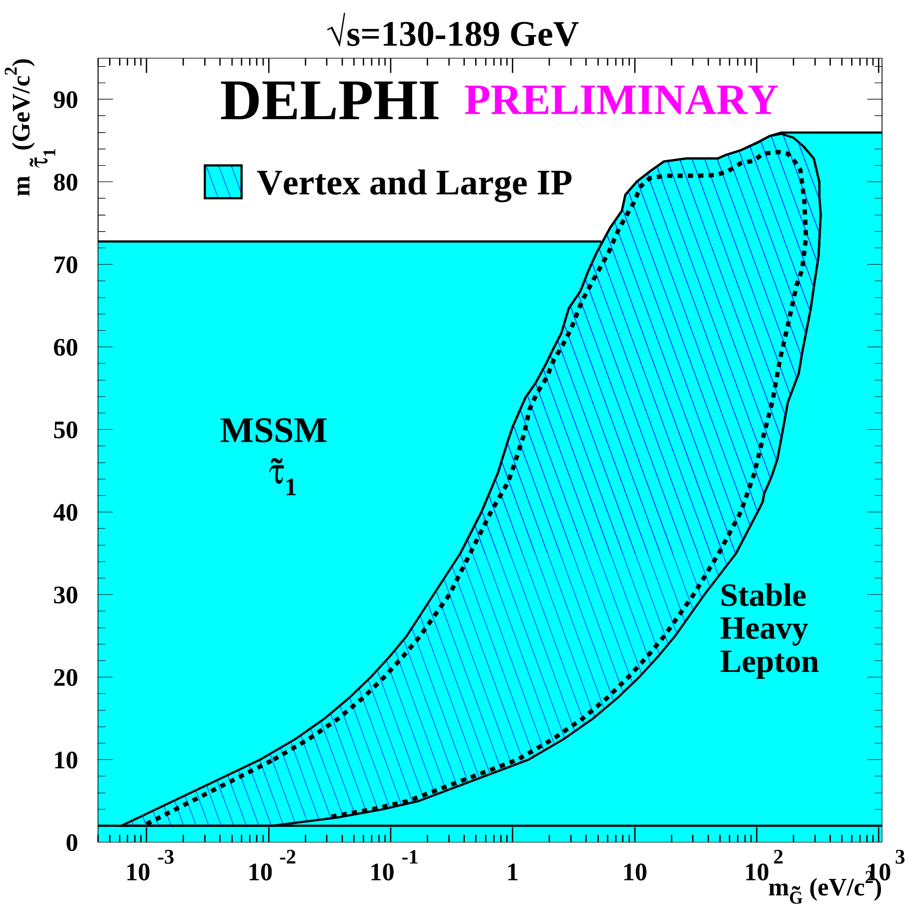
$\Downarrow$

kinks
or
large impact parameters
decay vertices,
stable charged particles



An example of result:

NLSP=$\tilde{\tau}_1$, search for $e^+e^- \rightarrow \tilde{\tau}_1\ \tilde{\tau}_1 \rightarrow \tau\tau\ \tilde{G}\ \tilde{G}$:



$M_{\tilde{\tau}_1} > 73$ GeV

if three co-NSLP $\tilde{l}$:
$M_{\tilde{l}} > 75$ GeV

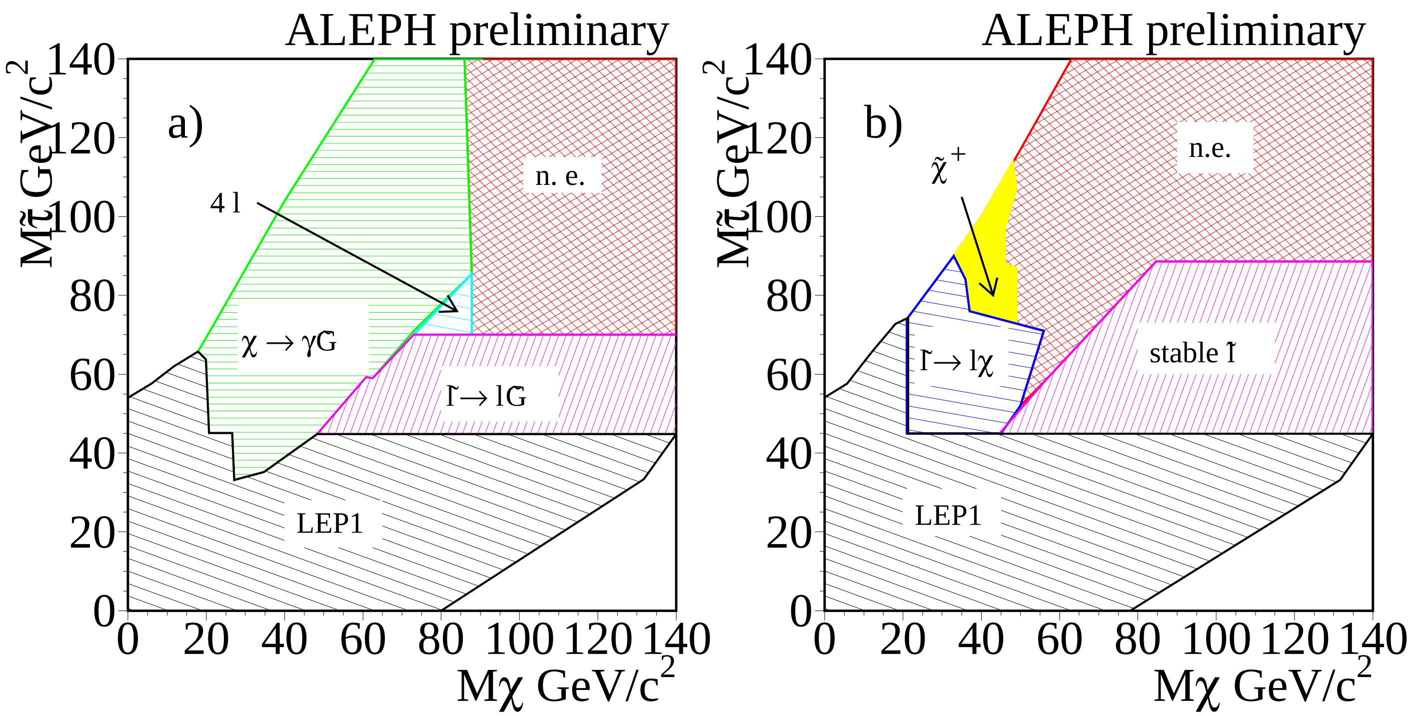
NB: minimal σ assumed

Constraints on GMSB model parameters:

An example: scan performed by ALEPH (189 GeV)

Combining the results from different analyses (NSLP=$\tilde{\chi}_1^0$ or $\tilde{\tau}_1$, any NLSP lifetime):

Short NLSP lifetime   Long NLSP lifetime



After a (yet limited) scan over the model parameters:

$$\mathbf{NLSP} = \tilde{\tau}_1 : M_{\tilde{\tau}_1} > \mathbf{67\ GeV}$$
$$\mathbf{NLSP} = \tilde{\chi}_1^0 : M_{\tilde{\chi}_1^0} > \mathbf{45\ GeV}$$
$$\Lambda > \mathbf{9\ TeV} \Rightarrow M_{\tilde{G}} > \mathbf{2.10^{-2}\ eV}$$

Beware: the validity of these results is wide (the model is a general GMSB model) but probably not absolute !

Search for extra dimensions

- Framework

  Extra spatial dimensions:

  •appear in any superstring theory (usually, 6 extra dimensions)

  •more generally, can solve the hierarchy problem

- Parameters

  $\mathbf{n}$ extra compact spatial dimensions of radius $\mathbf{R}$, with

  $\mathbf{M_D}$ quantum gravity scale in $\mathbf{n+4}$ dimensions

  $$\boxed{\mathbf{M^2_{Pl} \sim R^n\, M_D^{2+n}}}$$

  ⇒No more hierarchy if $\mathbf{R}$ and $\mathbf{n}$ such that $\mathbf{M_D}\sim$ EW scale

  NB: if $\mathbf{M_D} \sim 1$ TeV:

  $\mathbf{n} = 1$ ruled out ($\mathbf{R} \sim$ solar system distances)

