International Workshop on
Quantum Effects in the MSSM
Barcelona
September 9-13, 1997

Searches for Charginos, Neutralinos and Higgs bosons

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INFN Bologna

- *Introduction*
- *Charginos*
- *Neutralinos*
- *SM Higgs*
- *MSSM Higgs*
- *A few other SUSY searches*
- *Conclusions*

Introduction: LEP 2 Data

Data Sets Above the Z^0 - per expt.

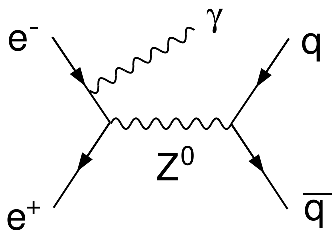
Year	CM Energy (GeV)	Luminosity (pb^{-1})	# of $Z/\gamma \to q\bar{q}$	# of $Z/\gamma \to W^+W^-$
Autumn 1995	130-136	5	350	-
Summer 1996	161	10	300	30
Autumn 1996	172	10	250	100
Summer 1997	183	~14	~300	~120

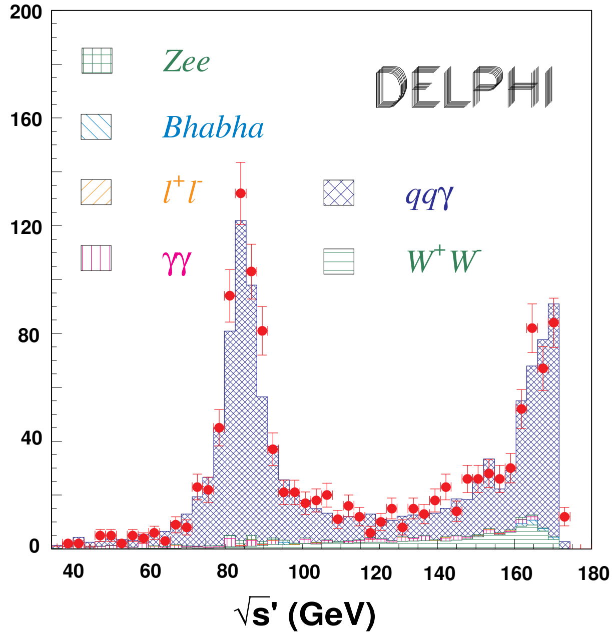
- *Highest energy available at an e^+e^- collider*
- *Good opportunity to extend to a new frontier a lot of Searches*
- *Aim for 1997: $\sqrt{s}$ = 181-4 GeV- L = 30-50 pb^{-1}*
- *1998 and beyond: 300-400 pb^{-1} at $\sqrt{s}$ = 192 GeV*

Introduction: Hermetic Detectors

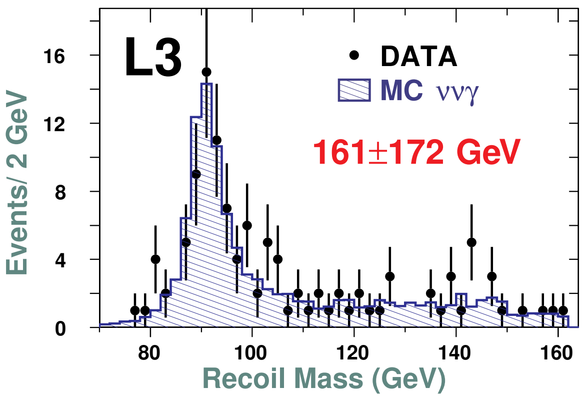
- Event topologies that could originate from SUSY signals:
  - Isolated Leptons (particle identification)
  - Acoplanar Jets (tracking, calorimetry)
  - Missing Energy (hermeticity)

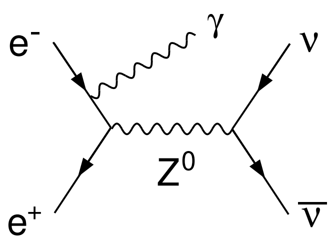
Good efficiency and resolution for the hadronic system



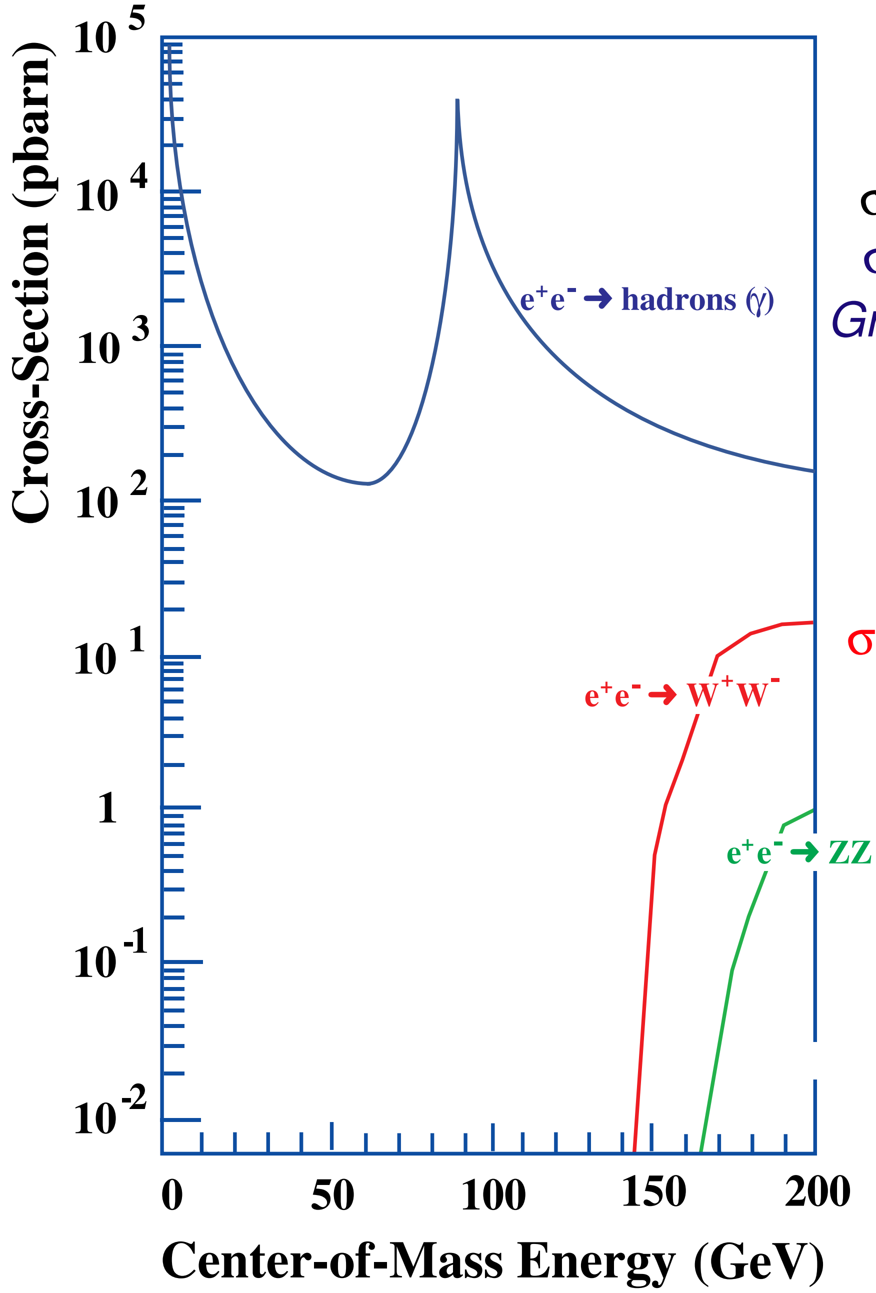


... and for γ 's and leptons: hermeticity for missing energy





Background for Searches



$\sigma\,(e^+e^- \to l\bar{l}\gamma) \sim 90$ pb

$\sigma\,(e^+e^- \to q\bar{q}\gamma) \sim 300$ pb

Great reduction compared to LEP 1

Now Sizeable

$\sigma\,(e^+e^- \to W^+W^-) \sim 3\text{-}15$ pb

$\sigma\,(e^+e^- \to ZZ) \sim 1$ pb

- *Four fermion processes, small cross section but difficult to eliminate*
- *Two photon processes $\gamma\gamma \to q\bar{q}$, $l\bar{l}$ have large cross-section ($\sigma \sim 40$ nb) but their contribution to the background can be greatly reduced*

Introduction: SUSY

In SUSY models all "normal" particles are accompanied by their supersymmetric partners, whose spin differ by 1/2.

Particles, R = +1			Sparticles, R = - 1			
Particle	Spin	Charge	Sparticle	Spin	S-name	Mass eigenstates
e	1/2	- 1	$\tilde{e}_L, \tilde{e}_R$	0	selectron	
μ	1/2	- 1	$\tilde{\mu}_L, \tilde{\mu}_R$	0	smu	
τ	1/2	- 1	$\tilde{\tau}_L, \tilde{\tau}_R$	0	stau	
$\nu = \nu_e, \nu_\mu, \nu_\tau$	1/2	0	$\tilde{\nu}$	0	sneutrino	
q = u,d,s,c,b,t	1/2	2/3, -1/3	$\tilde{q}_L, \tilde{q}_R$	0	squark	
g	1	0	$\tilde{g}$	1/2	gluino	
γ	1	0	$\tilde{\gamma}$	1/2	photino	neutralinos
Z^0	1	0	$\tilde{Z}^0$	1/2	zino	
$H_1^0,\ H_2^0$	0	0	$\tilde{H}_1^0,\ \tilde{H}_2^0$	1/2	neutral Higgsinos	($\tilde{\chi}_1^0$ - $\tilde{\chi}_4^0$)
$H^\pm$	0	$\pm$ 1	$\tilde{H}^\pm$	1/2	charged Higgsino	charginos
$W^\pm$	1	$\pm$ 1	$\tilde{W}^\pm$	1/2	wino	($\tilde{\chi}_1^\pm,\ \tilde{\chi}_2^\pm$)
G	2	0	$\tilde{G}$	3/2	gravitino	

sfermions

gauginos

	Spin		
	0	1/2	1
Particles and Sparticles	$\tilde{l}$, $\tilde{q}$, H_1^0, H_2^0, $H^\pm$	l, q, $\tilde{\chi}_1^0$ - $\tilde{\chi}_4^0$, $\tilde{\chi}_1^\pm,\ \tilde{\chi}_2^\pm$	$\gamma,\ Z^0$, $W^\pm$

Introduction: MSSM

MSSM

m_A, $\tan\beta$

μ, A_t, A_b Higgs /stop /sbottom mixing parameters

M_1, M_2, M_3

$m_{\tilde{l}_R}$, $m_{\tilde{l}_L}$, $m_{\tilde{\nu}_L}$ Slepton, sneutrino masses

$m_{\tilde{q}_L}$, $m_{\tilde{q}_R}$ Squark masses

Constrained MSSM

Unifies M_1, M_2, M_3 at the GUT scale $\rightarrow$ $m_{1/2}$

$M_2 \sim 0.8\ m_{1/2}$ $M_1 \sim 0.5\ M_2$ $M_3 \sim 3.5\ M_2$

SUGRA

Unifies also $\tilde{l}$, $\tilde{\nu}$, $\tilde{q}$ masses at the GUT scale $\rightarrow$ m_0

$$m_{\tilde{l}_R} = m_0^2 + 0.15\ m_{1/2} + 0.23\ m_Z^2\ |\cos 2\beta|$$

$$m_{\tilde{l}_L,\tilde{\nu}} = m_0^2 + 0.52\ m_{1/2} + 0.27\ m_Z^2\ |\cos 2\beta|$$

$$m_{\tilde{q}} = m_0^2 + 6\ m_{1/2} + a \cdot m_Z^2\ |\cos 2\beta|$$

Introduction: MSSM

- M_2: SU(2) gaugino mass at electroweak scales
- $\tan\beta$: ratio of VEV of Higgs doublets $<V_2>/<V_1>$
- μ: superpotential Higgsino mass
- m_0: common mass of squarks and sleptons at the GUT scale (universal scalar mass)
- A_0: trilinear scalar Yukawa-like coupling

