Status and Reach of SUSY searches at LEP 2

Presentation by
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for the

Workshop on Physics and Detectors for Future e^+ e^- Linear Colliders

at

Keystone, CO

September 27th, 1998

On the plate:

Introduction
LEP 2 status&reach for {- inos
sleptons
Stop/Sbottom
Acoplanar Photons
Single Photons
GMSB
R-Parity Violating Decays}
Summary

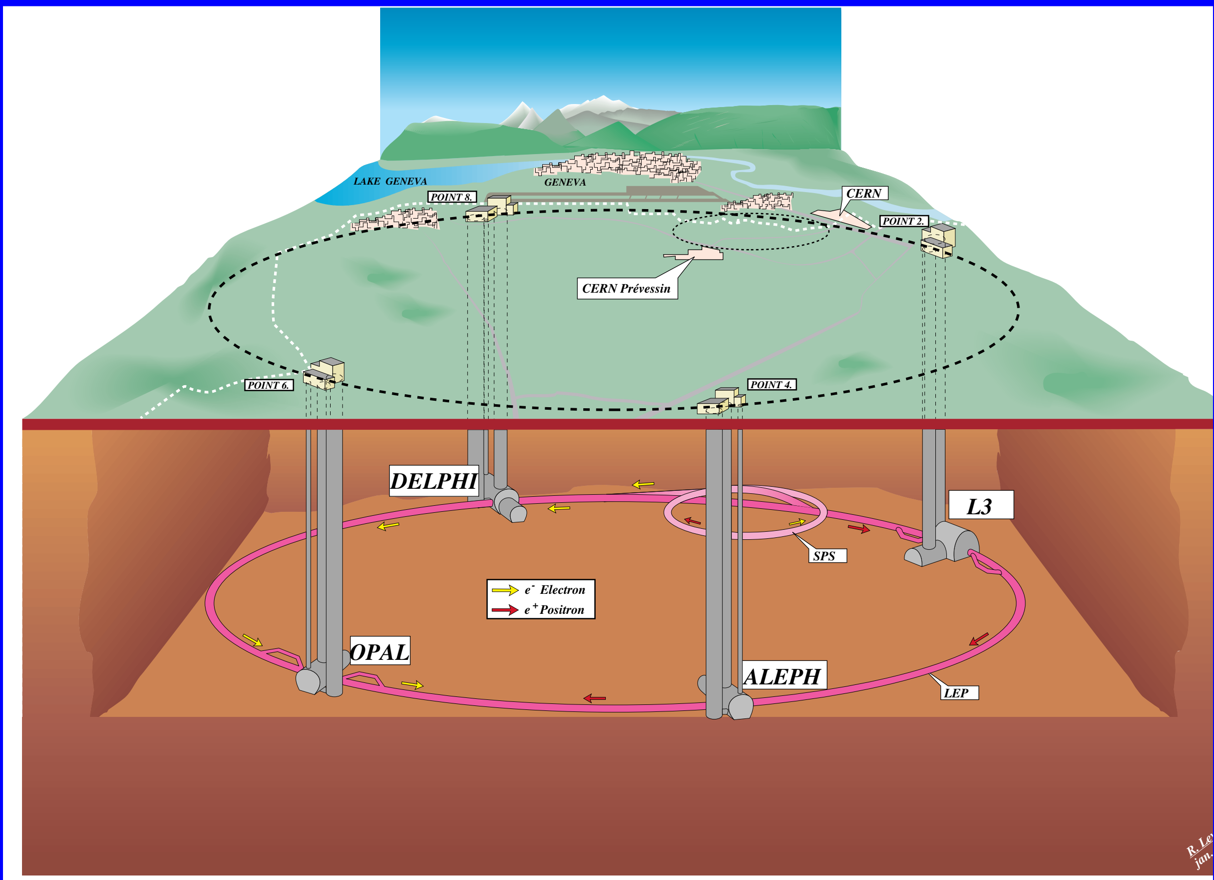
The LEP2 Program

$\int \mathcal{L}$ per Experiment per Running Period

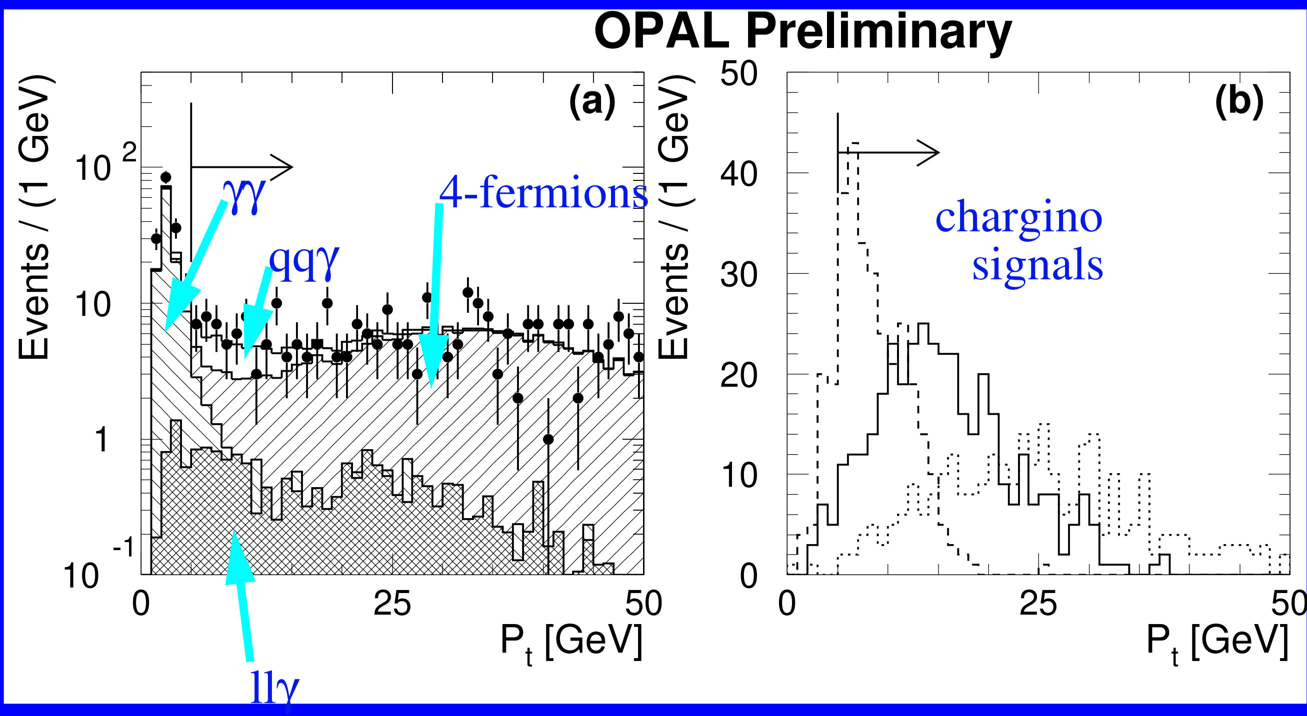
November-December 1995	~5 pb^{-1} at 130 and 136 GeV
July-October 1996	10 pb^{-1} at 161 GeV
October-November 1996	10 pb^{-1} at ~172 GeV
July -November 1997	~55 pb^{-1} at ~183 GeV
May->now 1998	>110 pb^{-1} at ~189 GeV