  $\mathbf{n} = 2$ gives $\mathbf{R}\sim 0.1/1$mm

- Phenomenology at EW scale

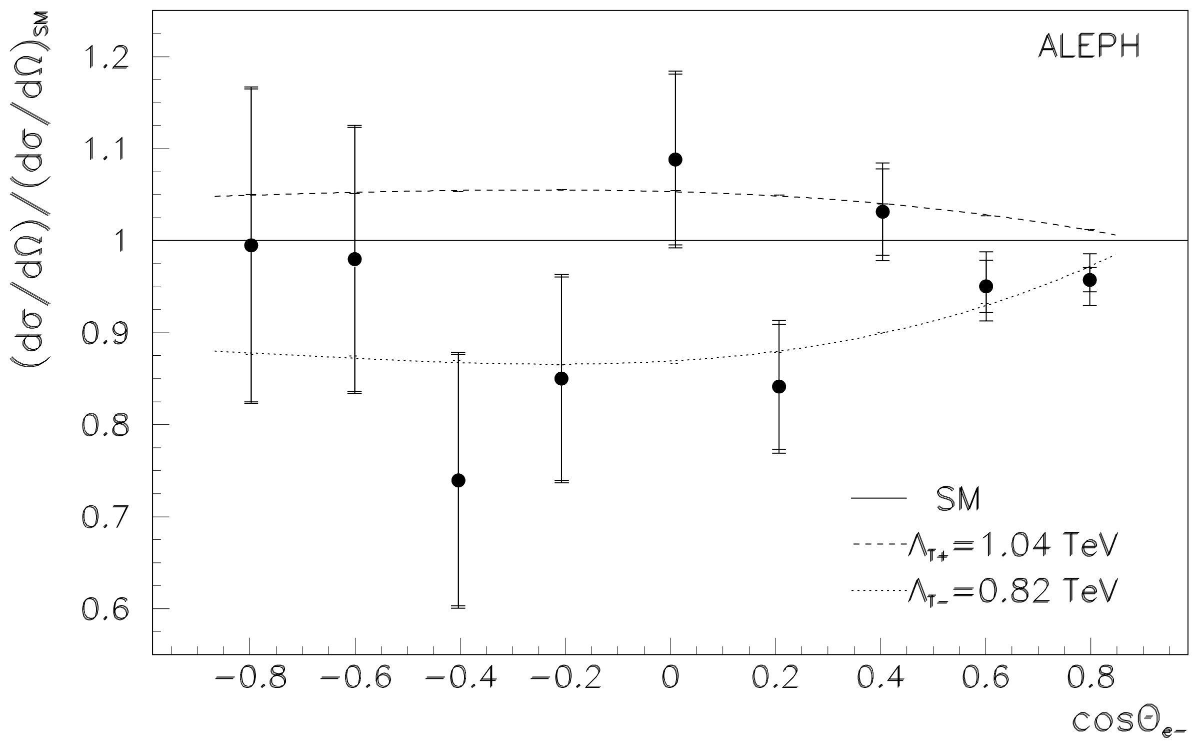
  Effects due to gravitons ($\mathbf{G}$) at EW scale: observable in both direct searches and indirect effects

Search for extra spatial dimensions:

- Direct effects: $\mathbf{e^+e^-} \rightarrow \gamma\ \mathbf{G}$ at LEP2
  From single photons (again !), constraints can be put on $\mathbf{M_D}$ for different $\mathbf{n}$ (eg DELPHI 189 GeV):

n	**2**	**4**	**6**
$\mathbf{M_D >}$	**1.11 TeV**	**0.7 TeV**	**0.53 TeV**

- Indirect effects: look for deviations / SM
  eg ALEPH 189 GeV (Bhabha process):



⇒Combining several final states, constraints are derived on the UV cut-off of the quantum gravity theory:

$$\mathbf{\Lambda_+ > 1.12\ TeV} \qquad \mathbf{\Lambda_- > 0.84\ TeV}$$

$\mathbf{\Lambda_+}$ ($\mathbf{\Lambda_-}$) stands for positive (negative) interference between SM and G exchange amplitudes

Higgs bosons

- The SM Higgs boson
- MSSM neutral Higgs bosons
- Neutral Higgs bosons beyond MSSM
- Charged Higgs bosons

The SM Higgs boson (LEP)

- Production: $e^+e^- \to H\ Z$
  - All **Z** final states investigated
  - BR($\mathbf{H \to b\bar{b}}$)$\sim$ 80%: searches rely heavily on b-tagging
- Status at 189 GeV:

  At the level of selections where data are compared with MC to test the *signal* and *signal+background* hypotheses:

	bkg **HZ**	data **HZ**	exp. limit (GeV)	obs. limit (GeV)	1-CLb at obs. lim.
A	44.4	53	95.9	92.9	4%
D	172.7	187	94.6	94.1	20%
L	91.1	94	94.8	95.3	64%
O	35.4	41	94.9	91.0	4%

$\Downarrow$

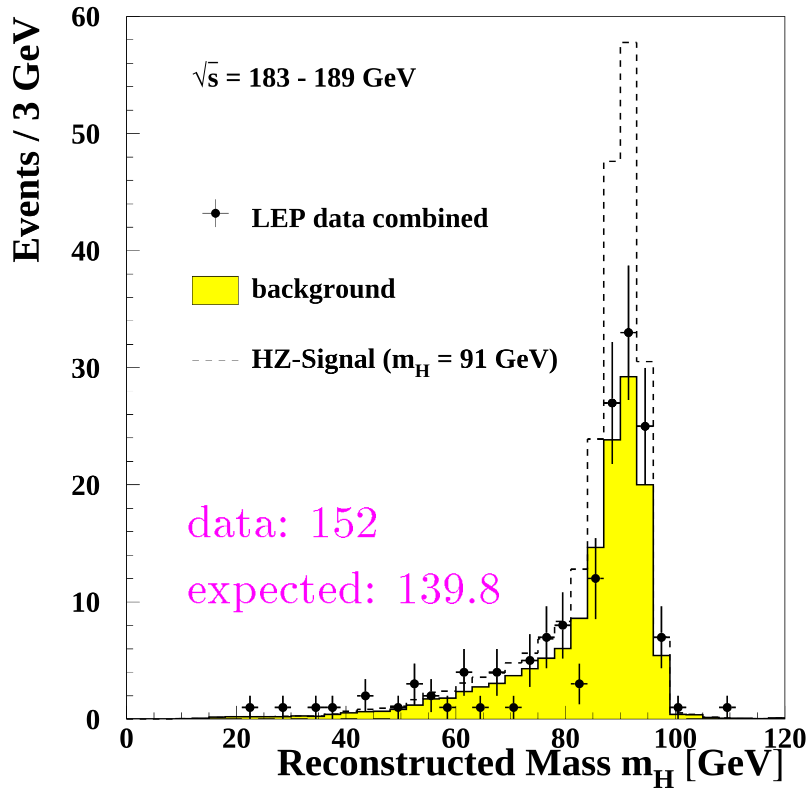
Excess of data in 3 experiments
which is partly signal-like in 2 of them

BUT

the effect is likely to be due to :
a statistical fluctuation of the dominant ZZ background
or
a systematic underestimate of the background (imperfect b-tagging simulation)

The SM Higgs boson, cont'd:

- An illustration of the data/MC agreement: the LEP combined reconstructed Higgs mass spectrum after tighter cuts