- **R-Parity Conservation:**

  - A new multiplicative quantum number, R_p, is generally assumed to be conserved:

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

  - $\rightarrow$ SUSY particles must be produced in pairs
  - $\rightarrow$ a sparticle decays down to the LSP
  - $\rightarrow$ the LSP is stable $\rightarrow$ Missing energy.
  - Usually:LSP = $\tilde{\chi}^0_1$

Introduction: MSSM

- **R-Parity Violation:**
  - $\rightarrow$ Single sparticles can be produced
  - $\rightarrow$ LSP can decay
  - $\rightarrow$ Lightest sfermion can be the LSP
  - 45 extra λ couplings from explicit breaking of R_p interactions parametrized in superpotential as:

$$W = \lambda_{ijk} L^i_L L^j_L E^k_R + \lambda'_{ijk} L^i_L Q^j_L D^k_R \quad (+ \lambda''_{ijk} U^i_R D^j_R D^k_R)$$

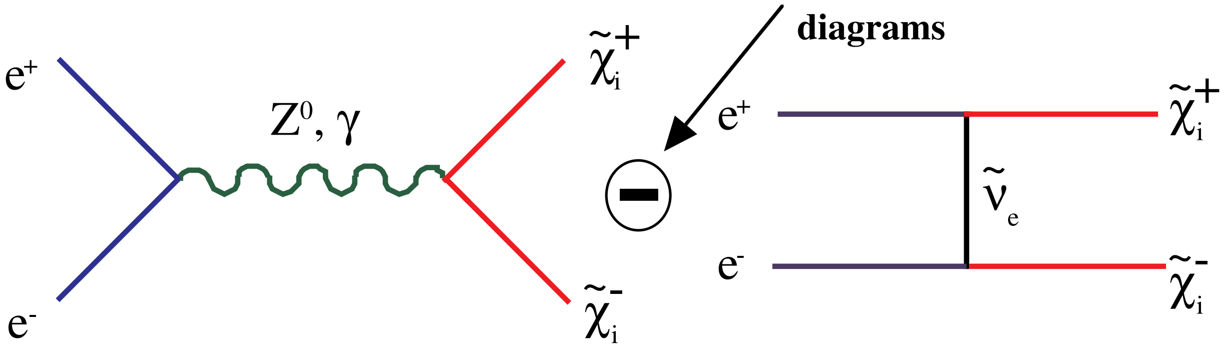
L^i_L and Q^i_L are the SU(2)-doublet lepton and quark superfields and E^i_R, U^i_R and D^i_R are the singlet superfields

Charginos

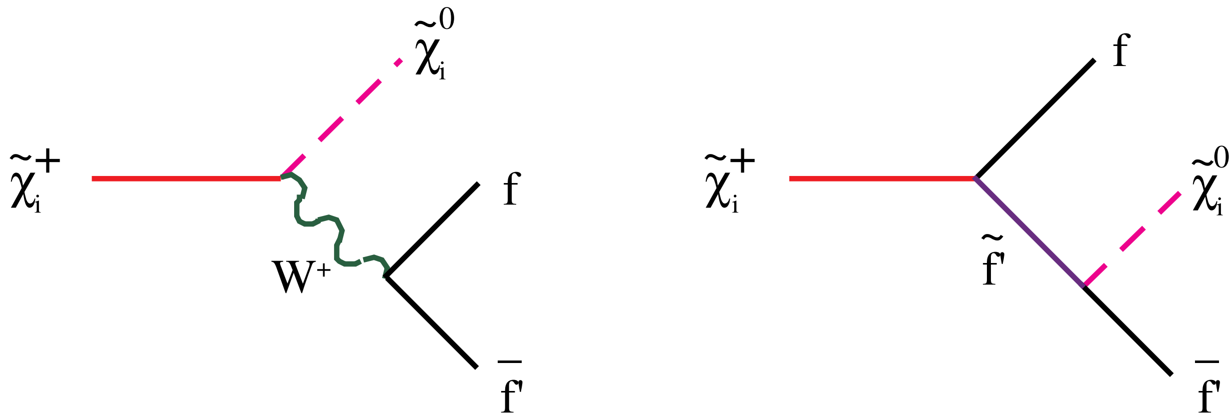
Mixtures of $\widetilde{W}^{\pm}$ e $\widetilde{H}^{\pm}$

Production

Destructive interference between s and t-channel diagrams



Decays



Large cross-sections at LEP 2, σ ~5-18 pb

Topologies

Acoplanar jets and missing energy

Jets and isolated lepton plus missing energy

Acoplanar leptons and missing energy

Experimentally the most important variable is:

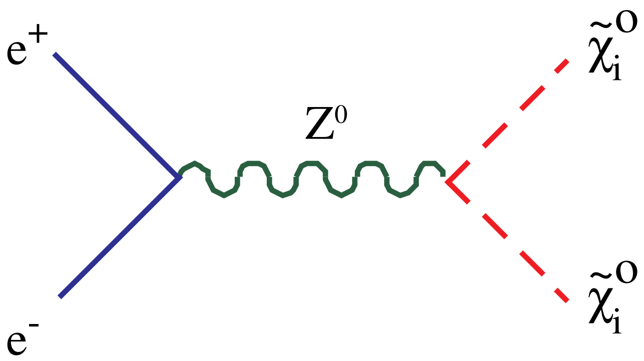
$$\Delta m = m_{\tilde{\chi}_1^+} - m_{\tilde{\chi}_1^0}$$

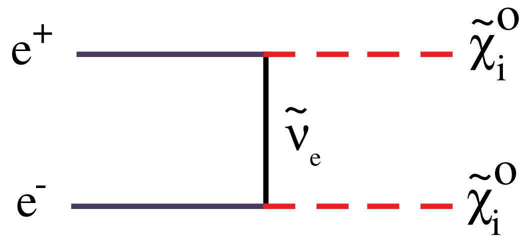
Backgrounds

Small Δm	$\gamma\gamma$ processes
Medium Δm	
Large Δm	WW

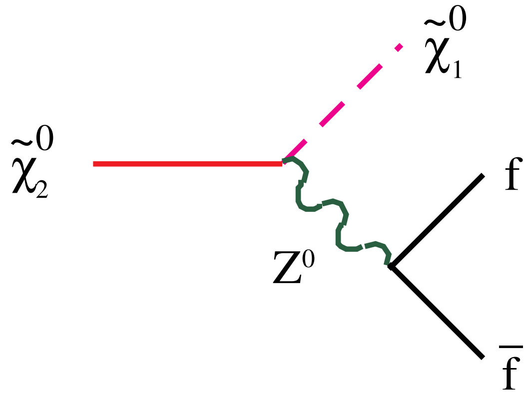
Neutralinos

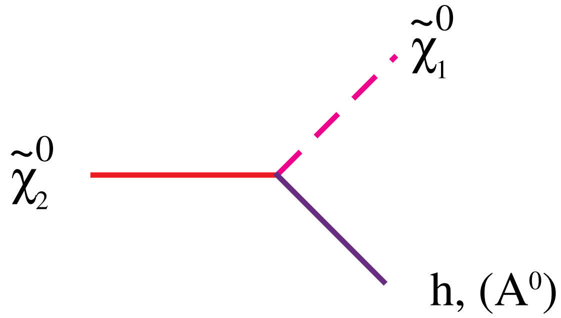
Production

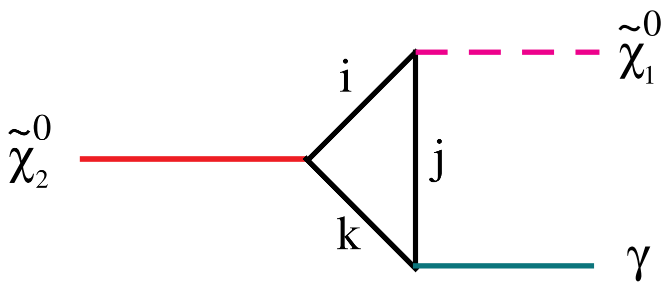




Decays







$$e^+e^- \rightarrow \tilde{\chi}^0_2\tilde{\chi}^0_1 \rightarrow \tilde{\chi}^0_1\tilde{\chi}^0_1\, f\bar{f}$$
$$\rightarrow \tilde{\chi}^0_1\tilde{\chi}^0_1\, \gamma$$

Large cross-sections at LEP 2, up to
$\sigma \sim 7$ pb

Topologies

Acoplanar jets and missing energy

Jets and isolated lepton plus missing energy

Acoplanar leptons and missing energy

Single photon events

Δm < 0.1 GeV

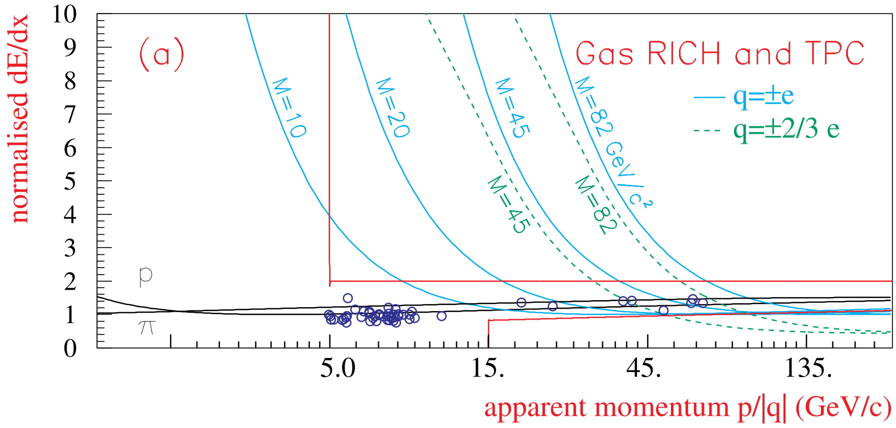
Search for long-lived heavy charged particles

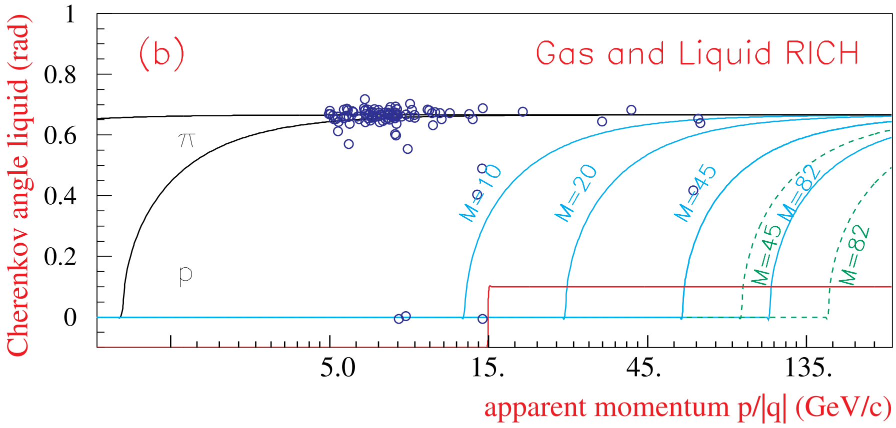
Topology

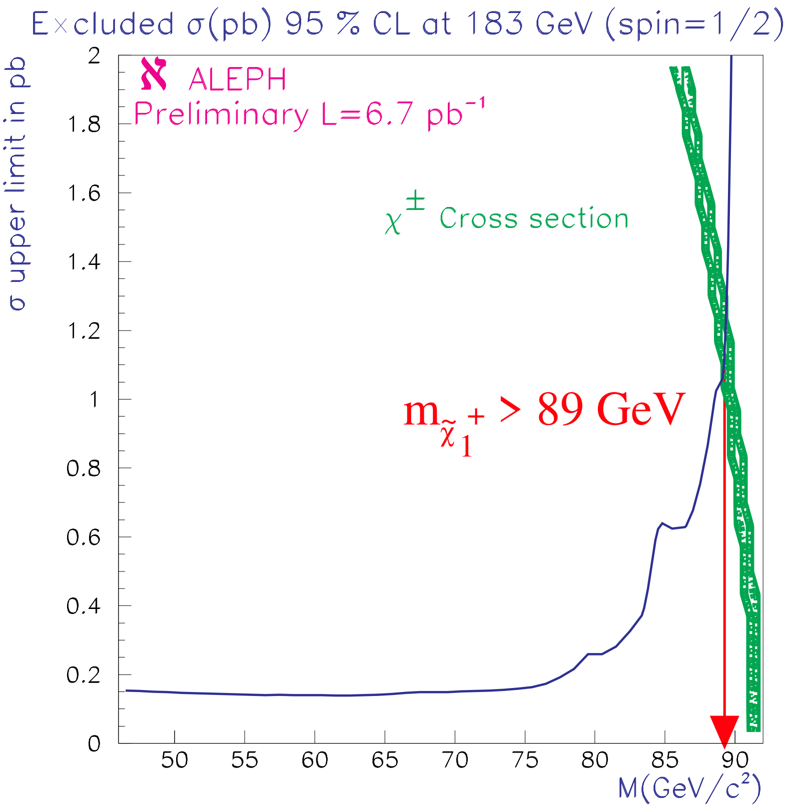
Two back-to-back tracks with very large dE/dx (ALEPH and DELPHI). DELPHI also used their RICH data.