(~35 pb^{-1} analyzed by LEP experiments, so far)

(200 pb^{-1} possible this year!!)



Backgrounds at LEP 2



two-photon events:

huge cross-section

missing energy, momentum

low P_t events

four-fermions:

missing P_t , acoplanar

leptons/jets especially from WW events

$Z\gamma^*$

when Z vanishes into neutrinos,

ZZ*

SUSY Higgs

h^oA^o

at LEP energies expected production by
Higgs-strahlung: $e^+e^- \rightarrow h^oA^o$
pair production: $^+e^- \rightarrow h^oA^o$

Decay Modes Used:
#1: $h^oA^o \rightarrow b\bar{b}b\bar{b}$
#2: $h^oA^o \rightarrow A^oA^oA^o \rightarrow b\bar{b}b\bar{b}b\bar{b}$
#3: $h^oA^o \rightarrow \tau^+\tau^-b\bar{b}$

#1:identified by four b-tagged jets
(lifetime, lepton and boosted sphericity tags)
low missing energy
#2: similar but for a six jet topology
Backgrounds: Z^oZ^{o*} (irreducible but small so far)
$(Z/\gamma^*) \rightarrow q\bar{q}+g$
hadronic W decays
#3: taus + b flavor

Higgs masses calculated from jet momenta
after energy-momentum-constrained fit

Results for tanβ>1

	ALEPH 189 GeV	DELPHI 189 GeV	L3 189 GeV	OPAL 189 GeV	Combined 183 GeV
m_{ho}	79.7	77.5	74	73.5	77
m_{Ao}	79.7	78.3	74	74.5	78

tanβ exclusion for
minimal scalar top mixing and soft SUSY
breaking masses of 1 TeV and
$m_{top} \leq 175$GeV
0.8<tanβ<2.1 excluded@95% CL! (LEP)