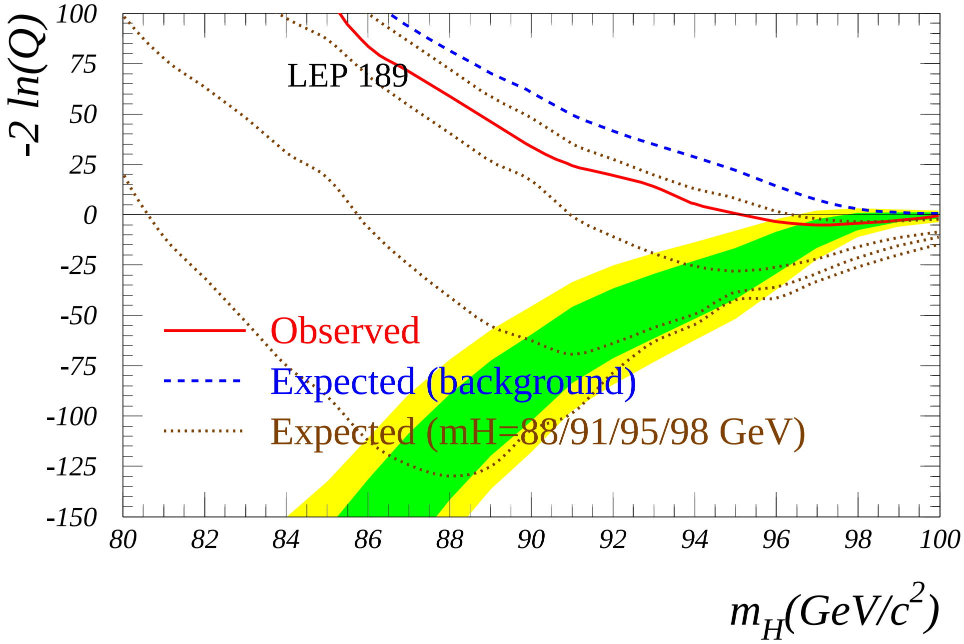


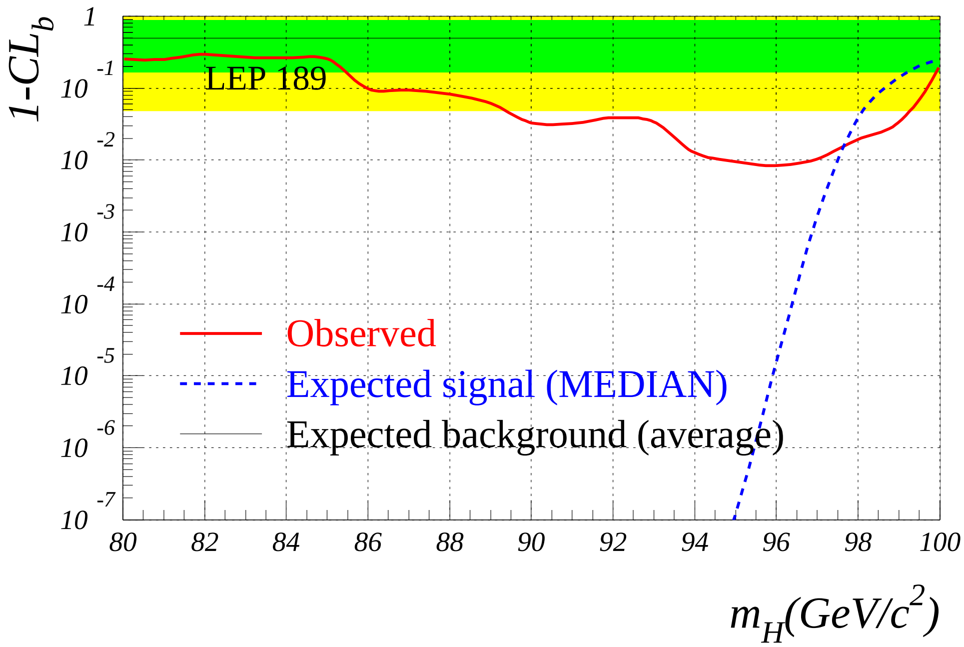
- Statistical analysis of the search results:

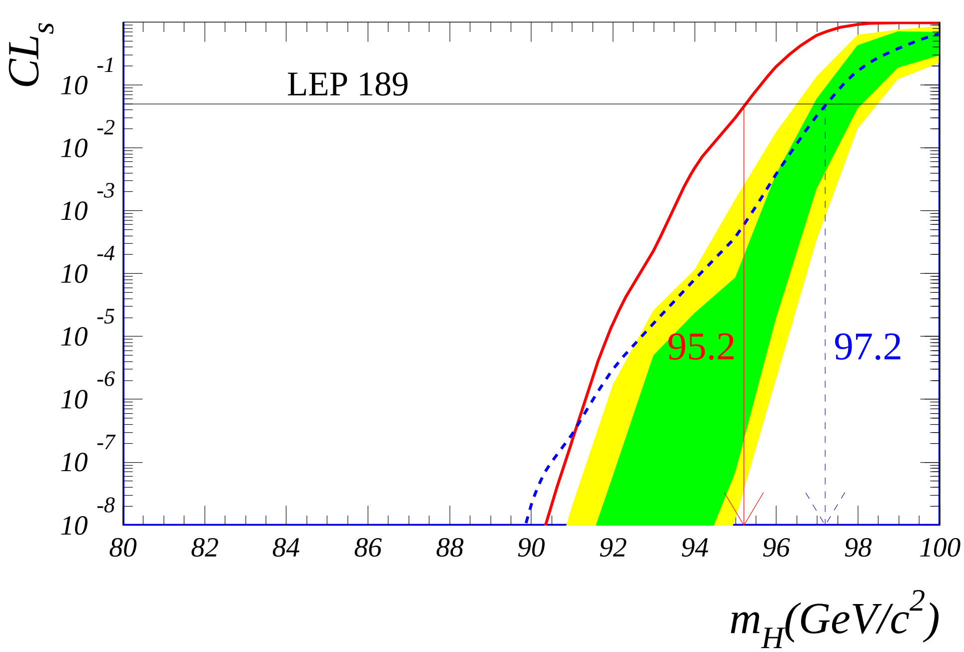
  To achieve the highest sensitivity to the Higgs boson signal, data and simulation are compared by means of a test-statistics (eg the $s + b$ over b likelihood ratio) which takes into account the rates AND the pattern of the candidates (eg 2d information like 'reconstructed M_H' vs 'b-tagging output') for each channel independently.

  Uncertainties are included (at the moment, only on signal efficiencies and background rates).

⇒ **Combined ADLO limit at 189 GeV:**
$M_H > 95.2$ GeV (exp. 97.2 GeV)


-2 ln(Q)
LEP 189
Observed
Expected (background)
Expected (mH=88/91/95/98 GeV)
$m_H(GeV/c^2)$

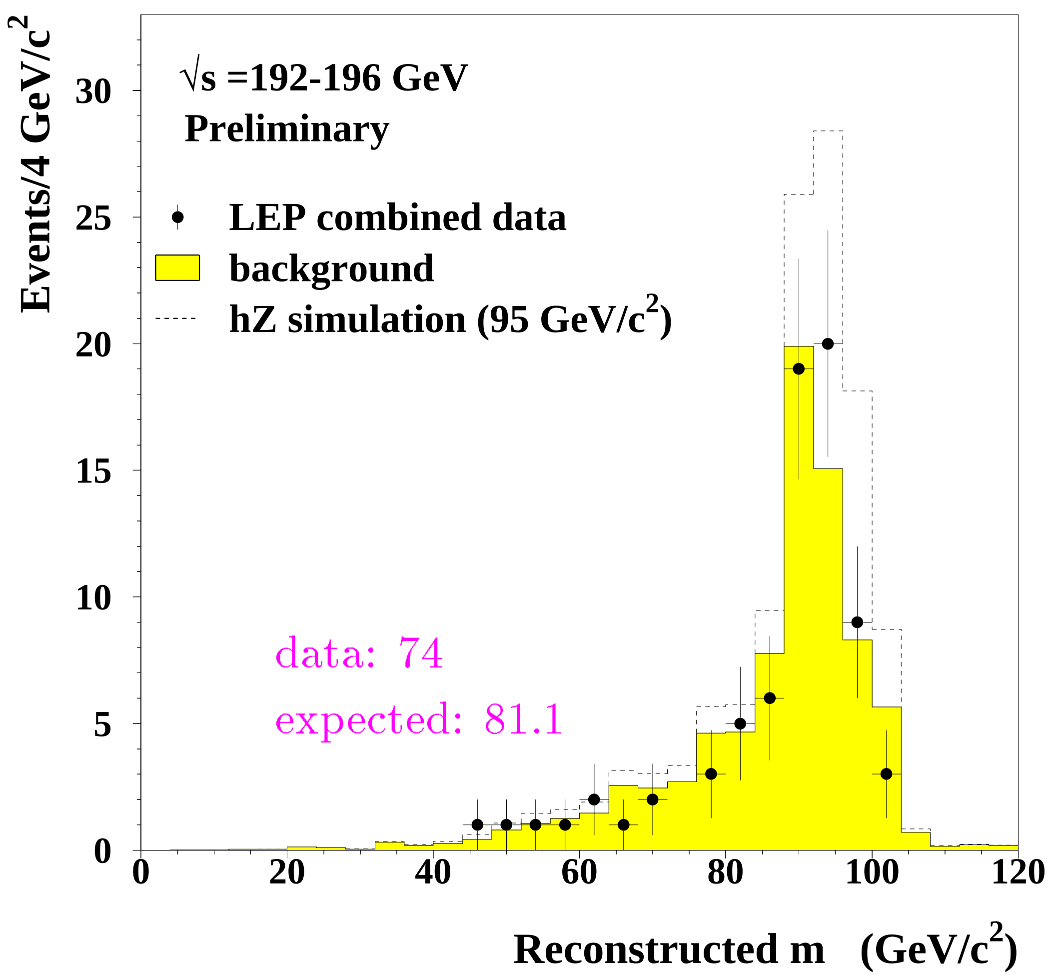

1-CL_b
LEP 189
Observed
Expected signal (MEDIAN)
Expected background (average)
$m_H(GeV/c^2)$


CL_s
LEP 189
95.2
97.2
$m_H(GeV/c^2)$

The SM Higgs, a recent update at 192/196 GeV:

	lumi (pb^{-1})	bkg **HZ**	data **HZ**	exp. limit (GeV)	obs. limit (GeV)
A	98	32.3	27	99.9	98.8
D	84	15.4	15	97.0	97.3
L	55	28.9	31	96.2	96.6
O	85	21.0	23	97.3	95.4
L	109	42.2	38	97.3	98.7

⇒Gain of 2/3 GeV gain in sensitivity



These results are VERY preliminary !