No signal observed → limit on pair-production cross-section of long-lived charged particles.

DELPHI searches at 172 GeV







$0.1 < \Delta m < 0.5$ GeV

Search for kinks in central detectors

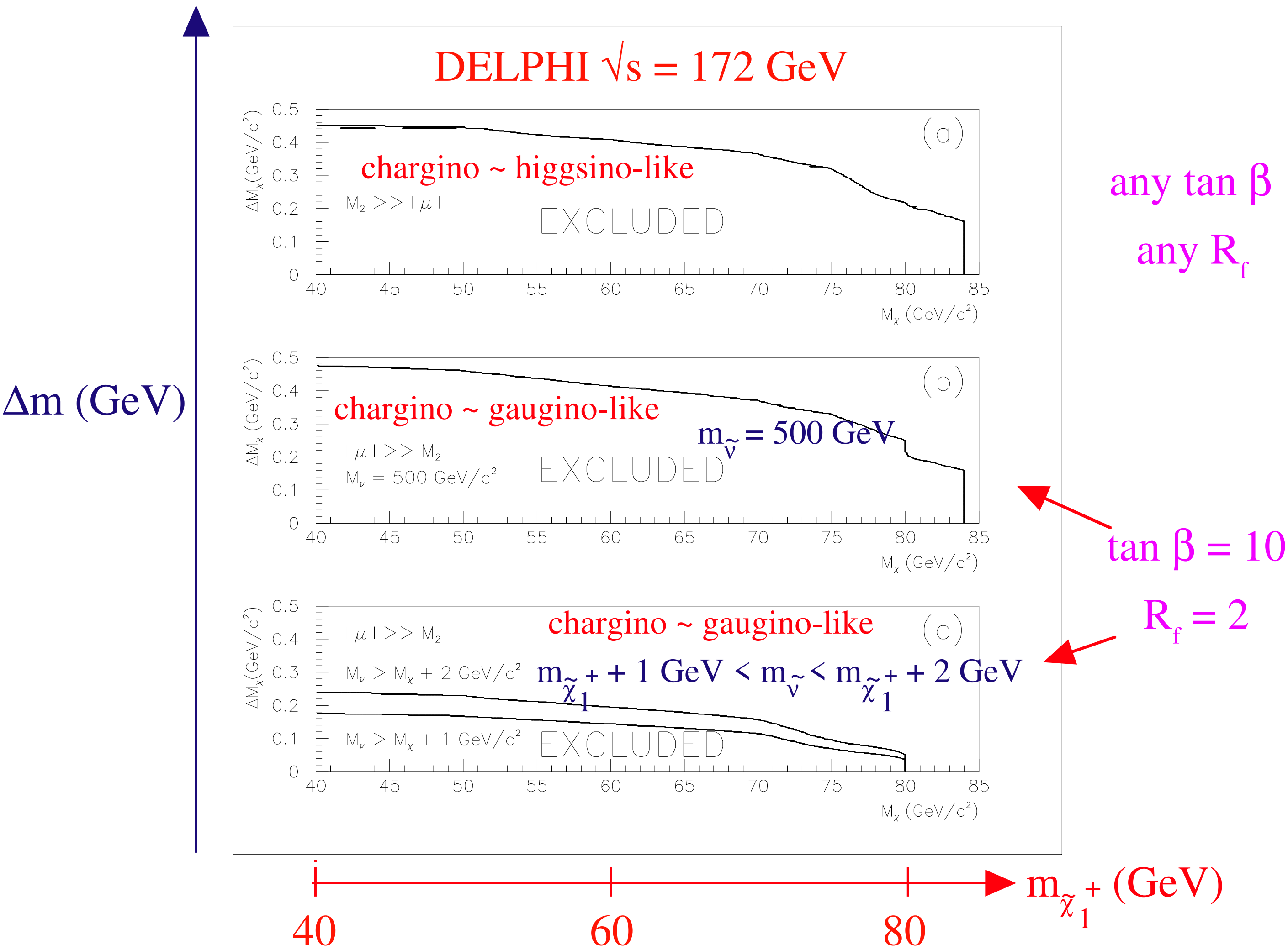
Topology

Heavy particles decaying in the central tracking detectors. Reconstruct the primary and secondary track with a Kink between them.

No excess of events observed over expected SM backgrounds → limit on quasi-stable chargino mass vs. Δm

MSSM limits with no gaugino mass unification

$M_1/M_2 = R_f * 5/3 \tan^2 \theta_W$



0.5 < Δm < 3.0 GeV

Search for ISR photons + X

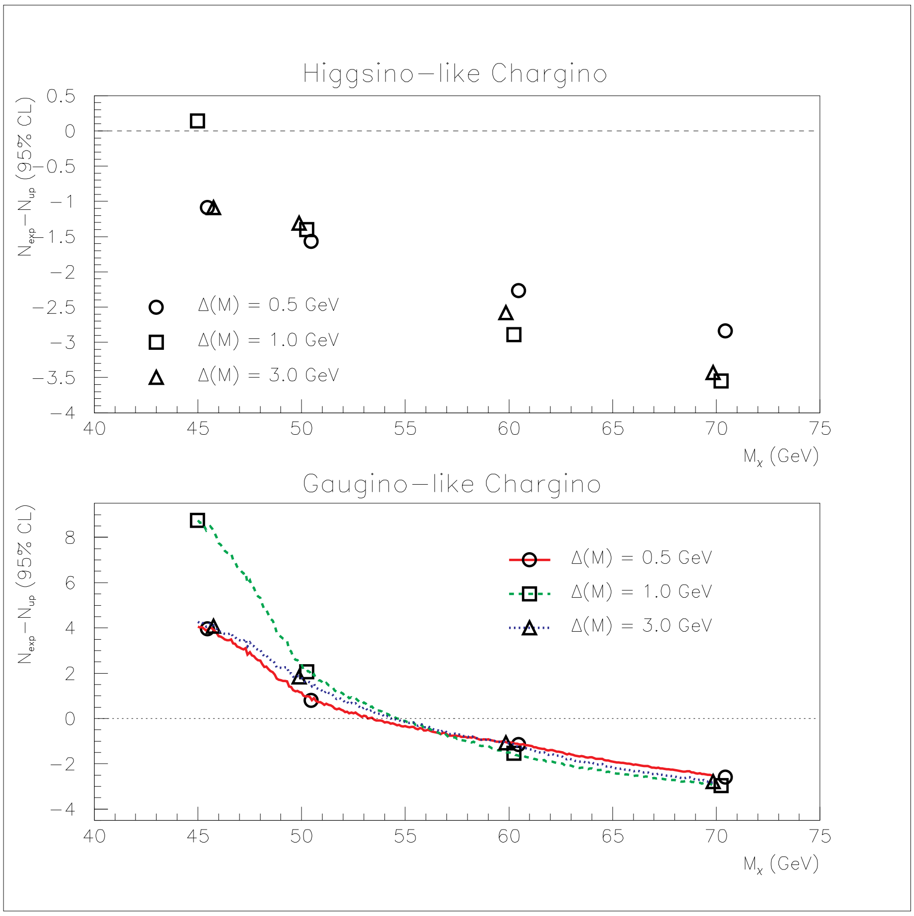
Signal events would have very small visible energy.

Require an ISR photon with energy > 4 GeV and p_t > 2 GeV.

Detection efficiency very low (few percent)

1 event observed, 2 expected from SM backgrounds

DELPHI $130 \leq \sqrt{s} \leq 172$ GeV



$m_{\tilde{\chi}_1^+} > 53.4$ (54.4) GeV for $\Delta m = 0.5$ (3) GeV

for a gaugino-like chargino and $m_{\tilde{\nu}} > 500$ GeV

Chargino Results (topological searches)

Results ($\sqrt{s} \leq 172$ GeV)

	Luminosity (pb-1)	Observed events	Expected (from SM backgrounds)
ALEPH	21.5	15	11.0
DELPHI	19.7	7	14.8
L3	20.8	5	4.5
OPAL	20.3	2	2.2

Preliminary results ($\sqrt{s} = 183$ GeV)

$L \sim 6.5\ pb^{-1}$

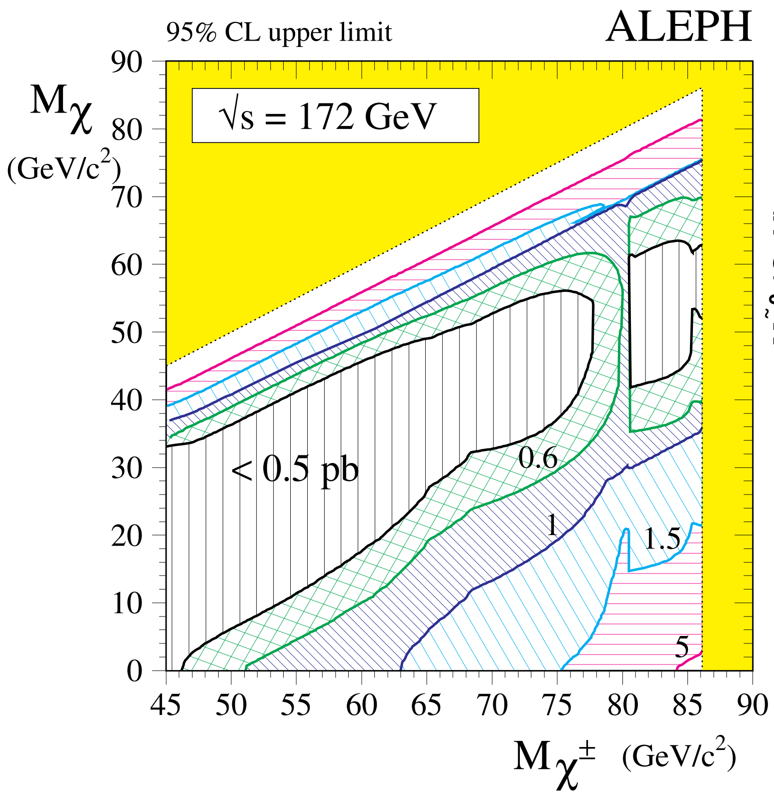
	Observed events	Expected events
ALEPH	2	*consistent*
DELPHI	3	3.5
L3	2	0.97
OPAL	0	0.52