Combined LEP Reach Limits

exclude up to

109 GeV @ 95% CL

5σ **discovery** up to 107 GeV

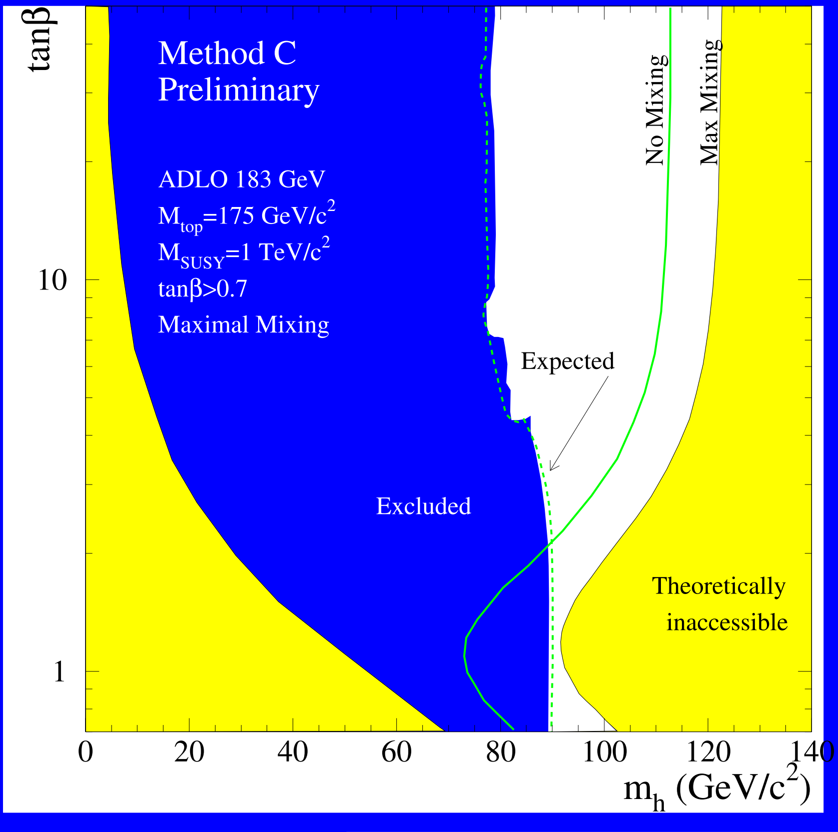
assuming

$200pb^{-1}$@200 GeV for each experiment

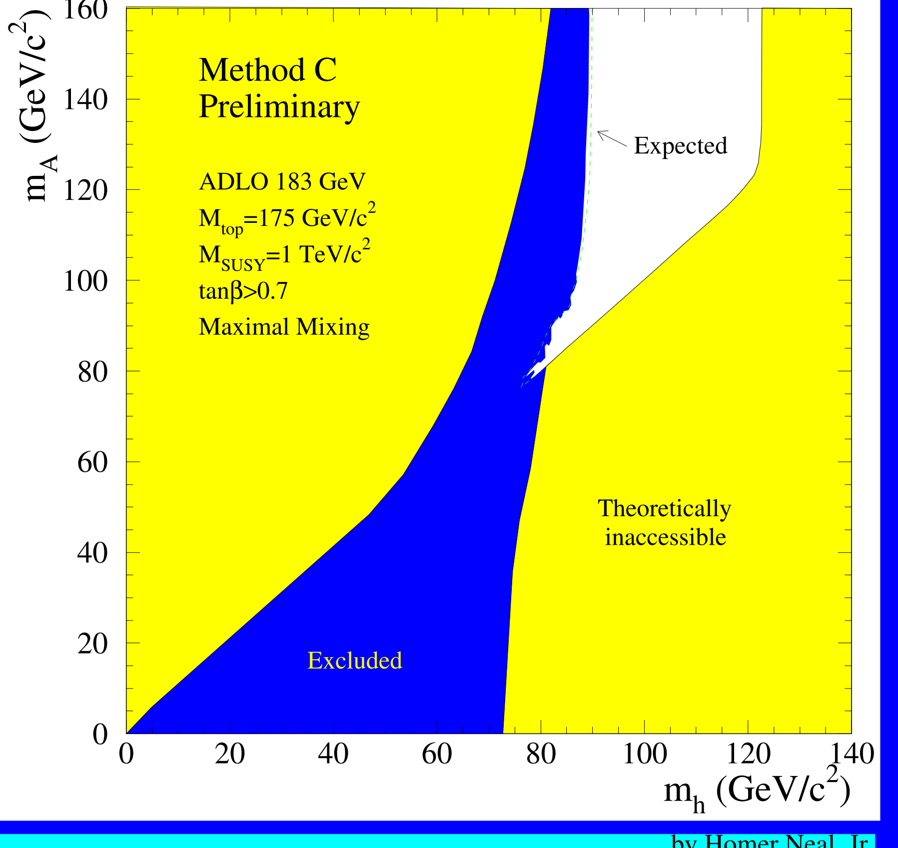
LEP h,A Search Results

blue areas are excluded at 95% CL

yellow areas are theoretically inaccessible

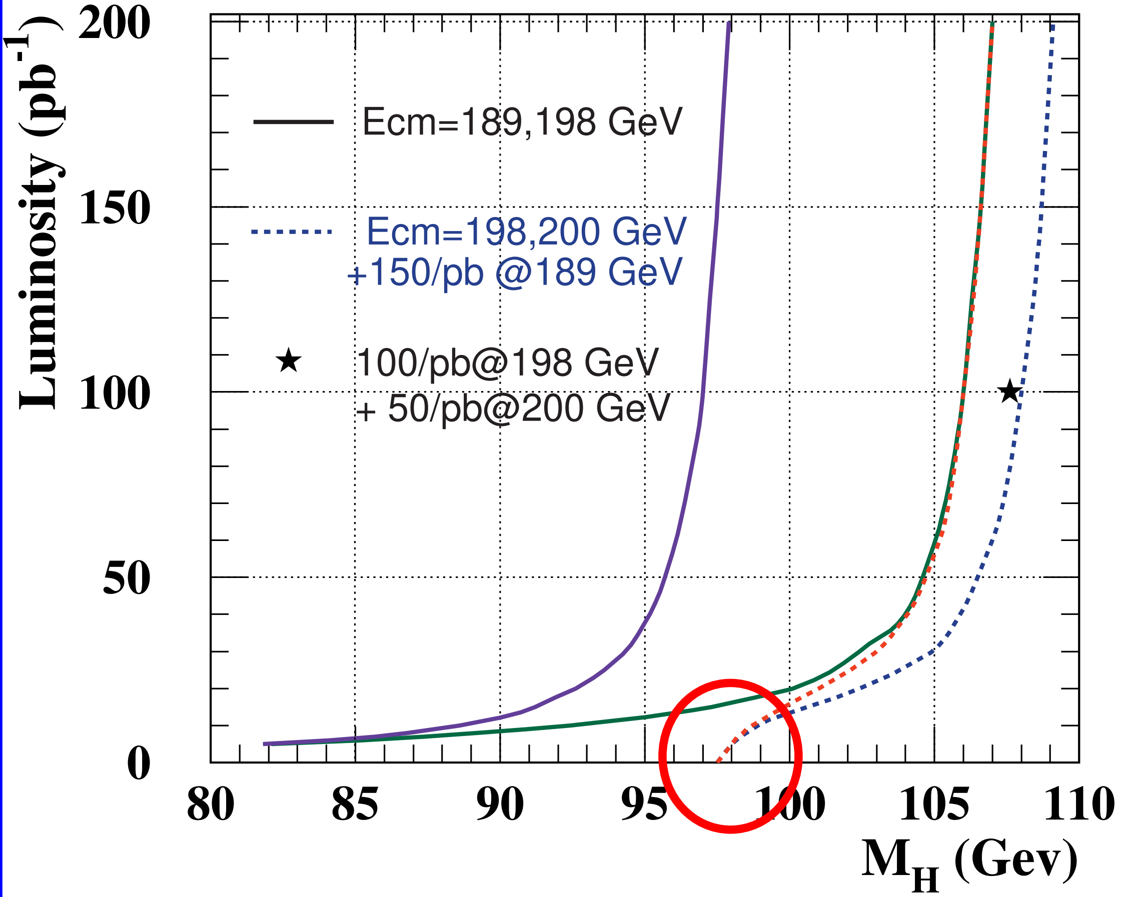


LEP
Working Group
for Higgs
bosons Searches

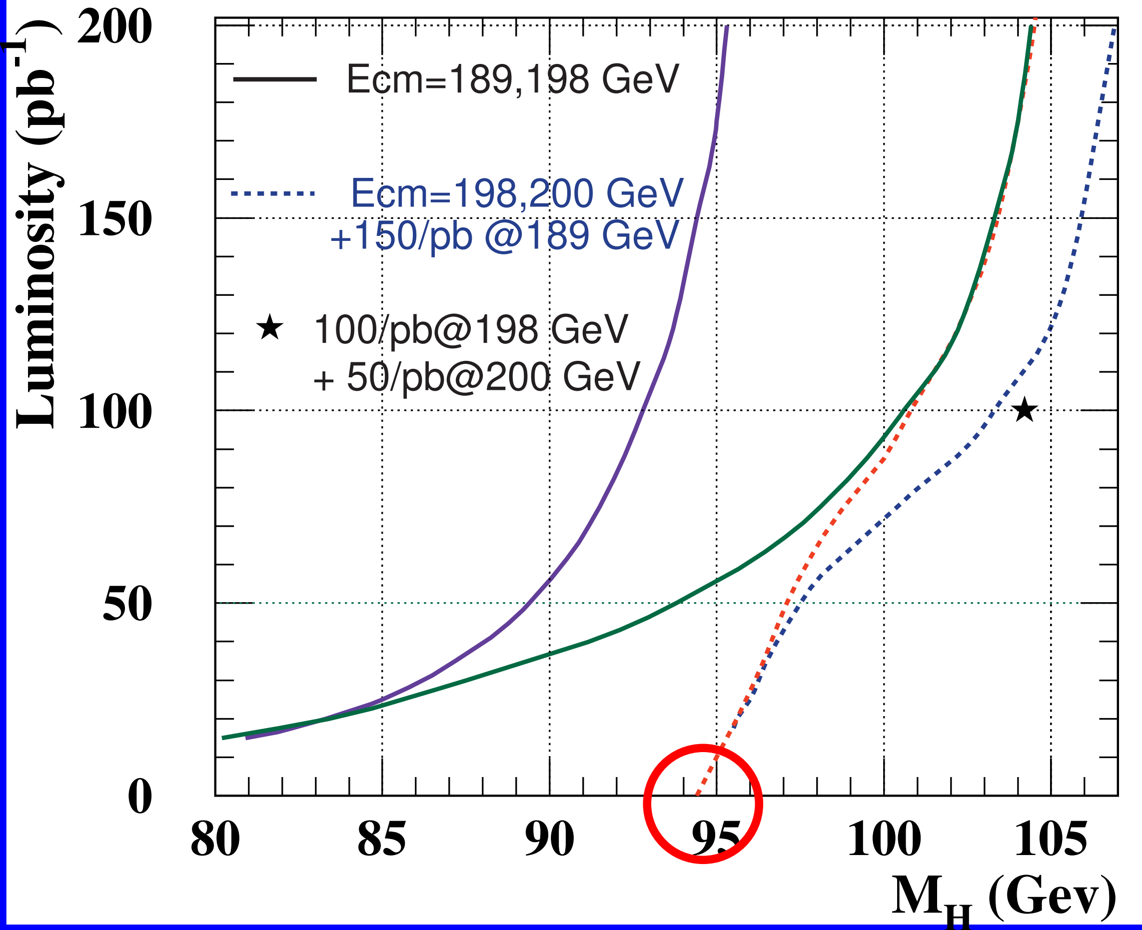


LEP2 Reach for SUSY Higgs Searches

Exclusion



Discovery



(CERN-EP/98-094 Eilam et. al.)

Charged Higgs

H^+H^-

	ALEPH	DELPHI	L3	OPAL	Combined
m_{H+}	59	59.2	57	56	

Too heavy in the MSSM for LEP2.

Lower/Any mass possible in general 2 Higgs Doublet Models

Decays studied:

$$H^+H^- \to cscs, \tau\nu cs, \tau\nu\tau\nu$$

Assuming: $BR(H^+ \to \tau\upsilon) + BR(H^+ \to cs) = 1$

	Method B	Method D
Observed Limit	68 GeV	72 GeV