The MSSM h and A bosons (LEP)

- Production: $e^+e^- \to h\ Z$ (cf. SM) and $e^+e^- \to h\ A$

  •Two processes complementary in the parameter space

  •BR($h, A \to b\bar{b}$)$\sim$ 90%: b-tagging crucial also for **hA** (main final state in 4**b**)

- Framework

  MSSM, Rp conserved

  + soft breaking terms unified at EW scale

- Parameters

  M_{top}

  M_{susy} : common sfermion mass term @ EW scale

  M_2 : common gaugino mass term @ EW scale

  A : common trilinear coupling @ EW scale

  μ : Higgs mixing parameter

  $\tan\beta$: ratio of Higgs doublet v.e.v.

  M_h or M_A

  Once the parameters governing the radiative corrections are set, there are only two free parameters chosen among $\tan\beta$, M_h and M_A.

- Benchmark scans:

  - M_{top} = 175 GeV
  - M_{susy} = 1 TeV, M_2 = 1.6 TeV
  - two extreme hypotheses about stop mixing:

    minimal mixing (A = 0, μ = -100 GeV) $\to$ light **h**

    maximal mixing ($A = \sqrt{6}M_{susy}$, μ = -100 GeV) $\to$ heavy **h**

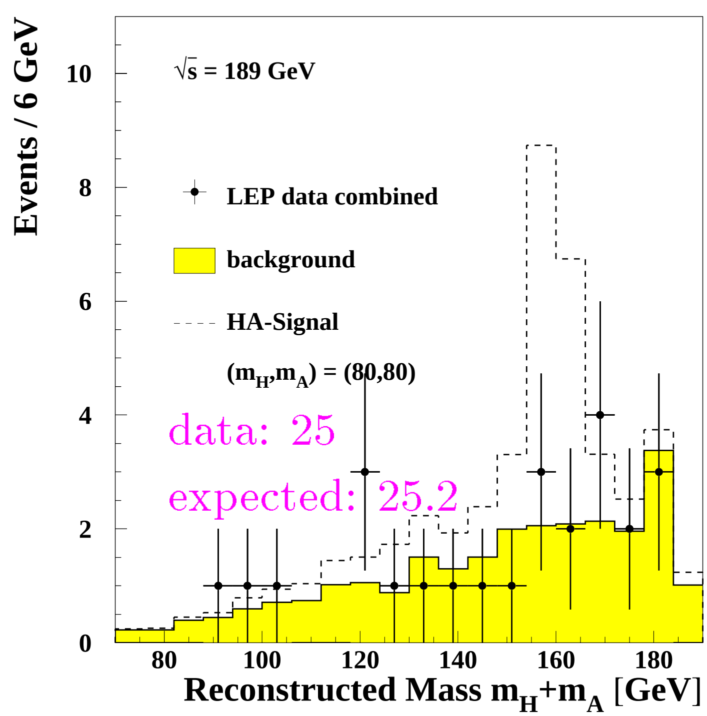
  The other parameters ($\tan\beta$, **h** or **A** masses) are varied.

- Status at 189 GeV:

  At the level of selections where data are compared with MC to test the *signal* and *signal+background* hypotheses:

	bkg hA	data hA	$\mathbf{M_h}$ limits (GeV) obs. (exp.)	$\mathbf{M_A}$ limits (GeV) obs. (exp.)
A	7.5	10	82.5 (83.1)	83.1 (83.6)
D	22.6	24	82.1 (81.1)	83.1 (82.2)
L	140.6	153	76 (78)	76 (79)
O	12.9	15	74.8 (76.4)	76.5 (78.2)

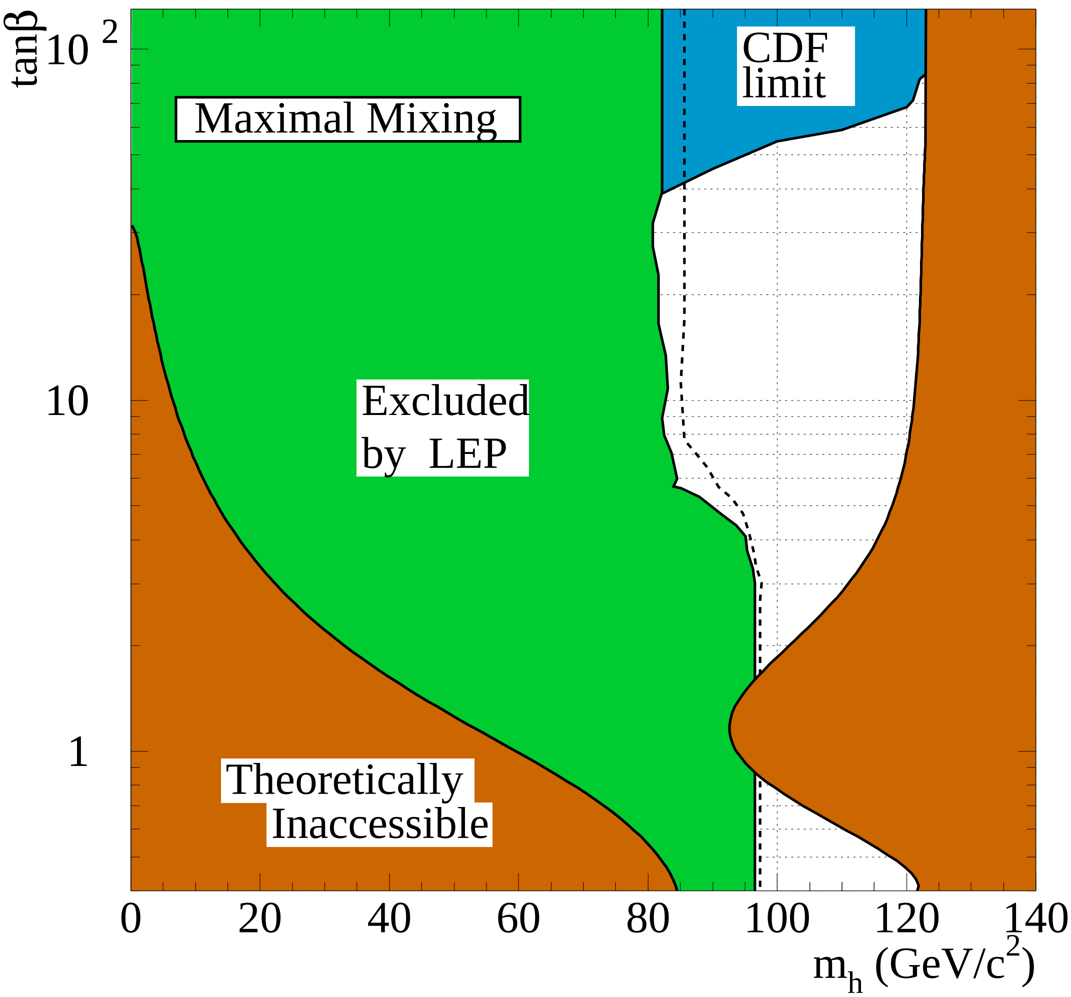
- An illustration of the data/MC agreement: the LEP combined reconstructed $\mathbf{M_h + M_A}$ mass spectrum after tighter cuts



- Statistical analysis of the search results: same method as for the SM Higgs boson

Exclusion for MSSM neutral Higgs bosons:

eg:



Combined ADLO limits at 189 GeV:

For any mixing and $\tan\beta > 0.4$

$M_h > 80.7$ GeV (exp. 85.4 GeV)

$M_A > 80.9$ GeV (exp. 85.5 GeV)

Excluded ranges in $\tan\beta$ for $M_{top} = 175$ GeV:

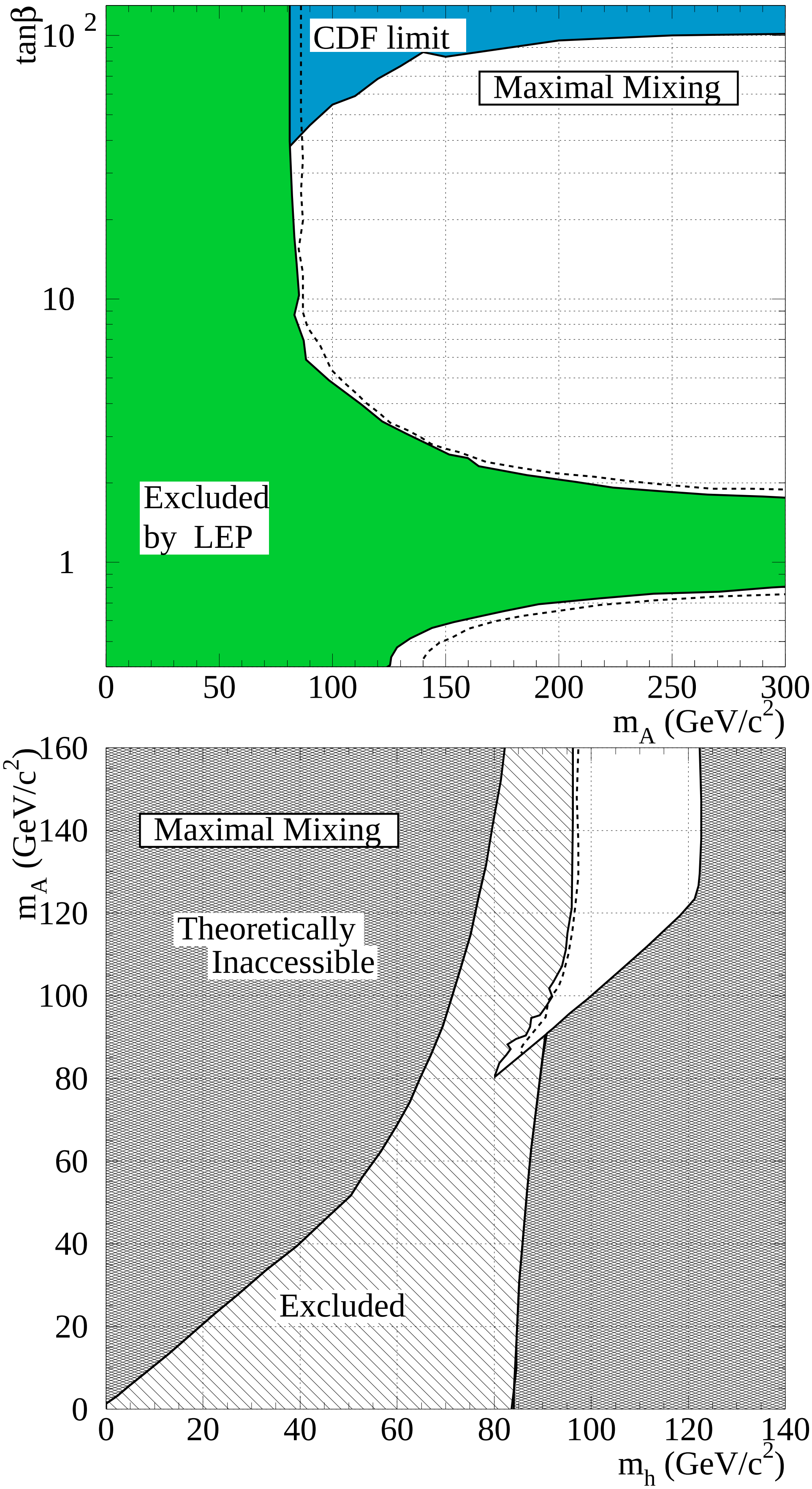
No mixing: 0.6 - 2.6 Maximal mixing: 0.9 - 1.6

Weaker bounds for higher M_{top}

NEW: Tevatron has a sensitivity at large $\tan\beta$ ($\mathbf{p\bar{p} \rightarrow b\bar{b}\ h,H,A}$)

Exclusion for MSSM neutral Higgs bosons:

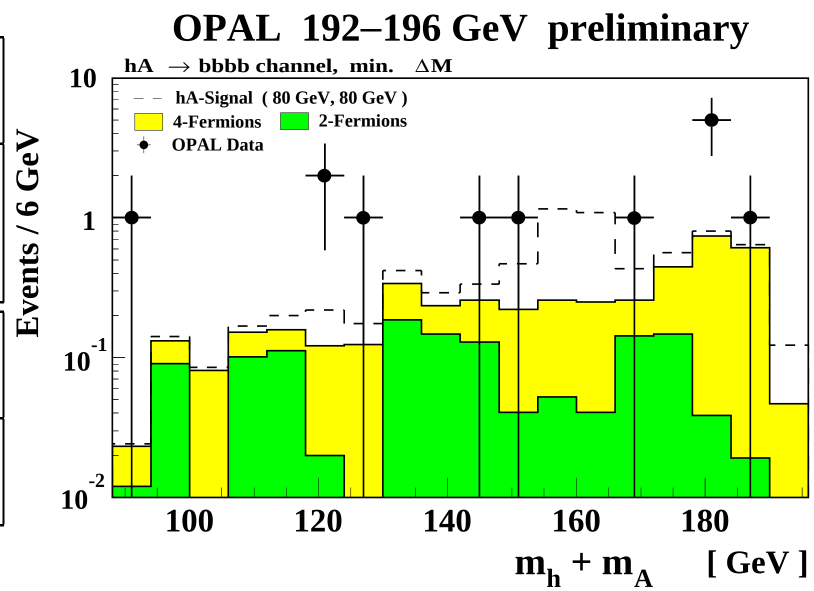
Exclusion in other planes:

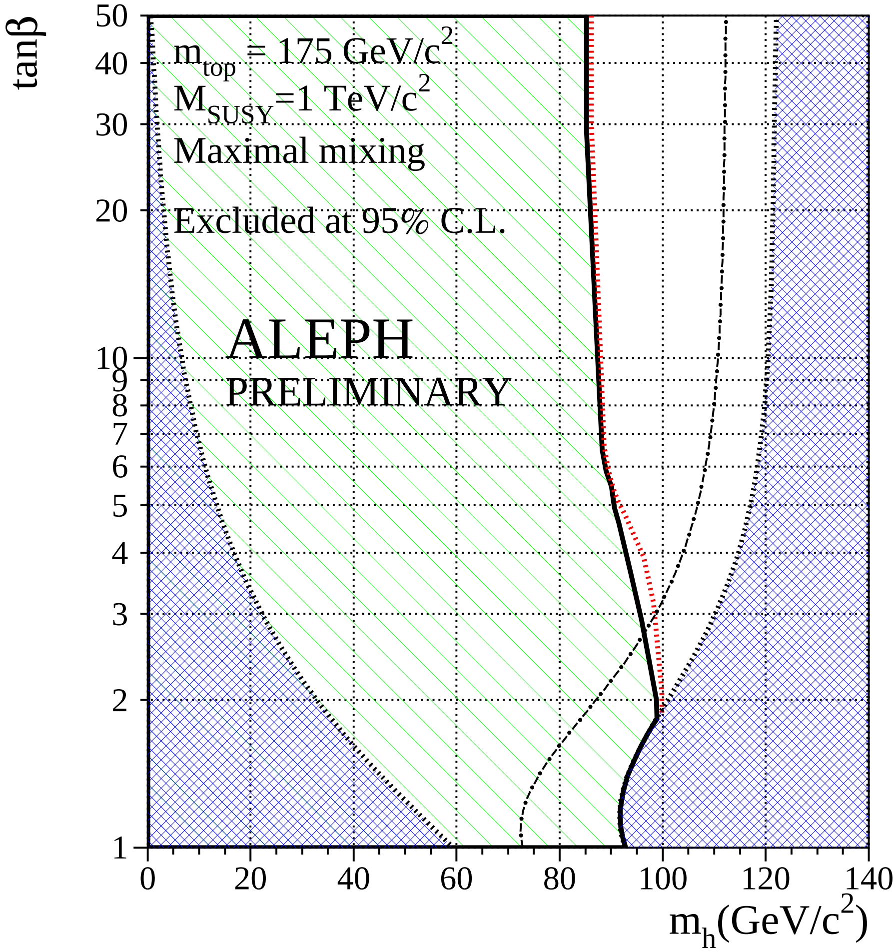


MSSM Higgses, a recent update at 192/196 GeV:

	lumi (pb^{-1})	bkg **hA**	data **hA**
A	98	4.8	1
D	84	2.6	2
O	85	6.8	14

	M_h (GeV) $>$ exp. / obs.
A	86.1 / 85.2
O	79.1 / 74.3





These results are VERY preliminary !

MSSM Higgs: towards more general constraints

To test robustness of benchmark limits:

MSSM full scans:

ie

scan all SUSY parameters

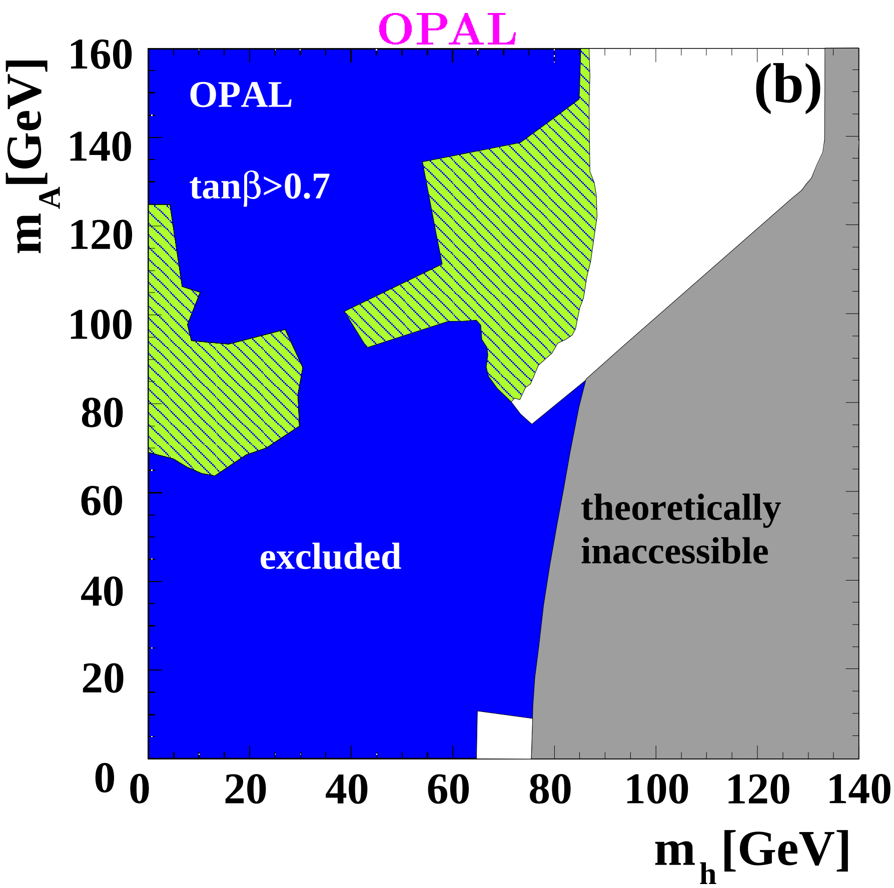
discarding parameter sets excluded by other constraints (eg. results from SUSY searches, Γ_Z measurement, $b \to s\gamma$ ....)