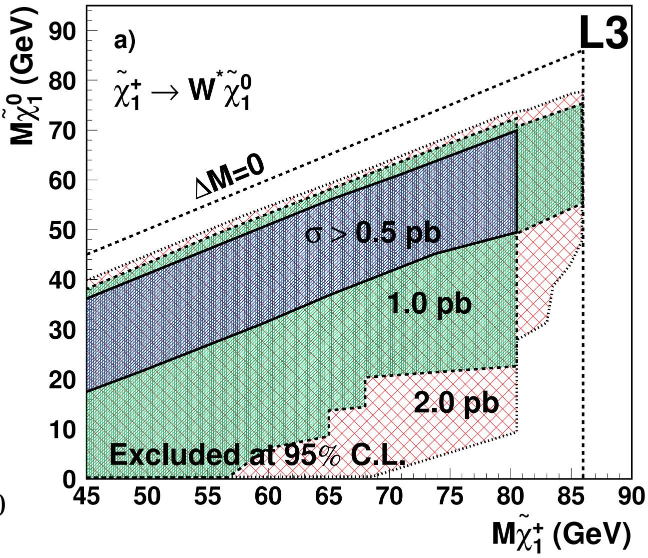
No significant excess observed

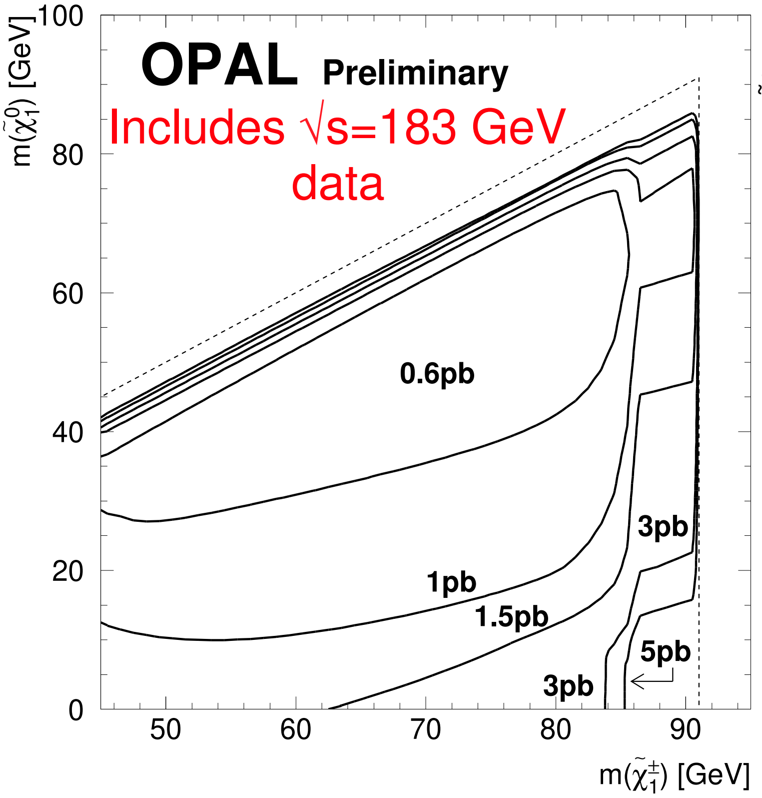
$\longrightarrow$ *limits derived*

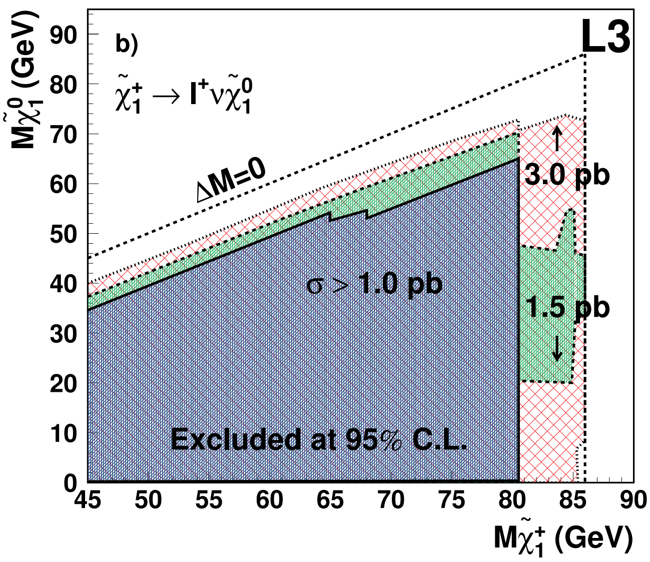
Large Δm: Topological searches

95% CL cross-section limits

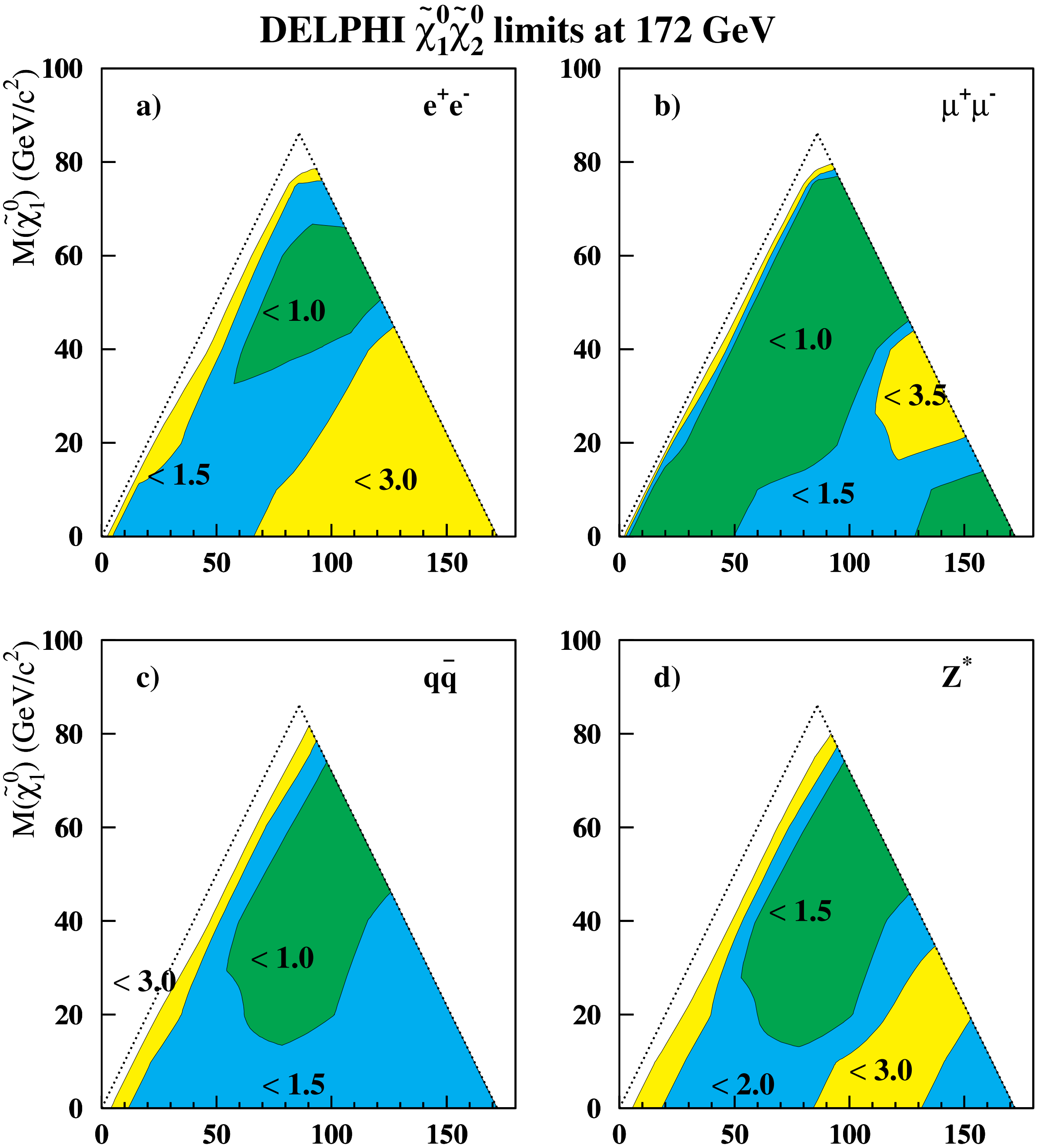




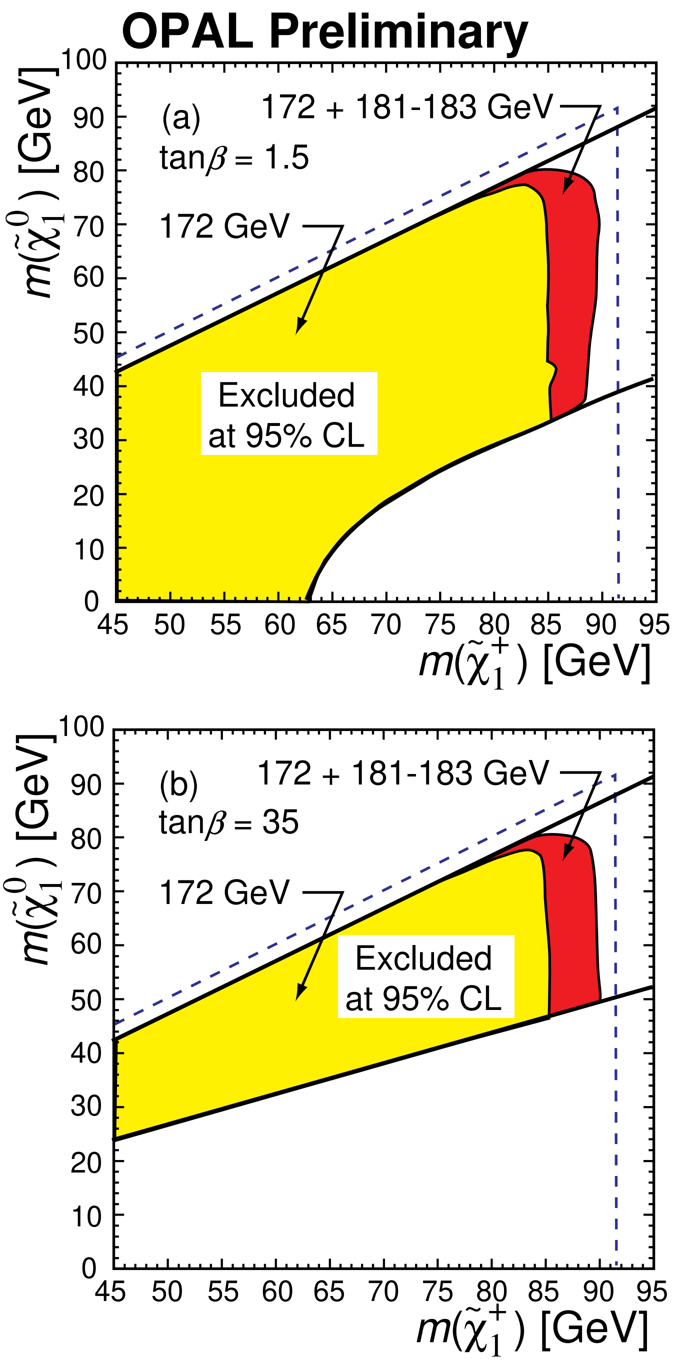




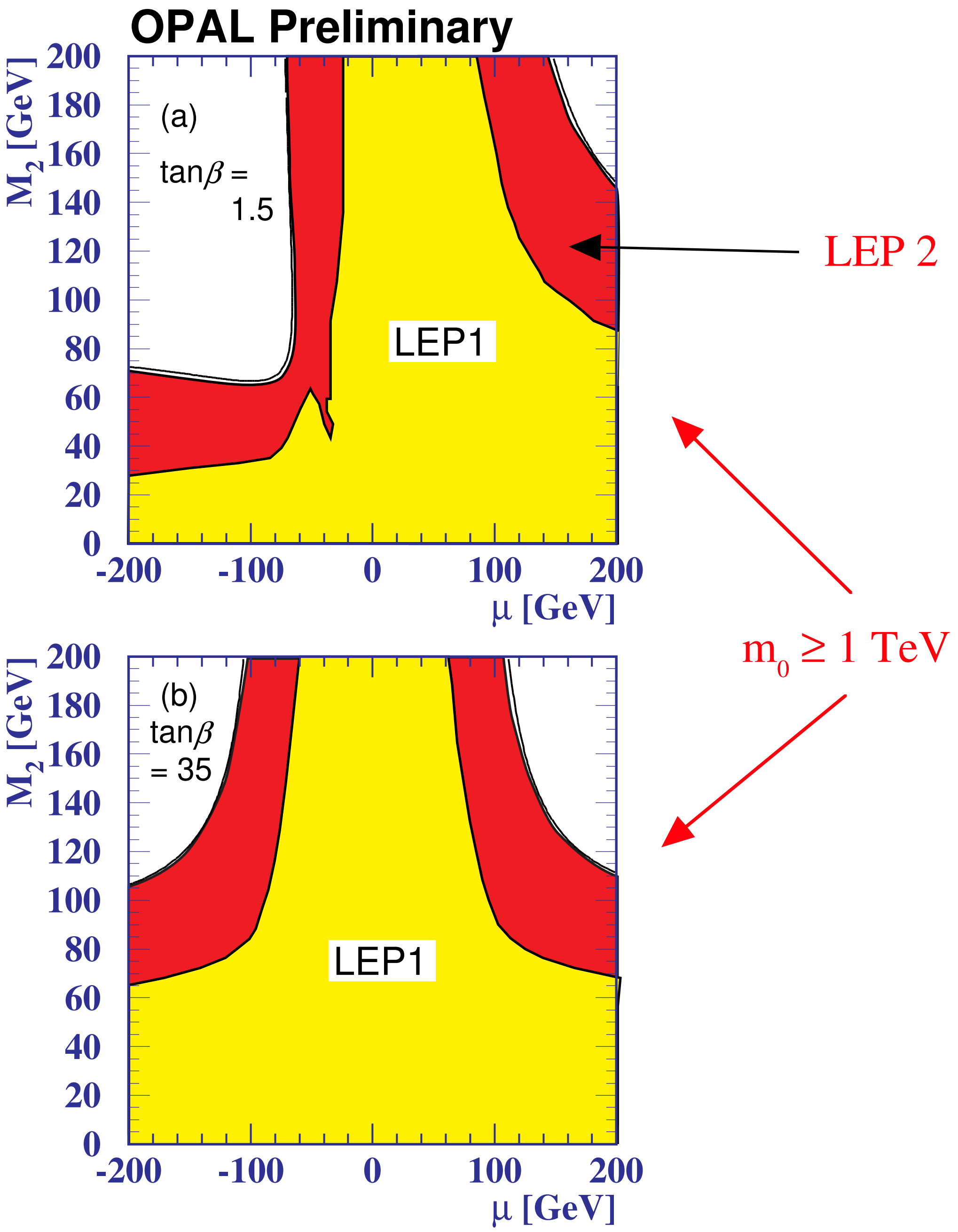
Neutralino cross-section limits



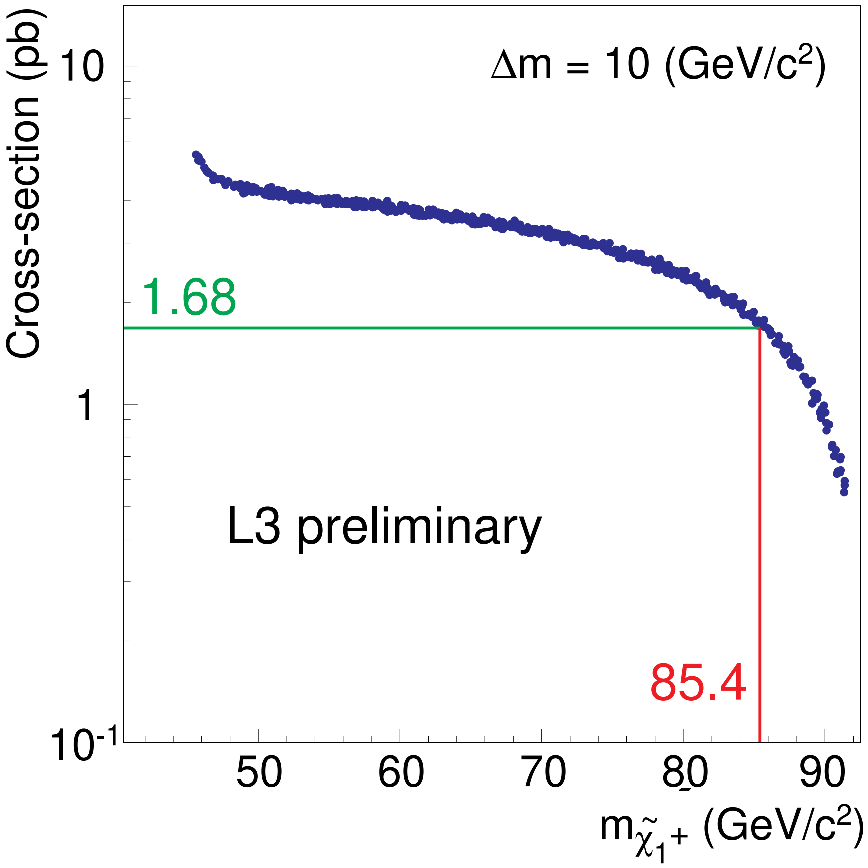
Chargino mass limits in the MSSM

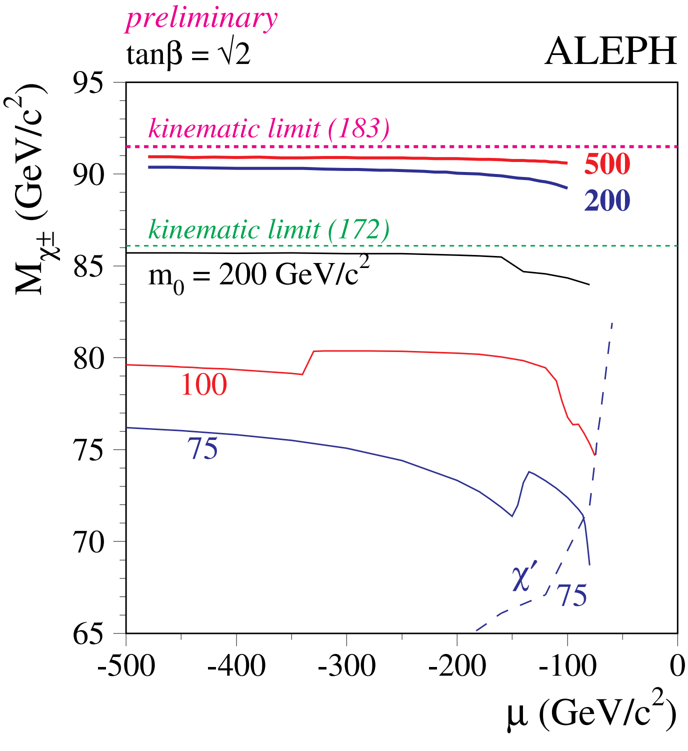


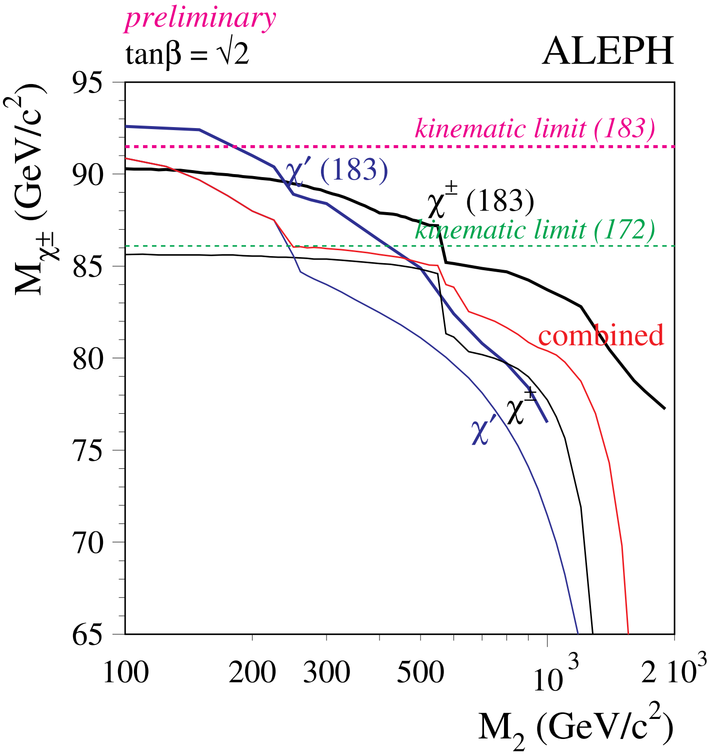
Limits in the (M_2, μ) plane



Chargino mass limits