Expected Limit	69 GeV	70 GeV

Constrained Models

A common m_0 and $m_{1/2}$
at the GUT scales is assumed

$(m_0, M_2, A_0, \mu, \tan\beta)$

define the spectrum of sleptons, charginos and neutralinos

m_0 ::common mass of squarks and sleptons at GUT scales

$m_{1/2}$::universal gaugino mass

A_0:: universal cubic coupling

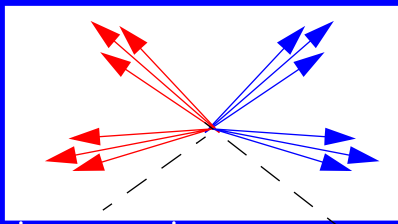
μ :: Higgsino mass parameter

$\tan\beta$ :: ratio of the Higgs field vacuum expectation values

($\tan\beta=1 \rightarrow 3$ and $\tan\beta=m_{top}/m_{bottom}=35$ yield ~meas. m_{top})

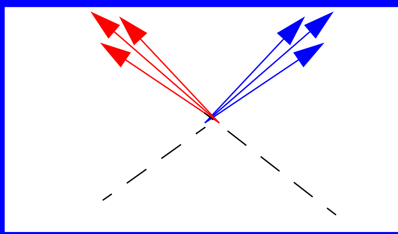
(M_2 :: SU(2) gaugino mass often used instead of $m_{1/2}$)

Topologies in the CMSSM



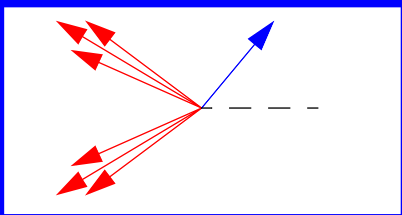
Background from 4-fermions and Z/γ*

$$\tilde{\chi}_1^+\tilde{\chi}_1^- \to W^{+*}\tilde{\chi}_1^o W^{-*}\tilde{\chi}_1^o \to q\bar{q} + q\bar{q} + \mathrm{E}_{miss}$$