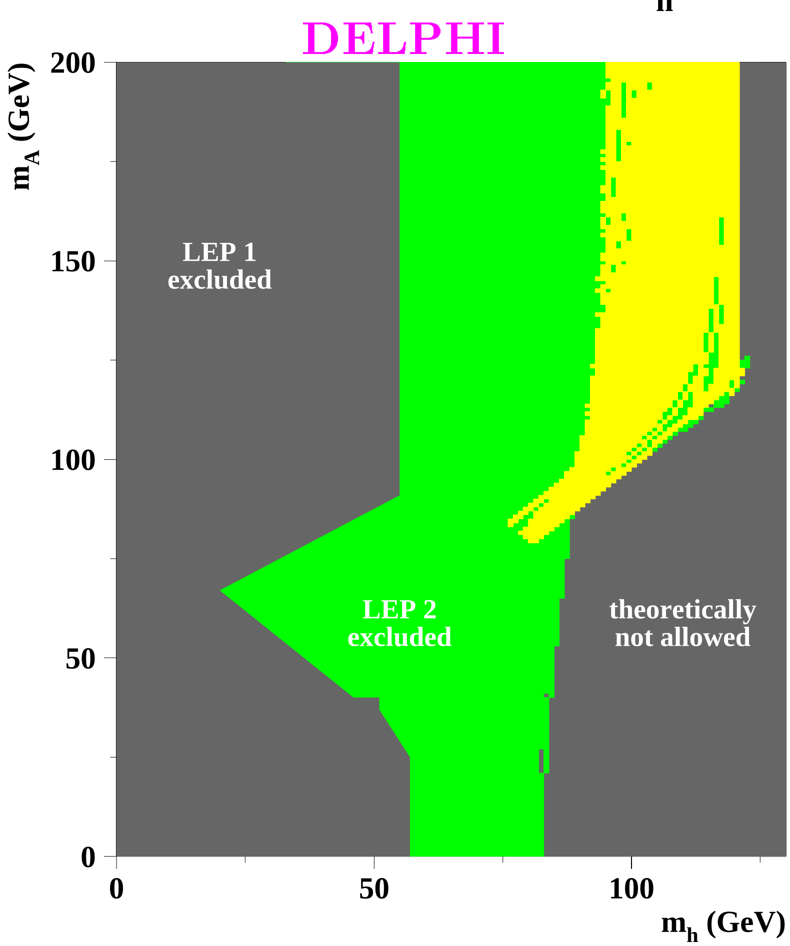
$\Downarrow$

- Benchmark limits confirmed in more than 99.99% of the parameter sets (ALEPH 183 GeV)
- Absolute limits from full scans can be derived and are a few GeV weaker than the benchmark limits, eg:

DELPHI 189 GeV:	M_h >75 GeV (bench.l. 82)
($\tan\beta > 0.5$)	M_A >80 GeV (bench.l. 83)
OPAL 189 GeV:	M_h >72 GeV (bench.l. 74.8)
($\tan\beta > 1$)	M_A >76 GeV (bench.l. 76.5)

MSSM full scans, results at 189 GeV:





h and A bosons beyond MSSM (LEP)

Beyond MSSM: three possibilities investigated so far:

- Higgs bosons **h, A** with fermionic couplings:
  The existing results are interpreted in a more general framework than MSSM, eg:
  - 2 Higgs doublet models (D and O 189 GeV)
  - general NMSSM model (D 189 GeV)

- Higgs boson **h** decaying in invisible products (all LEP expts):
  - dedicated searches in the **hZ** process
  - general constraints on σBR derived and compared with specific models
  - an example of result (L3 189 GeV):

  SM σ, BR(invis)=100%: $M_h > 95$ GeV

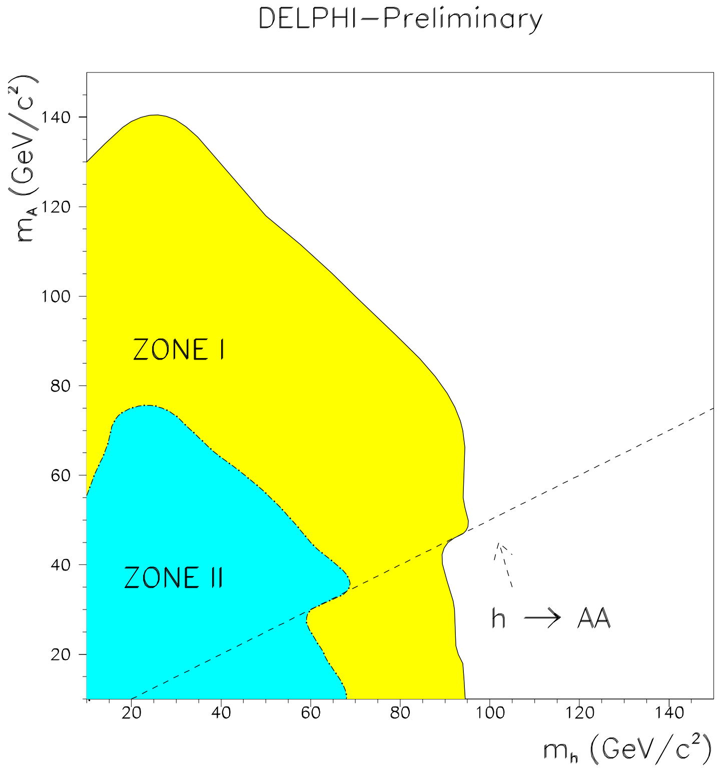
- Higgs boson **h** with anomalous couplings to photons (all LEP expts, DØ):
  - dedicated searches in the **hZ**, **h**γ and **hA** processes
  - general constraints on σBR or on anomalous couplings are derived and compared with specific models
  - an example of result (OPAL 196 GeV):

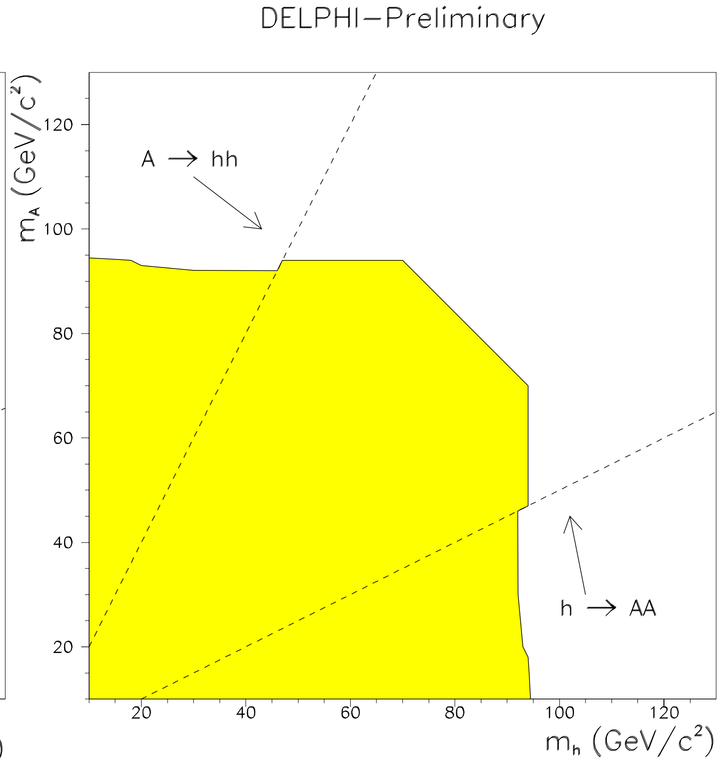
  SM σ, fermiophobic h: $M_h > 97.5$ GeV

$\Rightarrow$LEP has a sensitivity to exotic Higgs bosons too !