Chargino mass limits

Preliminary results with 183 GeV data
($\Delta m \geq 10$ GeV)

ALEPH	91 GeV
DELPHI	90.2 GeV
L3	90.9 GeV
OPAL	88.8 GeV

Neutralino lower mass limits

Include data at $\sqrt{s}$=183 GeV

Limits for stable neutralinos

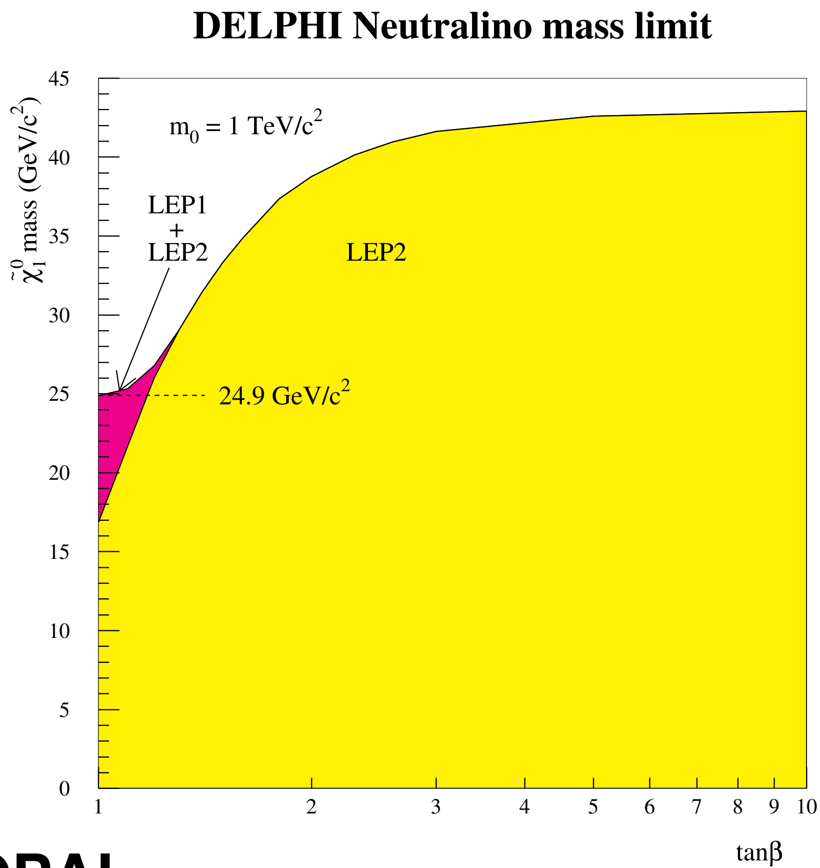
Δm (GeV)	Small $m\tilde{\nu}$	Large $m\tilde{\nu}$ (m0 > 500 GeV)
> 10	65.7 GeV	91 GeV
5	83.5 GeV	83.5 GeV
3	56.8 GeV	66.9 GeV
1	54.5 GeV	54.5 GeV
0.5	53.4 GeV	53.4 GeV
~0		89.0 GeV (no gaugino mass unification)

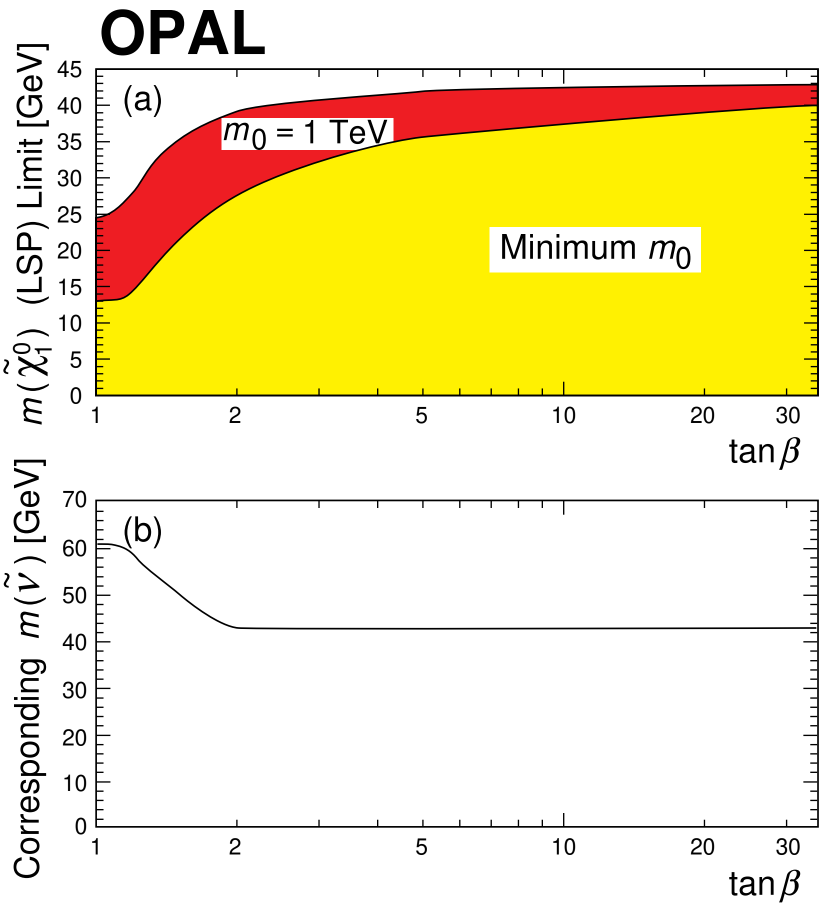
Limits for unstable neutralinos: $\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma$