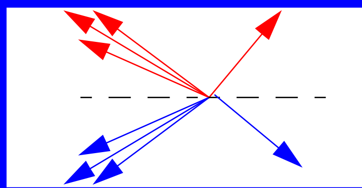


$$\tilde{\chi}_2^0\tilde{\chi}_1^0 \to Z^*\tilde{\chi}_1^0\tilde{\chi}_1^0 \to q\bar{q} + \mathrm{E}_{miss}$$

$$\tilde{t}\tilde{\bar{t}} \to c\tilde{\chi}_1^0 c\tilde{\chi}_1^0 \to c\bar{c} + \mathrm{E}_{miss},\ \tilde{b}\tilde{\bar{b}} \to b\tilde{\chi}_1^0\bar{b}\tilde{\chi}_1^0 \to b\bar{b} + \mathrm{E}_{miss}$$

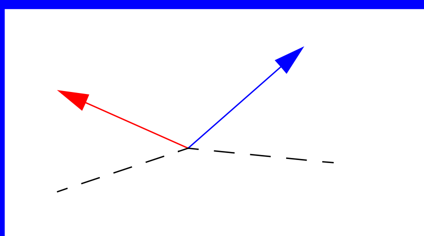


Background from 4–f Weν events



$$\tilde{\chi}_1^+\tilde{\chi}_1^- \to W^{+*}\tilde{\chi}_1^o W^{-*}\tilde{\chi}_1^o$$
$$\text{""} \to q\bar{q} + l + \mathrm{E}_{miss}$$

$$\tilde{t}\tilde{\bar{t}} \to bl\tilde{\nu}\bar{b}l\tilde{\nu}$$
$$\text{""} \to b\bar{b} + ll + \mathrm{E}_{miss}$$



Background from two-photon & 4-f events

$$\tilde{\chi}_1^+\tilde{\chi}_1^- \to W^{+*}\tilde{\chi}_1^o W^{-*}\tilde{\chi}_1^o \to l^+ + l^- + \mathrm{E}_{miss}$$

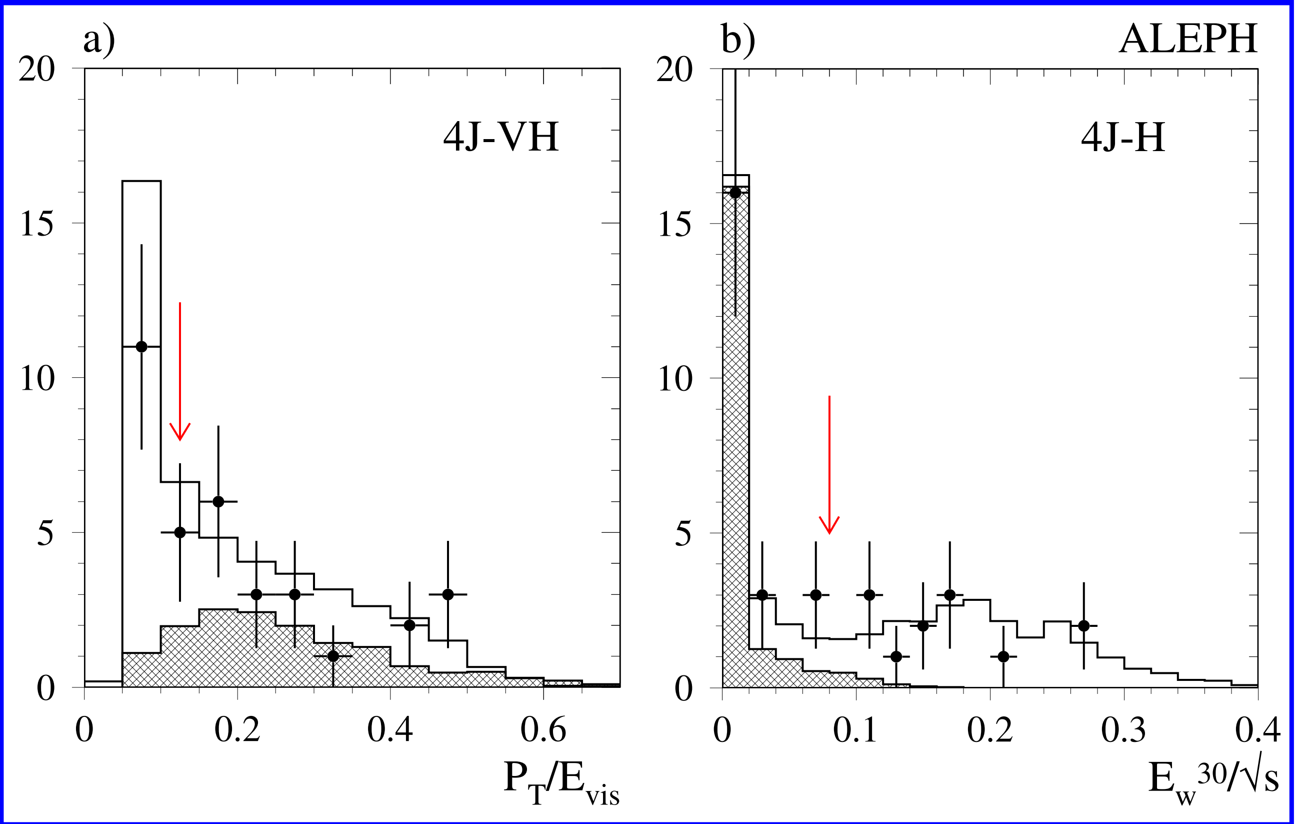
$$\tilde{\chi}_2^0\tilde{\chi}_1^0 \to Z^*\tilde{\chi}_1^0\tilde{\chi}_1^0 \to l^+l^- + \mathrm{E}_{miss}$$

$$\tilde{l}^+\tilde{l}^- \to l^+\tilde{\chi}_1^0 l^-\tilde{\chi}_1^0 \to l^+ l^- + \mathrm{E}_{miss}$$