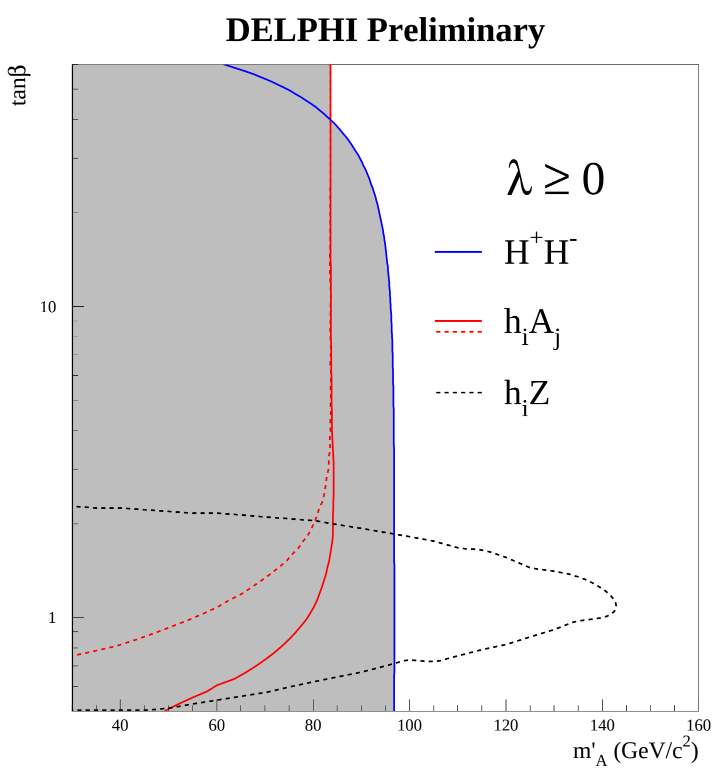
More general models, results at 189 GeV:

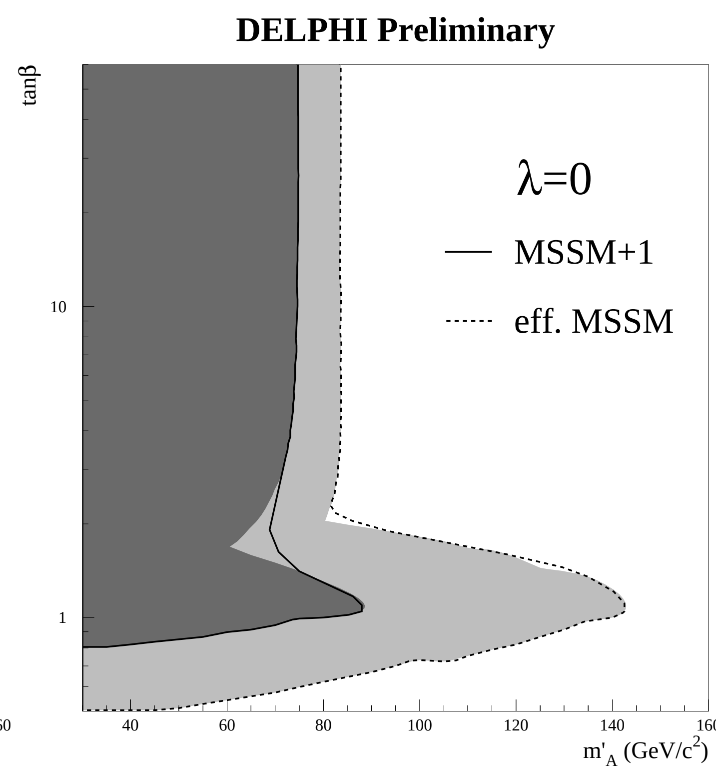
2HDM: M_h, M_A plane





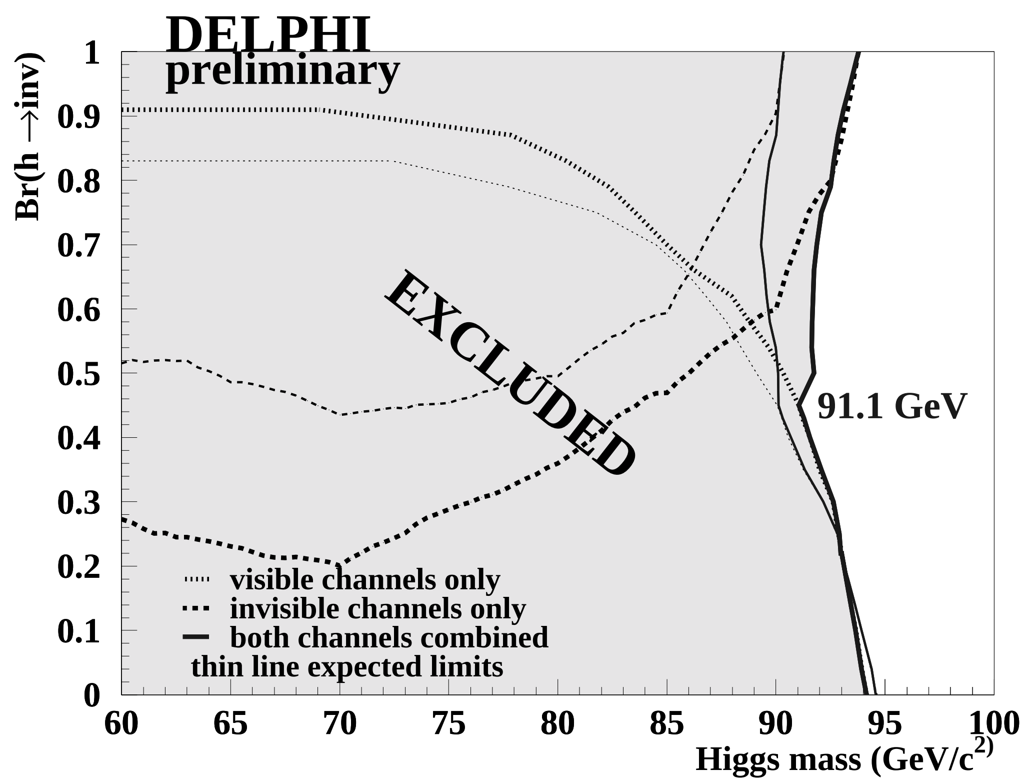
General MSSM: $\tan\beta$, $M_{A'}$ plane



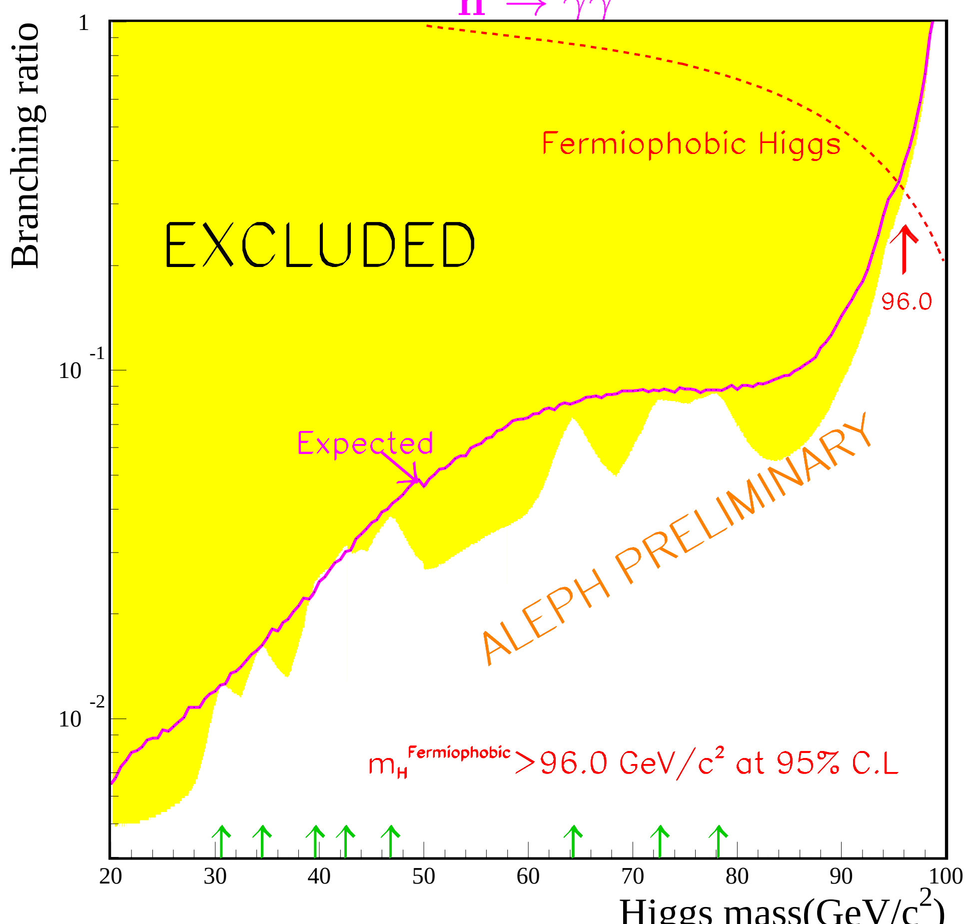


Other Higgs decays, results at 189 GeV:

h → invisible products



h → $\gamma\gamma$

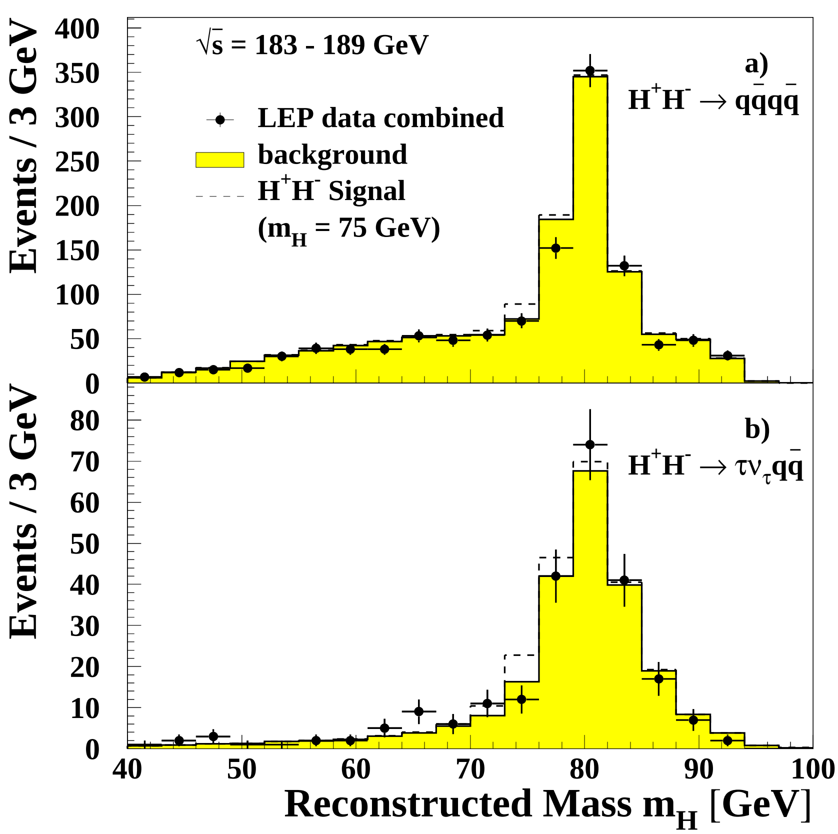


Charged Higgs bosons

- New results from LEP:
  - Framework: 2HDM $\Rightarrow e^+e^- \to H^+H^-$
  - Assumption: $H^+ \to c\bar{s}$ and $H^+ \to \tau^+\nu_\tau$ saturate the decays
  - Individual results at 189 GeV:

	bkg	data	exp. limit (GeV)	obs. limit (GeV)
A	333.5	302	69.5	65.5
D	213.0	215	66.5	66.9
L	523.5	499	71.2	67.5
O	241.1	252	68.5	68.7

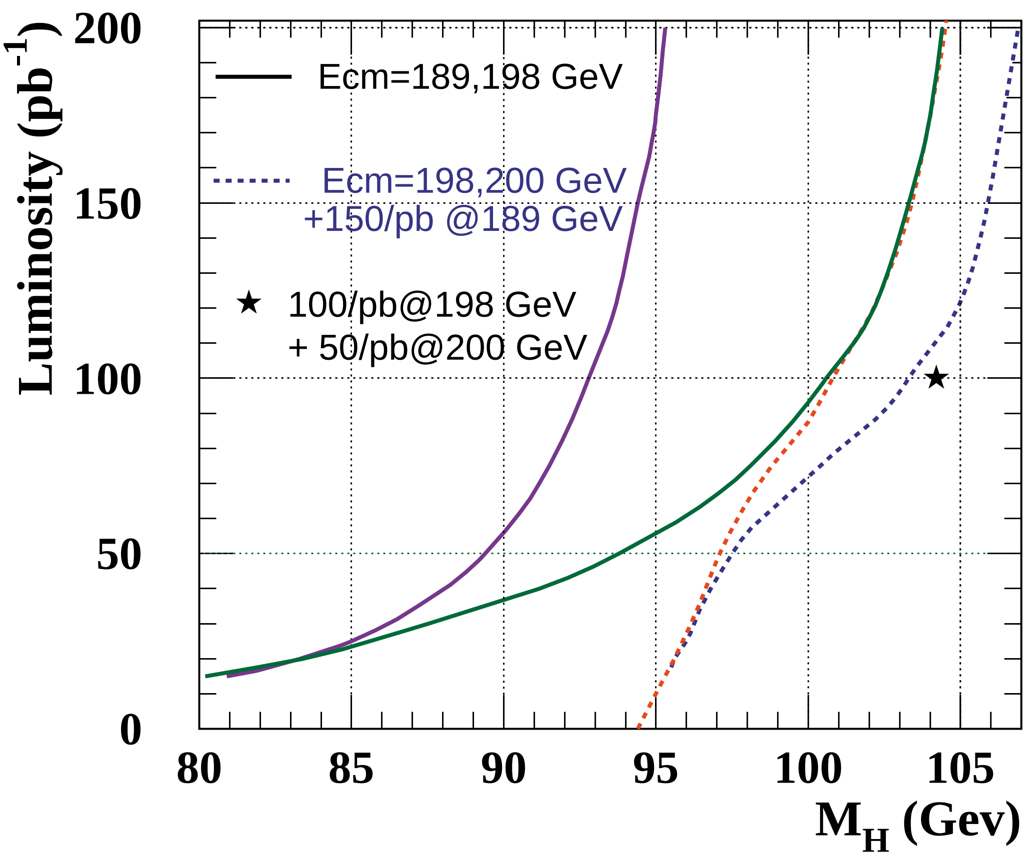
  - Combined ADLO results at 189 GeV:



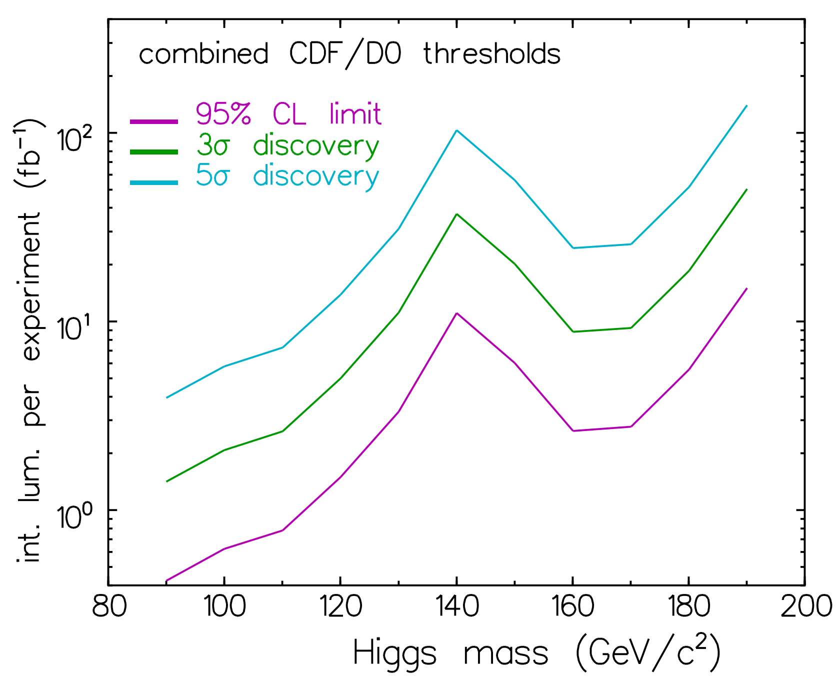
$M_H^\pm > 77.3$ GeV (exp. 74.9 GeV)

Prospects for the SM Higgs boson

LEP200 5σ discovery potential



Tevatron runII discovery and exclusion potentials



Conclusions

- Searches cover an impressive variety of topics and topologies
- To get higher sensitivity: combine experiments, combine different channels, put more information in statistical analysis of the search results
- Towards more model-independent results: relax assumptions, scan parameter values, test more general models
- A few results to keep in mind:

in SUSY with gravity mediated breaking:
$M_{\tilde{\chi}^0_1} > 30$ GeV in both R_p and $\not{R}_p$
$M_{\tilde{\chi}^\pm} > 67.7$ GeV in R_p and > 94 GeV in $\not{R}_p$
Higgs bosons:
SM: $M_H > 95$ GeV
MSSM benchmark: $M_{h,A} > 80$ GeV
$H^\pm$: $M_{H^\pm} > 77$ GeV

- Near future prospects:
  LEP running at 200 GeV (M_H tested up to $\sim$ 106 GeV) !!