Δm (GeV)	Small $m\tilde{\nu}$	Large $m\tilde{\nu}$ (m0 > 500 GeV)
> 10	71.8 GeV	84.5 GeV
1	84.5 GeV	84.5 GeV

LSP lower mass limits

Combine results from $\chi^{\pm}_1$, χ^0_1 and slepton searches

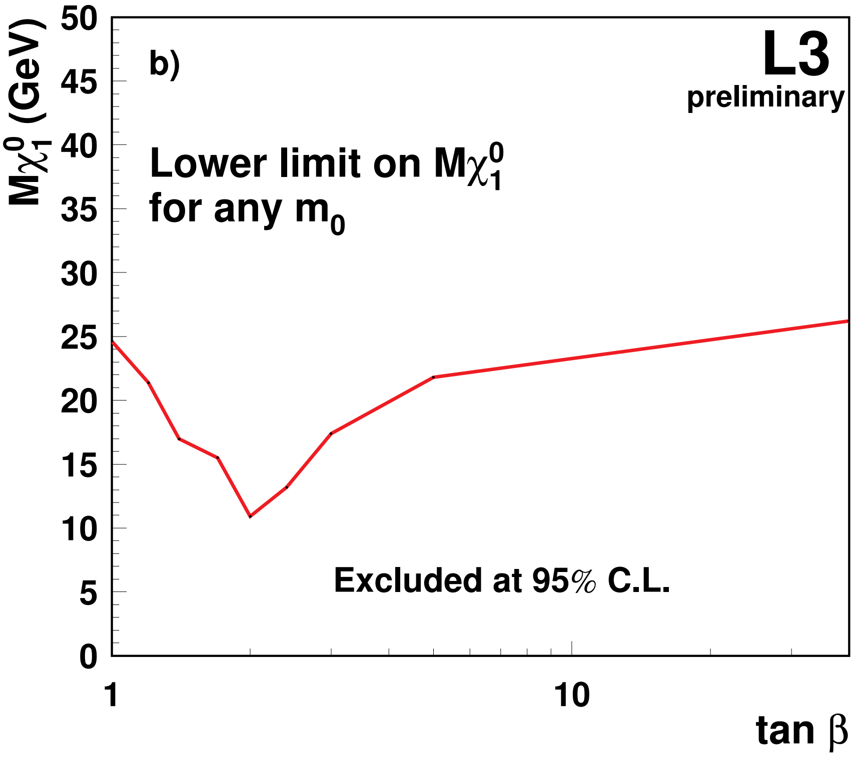


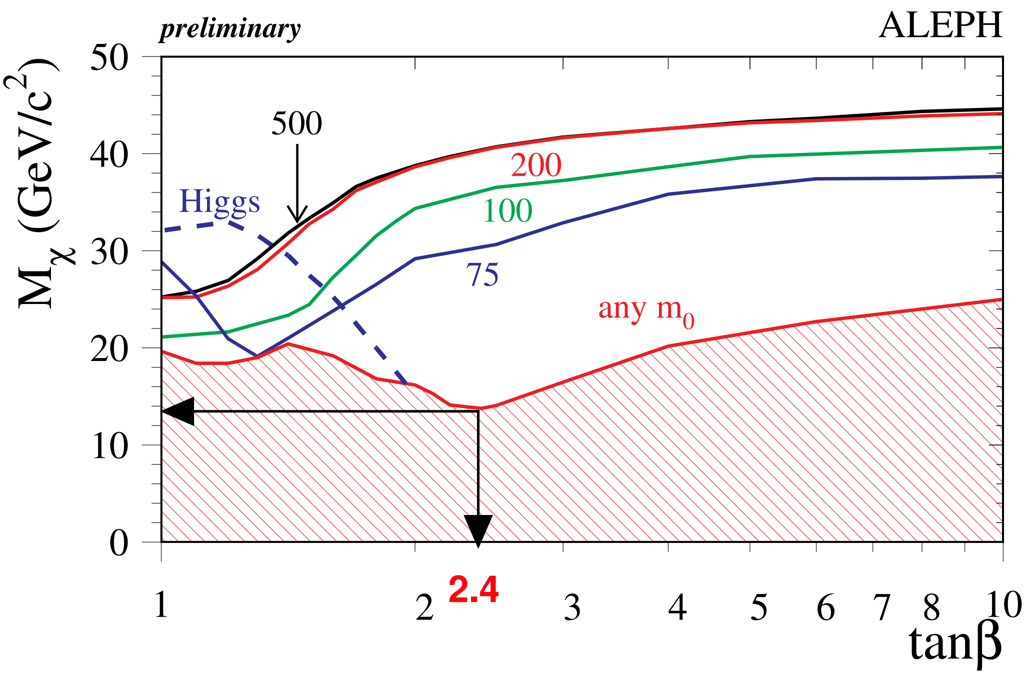


$m_{\chi^0_1}$ > 25 GeV

for m_0>500 GeV

LSP lower mass limits



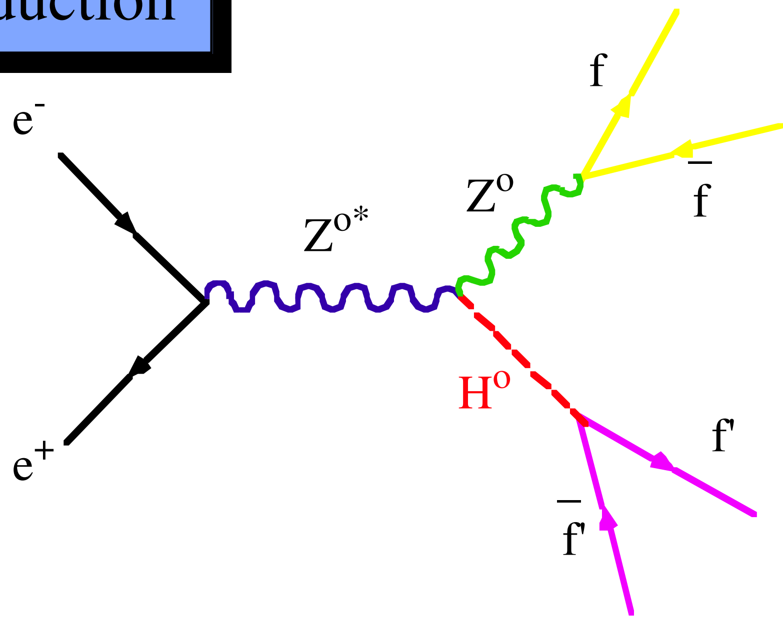


$\tilde{\chi}_1^0$ mass lower limit for any tan β and any m_0:

$m_{\tilde{\chi}_1^0} > 14$ GeV

Higgs boson (SM) at LEP 2

Production



At LEP 2 the dominant mechanism for the production of a Higgs boson, H^0, is the

Bjorken - Ioffe - Khoze process

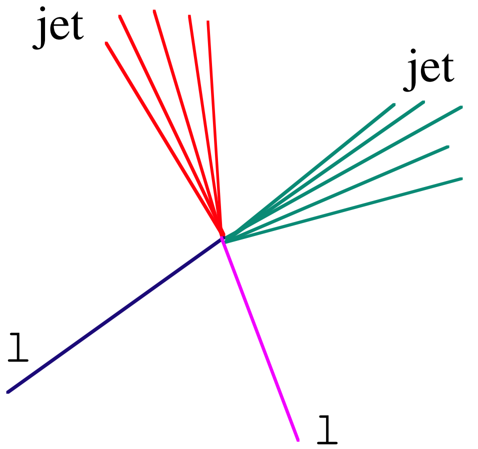
The difference with respect to LEP 1 is that the exchanged Z^0 is now virtual and that the Higgs boson is produced in association with a real Z^0 .

Up to $m_H = 80$ GeV the search for the Higgs boson can be considered as *relatively* simple. One can take advantage of the fact that the produced Z^0 is real.
The event topologies of Higgs events would be similar to the ones studied at LEP 1.

The final sensitivity of LEP 2 will be

$$m_H \sim \sqrt{s} - 100 \text{ GeV.}$$

Higgs event topologies

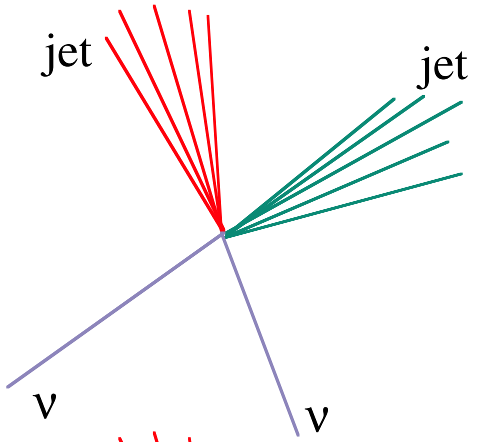


$Hl\bar{l}$

Isolated leptons and jets

Br ~ 6%

Det. efficiency ~ 70%

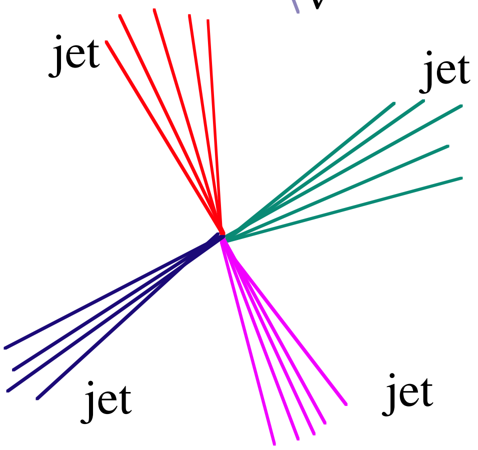


$H\nu\bar{\nu}$

Acoplanar jets

Br ~ 20%

Det. efficiency ~ 50%



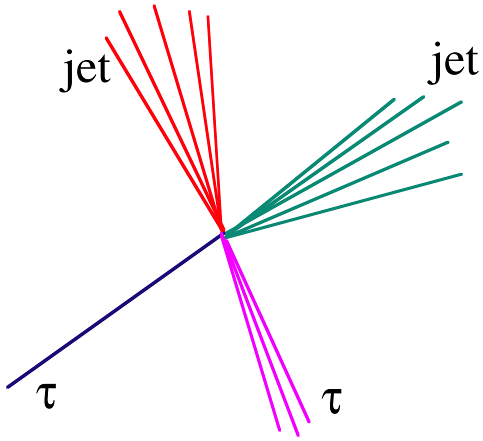
$Hq\bar{q}$

Four jets

Br ~ 65%

Det. efficiency ~ 25%

b-tagging of the two Higgs jets is crucial (BR $H \rightarrow b\bar{b}$ ~86%)