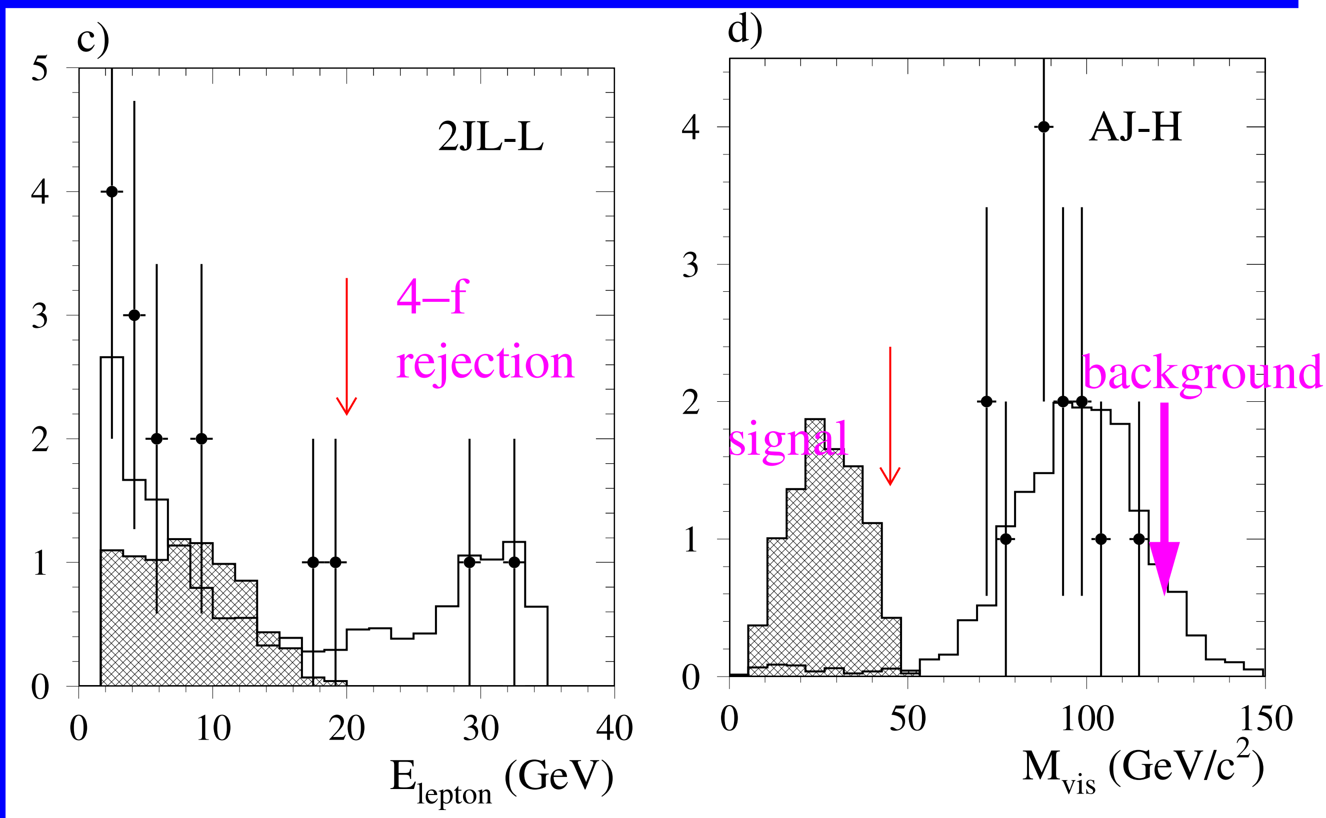
Assuming that R-parity is conserved

LSP=$\tilde{\chi}_1^0$

by Homer Neal, Jr.



CERN-PPE 97-128

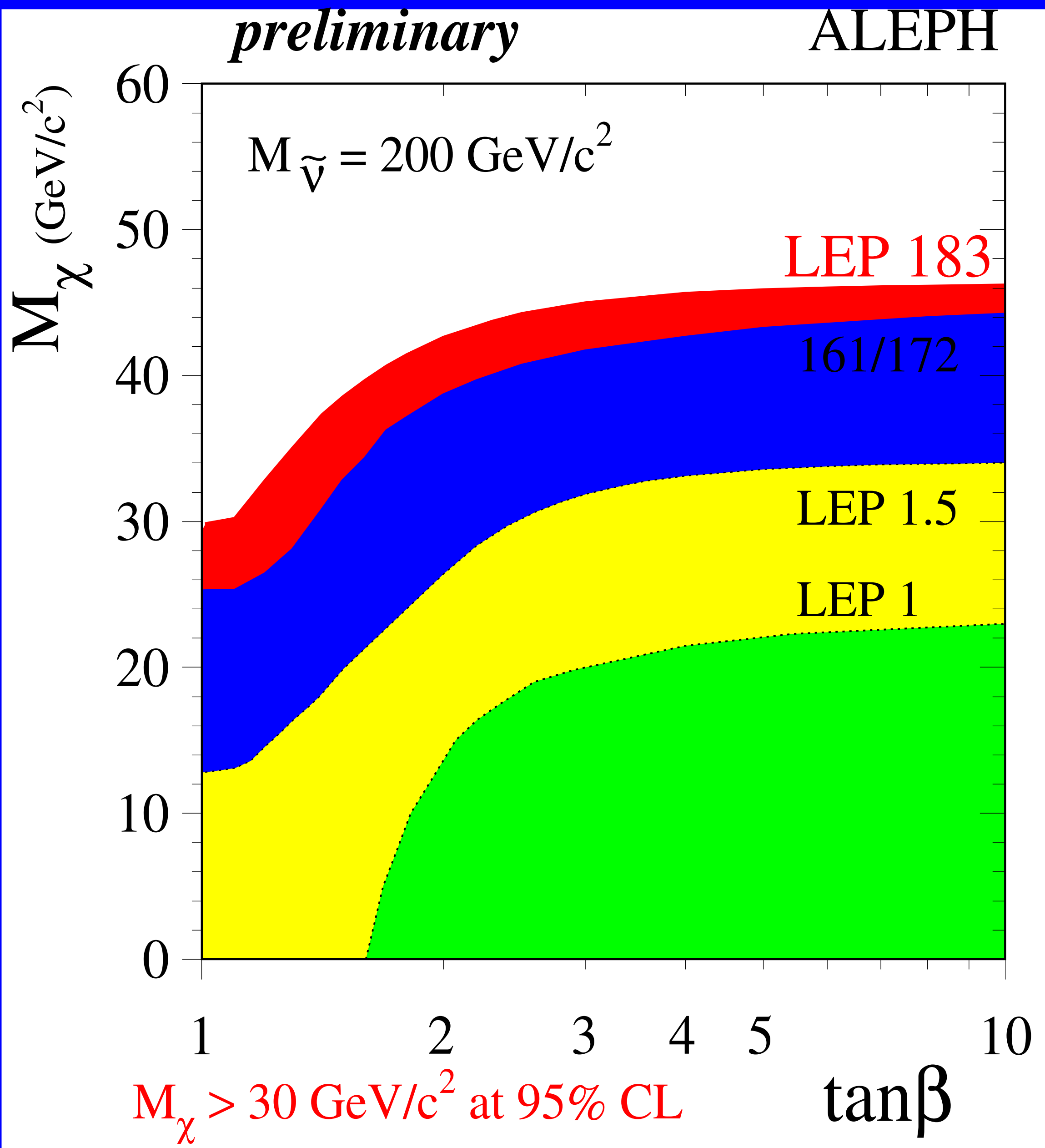


Neutralino Limits

$m_{\chi o}$	ALEPH	DELPHI	L3	OPAL
all m_o 183 GeV	26	23.4	25.9	24.2
large m_o 189 GeV	32	30.6 $M_1/M_2 \geq 0.5$ $\tan\beta > 1$ $m_\nu > 300$ GeV	30.1	32.8 $m_o > 500$ GeV