$\tau\bar{\tau}q\bar{q}$, $q\bar{q}\tau\bar{\tau}$

Taus + jets

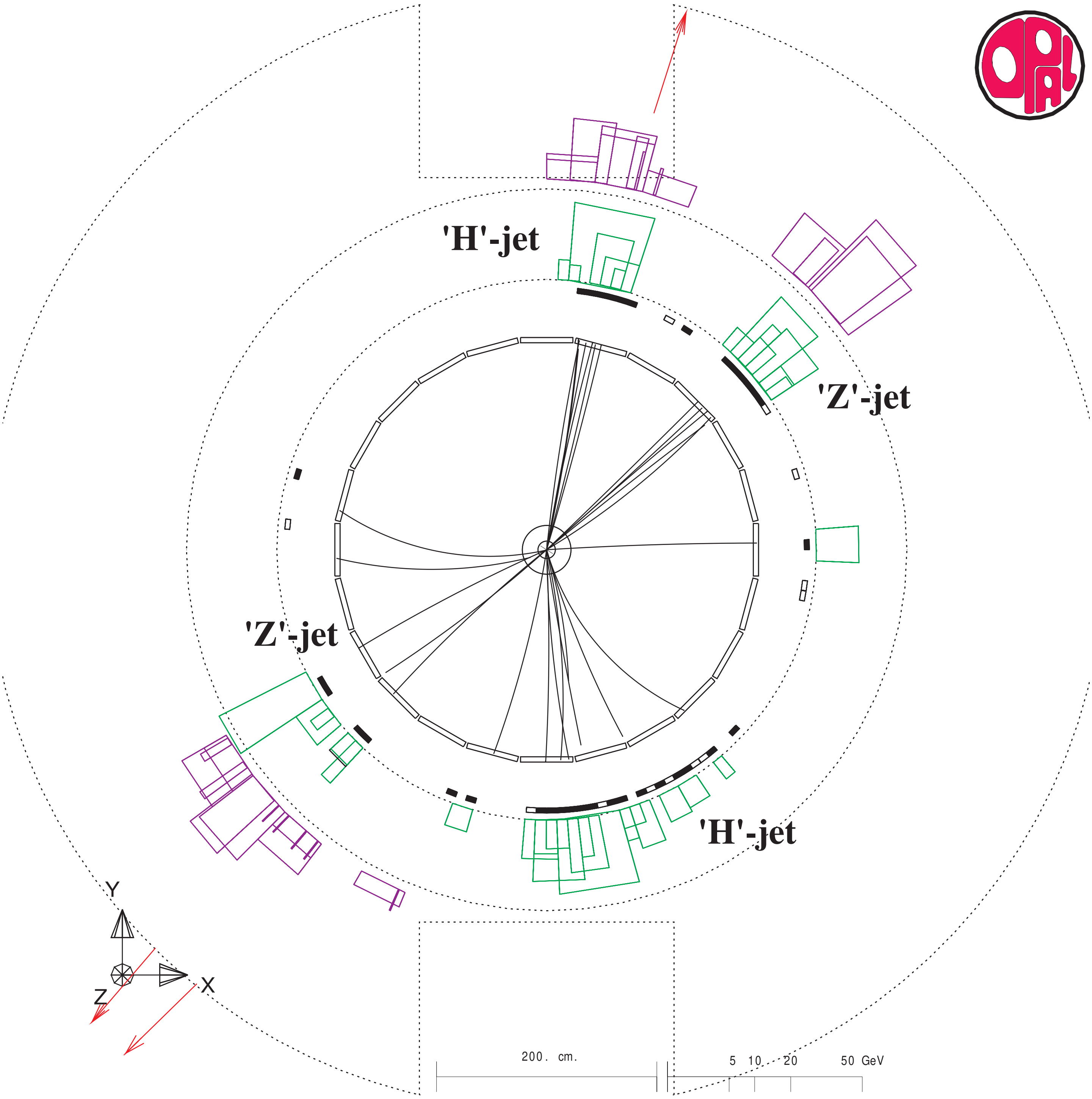
Br ~ 9%

Det. efficiency ~ 25%

Example of a Higgs candidate event

OPAL H$q\bar{q}$ candidate

(m_H = 75.6)

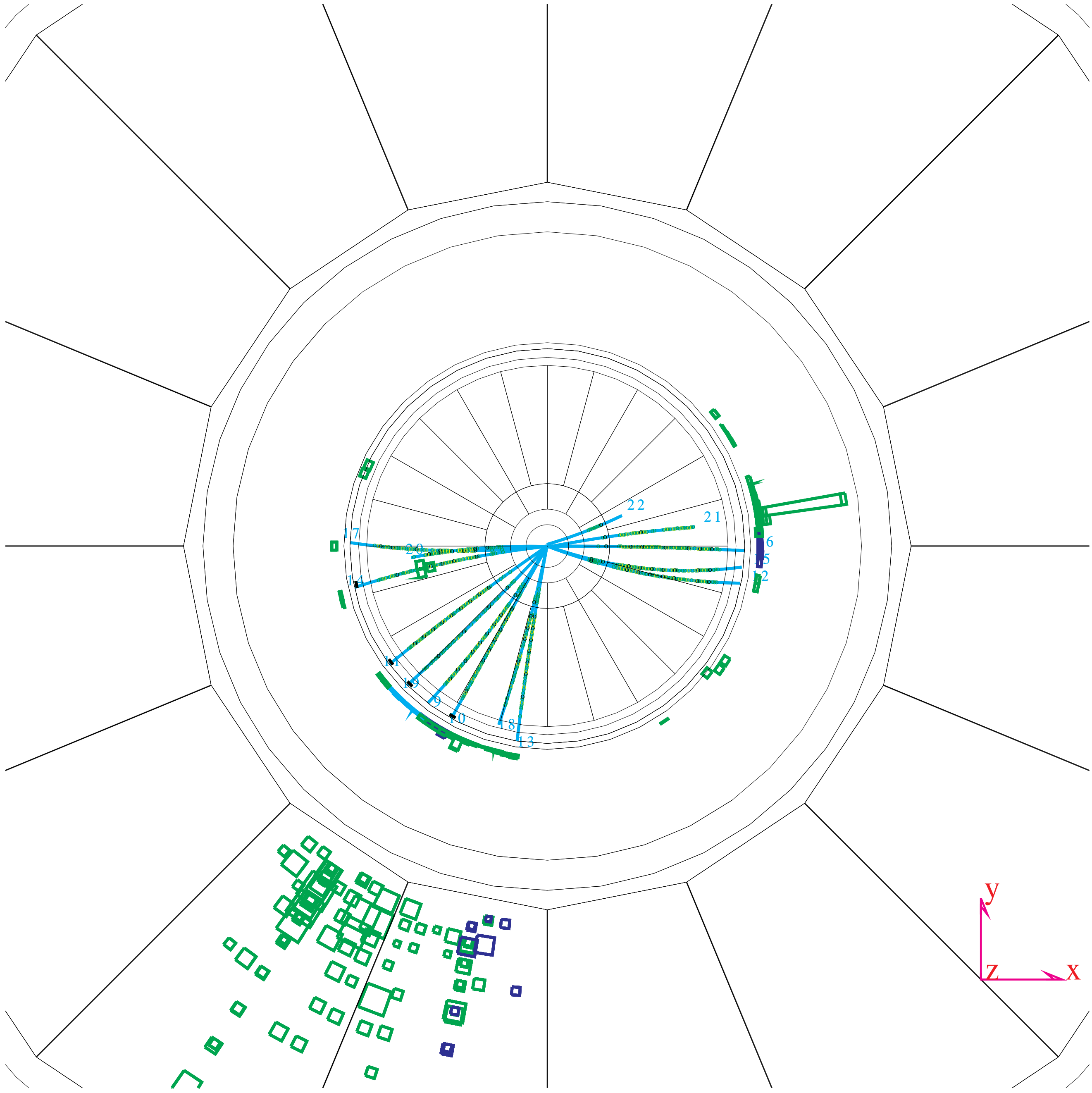


Example of a Higgs candidate event

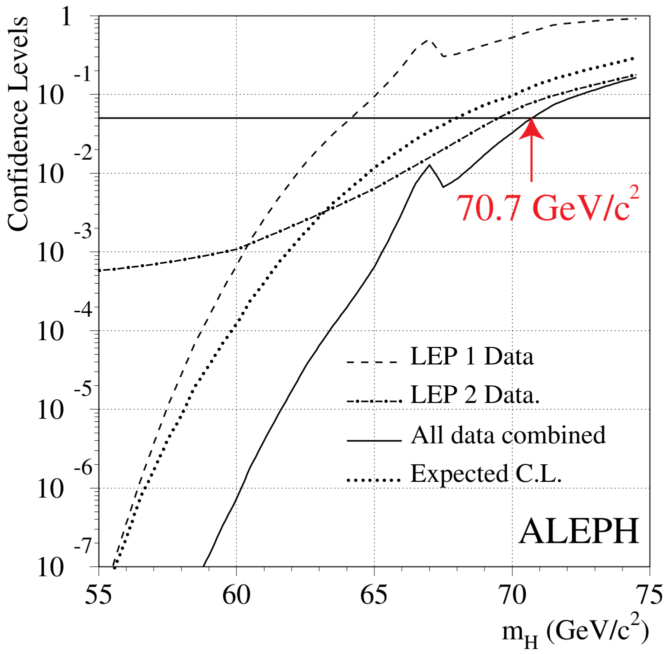
L3 $H\nu\bar{\nu}$ candidate

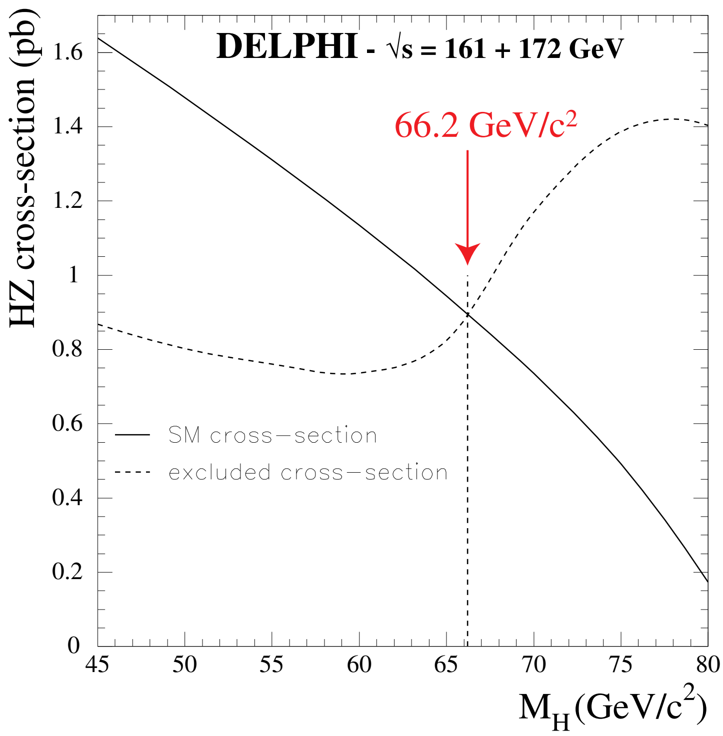
$m_{jet\text{-}jet} = 81$ GeV

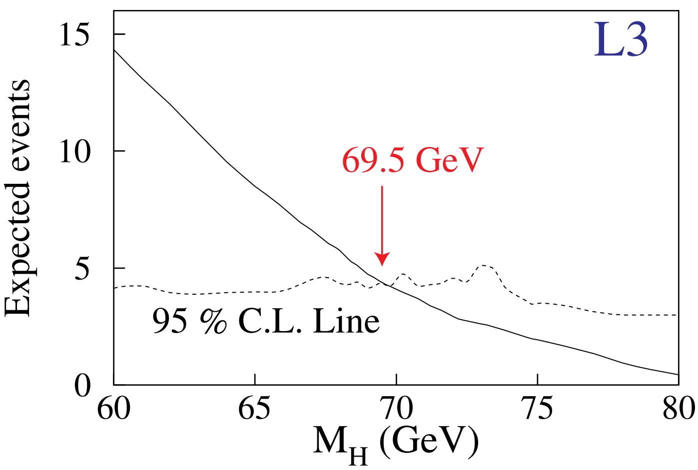
Run # 671712 Event # 5249 $\sqrt{s} = 183$ GeV

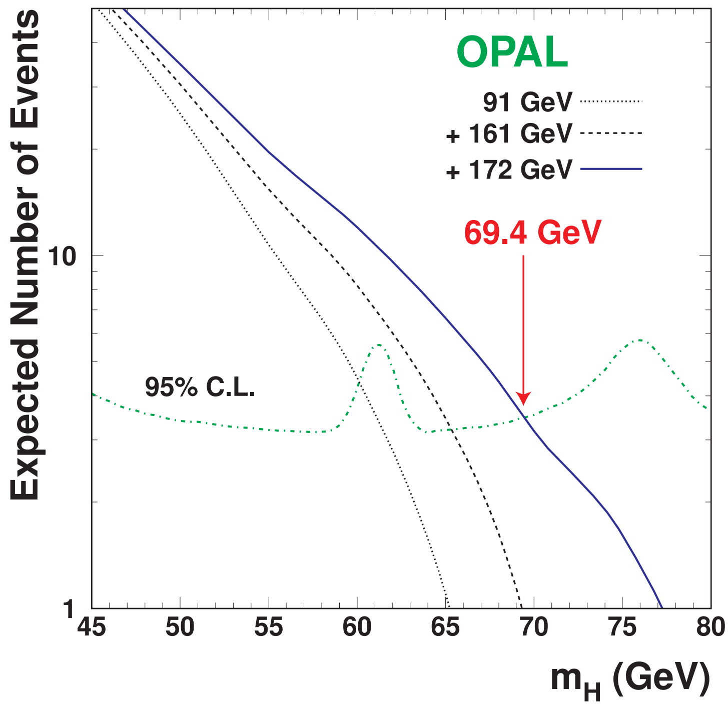


SM Higgs boson lower mass limits









SM Higgs boson search results

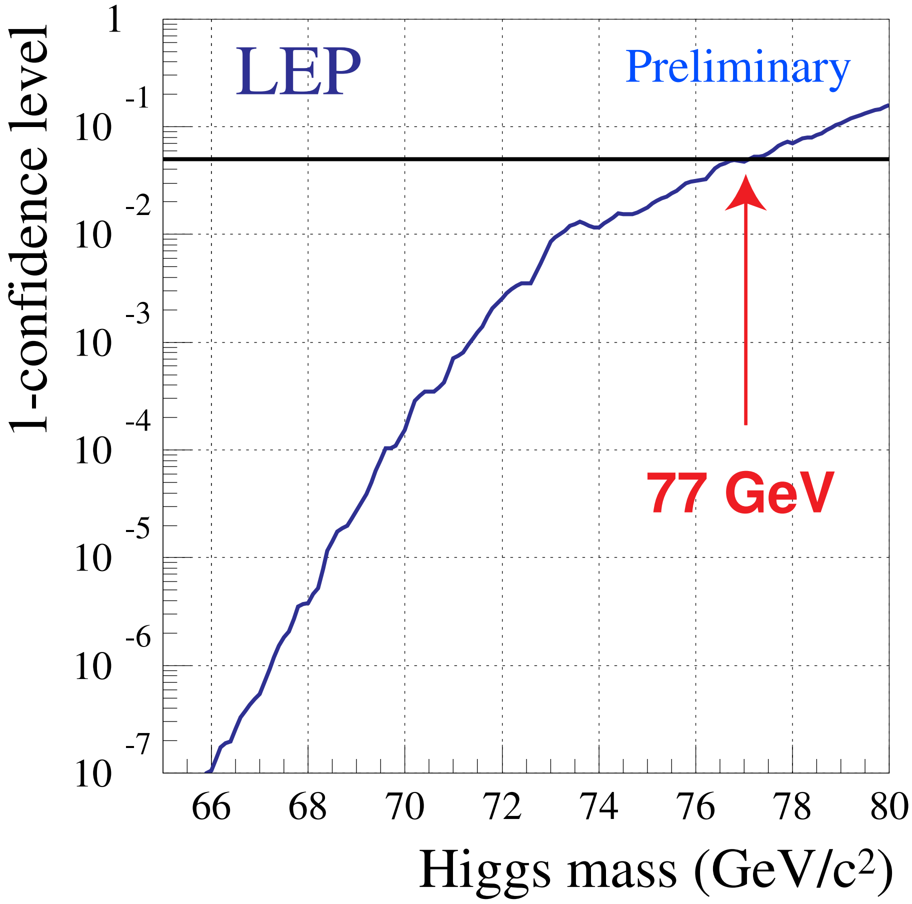
Results of searches for the SM Higgs boson at $\sqrt{s}$ = 161 - 172 GeV

	Overall efficiency	Observed events	Expected events	95% CL lower limit
ALEPH	29%	0	0.9	70.7
DELPHI	29%	2	4.3	66.2
L3	40%	33	38.2	69.5
OPAL	31%	2	3.6	69.4

Next: $\rightarrow$ combine the data from the four LEP experiments

SM Higgs boson lower mass limits

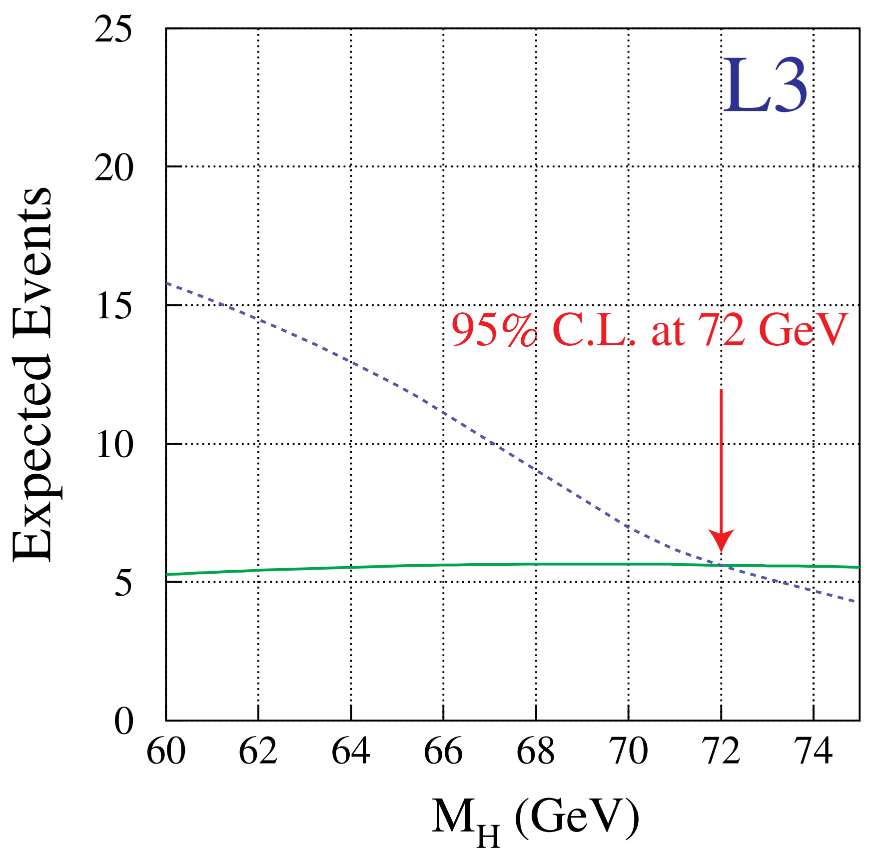
LEP combined limit
($\sqrt{s} \leq 172$ GeV)



SM Higgs boson lower mass limits

Preliminary results with $\sqrt{s}$ = 183 GeV data

	Luminosity ($\sqrt{s}$ = 183 GeV)	Observed events	Exp. events	95% CL lower limit
ALEPH	5	0	0.62	74.0
DELPHI	5.6	0	-	73.0
L3	6.1	4	3.36	72.0
OPAL	-	-	-	-



Higgs bosons (MSSM)

Model with 2 complex doublet Higgs fields

$$\phi_1 = \begin{pmatrix} \phi_1{}^a \\ \phi_1{}^b \end{pmatrix} \qquad \phi_2 = \begin{pmatrix} \phi_2{}^a \\ \phi_2{}^b \end{pmatrix}$$

From this we expect 5 Higgs bosons:

h^0, H^0	Scalar	$m_{h^o} < m_{H^o}$
A^0	Pseudoscalar	
$H^{\pm}$	Scalar	

$\tan\beta = \Phi_2/\Phi_1$

α mixing angle of the neutral scalar sector

In the MSSM there are constraints which reduce the number of free parameters to 2, we will use ($\tan\beta$, m_{h^o}).

At the tree level these relations hold:

$$m_{h^o} < m_{Z^o} < m_{H^o}$$

$$m_{h^o} < m_{A^o}$$

$$m_{W^{\pm}} < m_{H^{\pm}}$$

1 loop corrections modify these relations (depending on m_t and $m_{\tilde{}}$):

$$m_{h^o} < m_{Z^o} + \varepsilon\,(m_t, m_{\tilde{}})$$

As an example if m_t = 170 GeV $\quad m_h < 125$ GeV

2 possible production mechanisms at LEP:

$e^+e^- \rightarrow h^0Z^0$ Bjorken mechanism

$e^+e^- \rightarrow h^0A^0$ Pair production

$\sigma\,(h^0Z^0) = \sigma_{HSM} \sin^2(\beta\text{-}\alpha)$

$\sigma\,(H^0Z^0) = \sigma_{HSM} \cos^2(\beta\text{-}\alpha)$

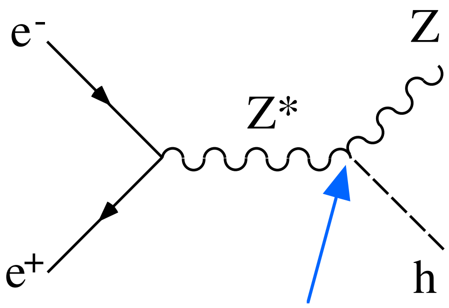
Same topologies as for H^0_{SM}

$\sigma\,(h^0A^0) = (1/2)\,\sigma_{\nu\bar{\nu}} \cos^2(\beta\text{-}\alpha) \rightarrow$ topologies bbbb, $\tau\tau$bb, $\tau\tau\tau\tau$

BR (h^0) ~ BR (A^0) ~ BR (H^0) ~ BR (H^0_{SM})

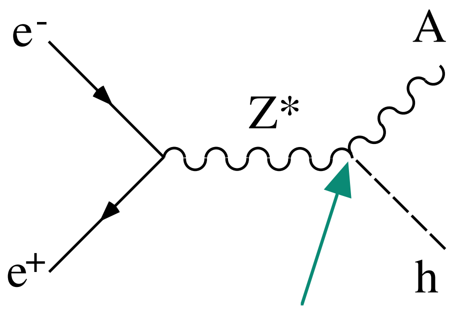
MSSM Higgs bosons

$e^+e^- \rightarrow hZ$



$\sin^2(\beta-\alpha)$

$e^+e^- \rightarrow hA$



$\cos^2(\beta-\alpha)$

Complementary

Dominates for
Large tan β

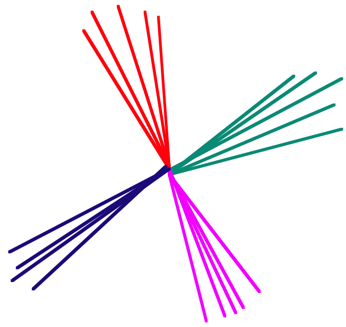
Dominates for
Small tan β

Topologies

- *Same as for the SM H^0*
- *Invisible decays*

  $(h \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0,\ Z \rightarrow l^+ l^-,\ q\bar{q})$
- $m_A < m_A/2 \rightarrow h \rightarrow AA$

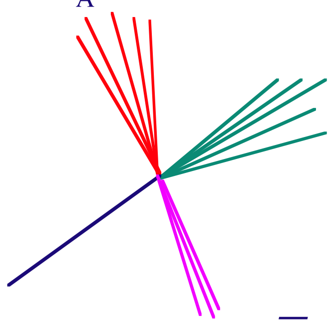
Topologies



$hA \rightarrow b\bar{b}b\bar{b}$

(four jets, all with b-flavour)

if $m_h > 2m_A$ $hA \rightarrow b\bar{b}b\bar{b}b\bar{b}$



$hA \rightarrow \tau^+\tau^- b\bar{b}$

(two b-jets and two taus)