more general

CDM Implications

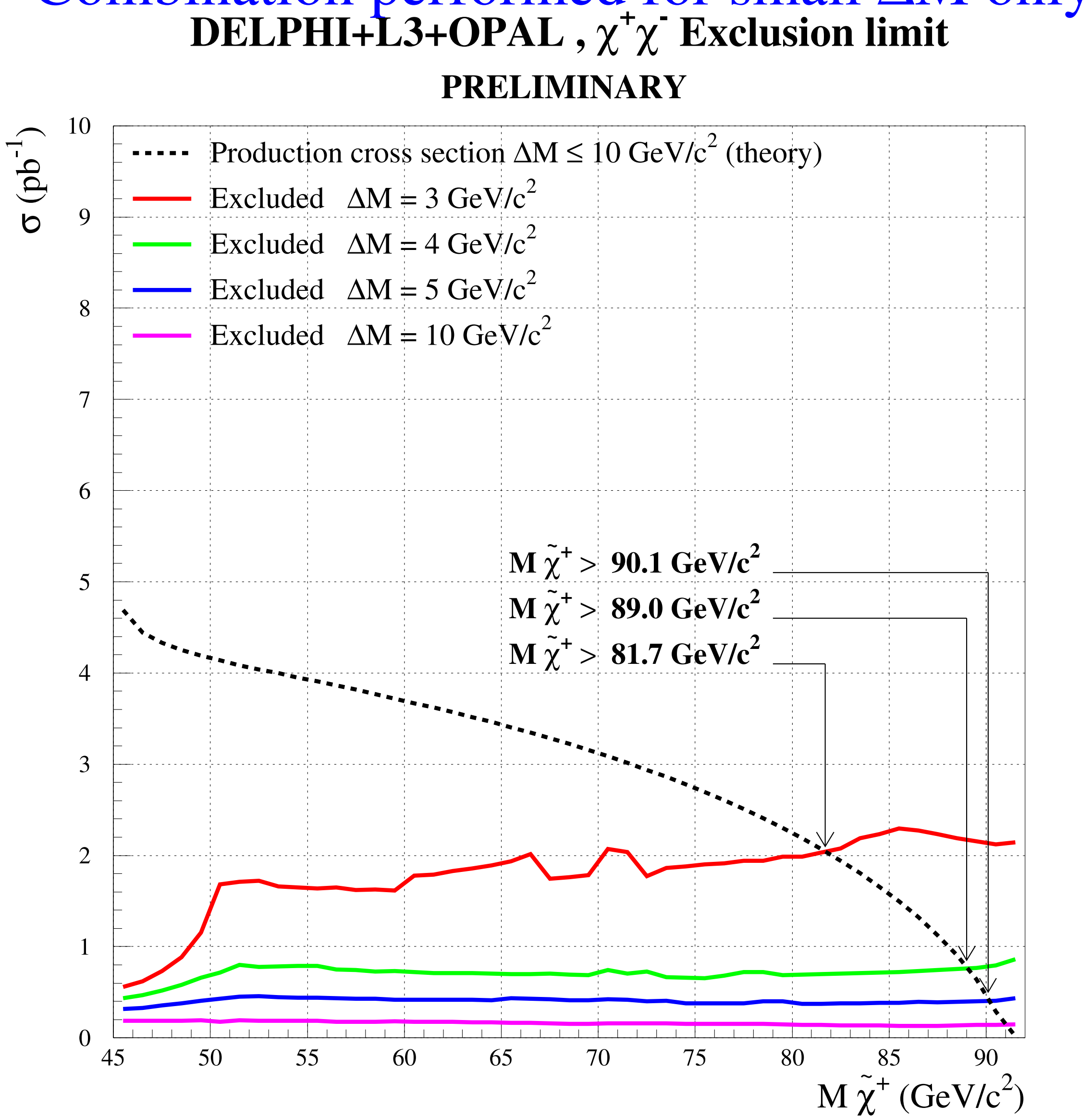


$M_\chi > 30$ GeV/c^2 at 95% CL

Chargino Limits

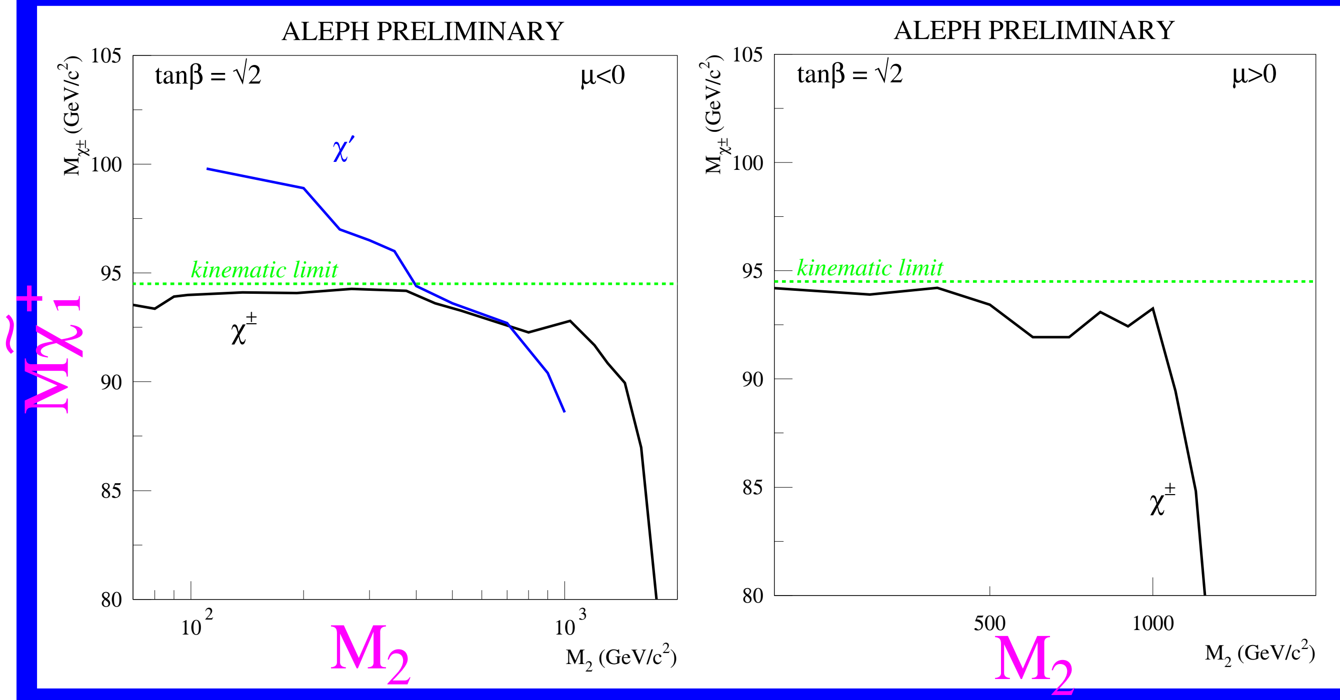
$m_{\chi+}$ 32->36 pb^{-1} 189 GeV	ALEPH	DELPHI	L3	OPAL
	see plot	91.2 Vancouver large m_ν ΔM>10 GeV	93.7 Vancouver large m_ν $\tan\beta$=1.41 μ=-200 GeV	93.0 Vancouver large m_o ΔM>10 GeV $\tan\beta$=1.5

Combination performed for small ΔM only

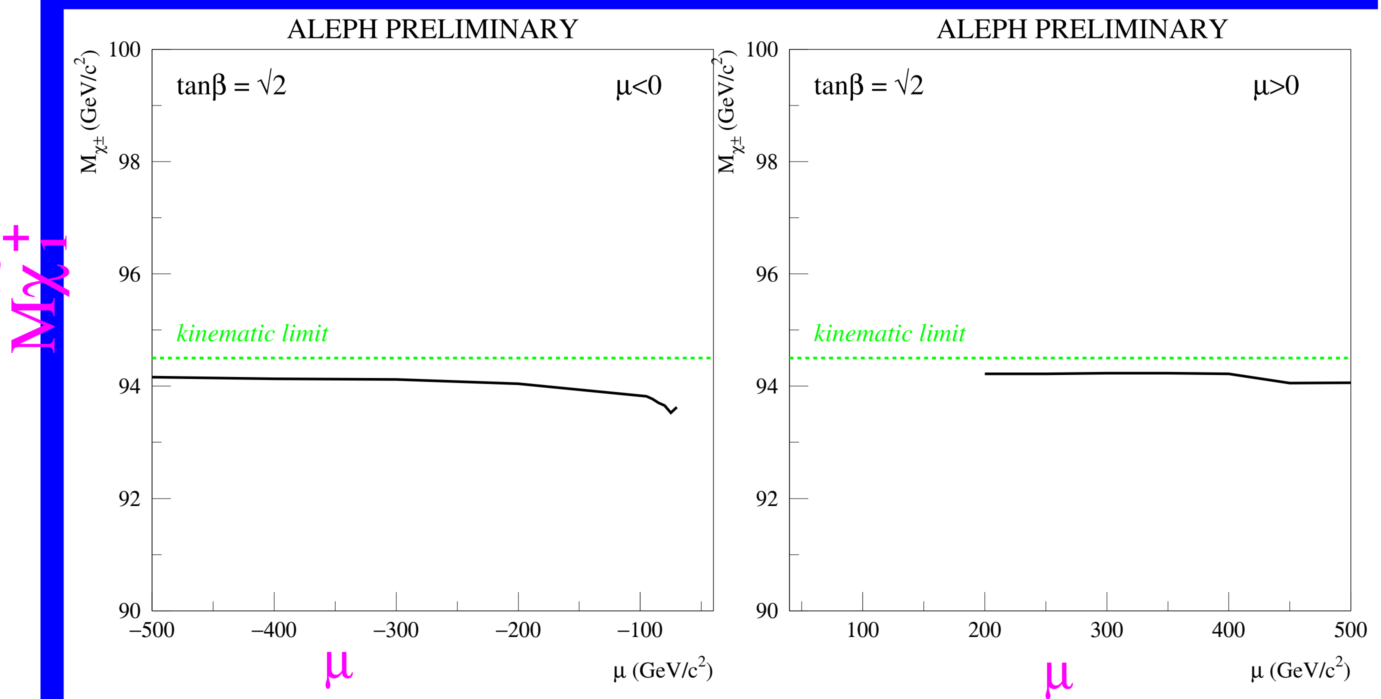


LEP SUSY Working Group
Preliminary results from the combination of LEP experiments
(http://www.cern.ch/lepsusy/)

Limits usually weakest at low ΔM^+; high $\gamma\gamma$ background



higgsino region

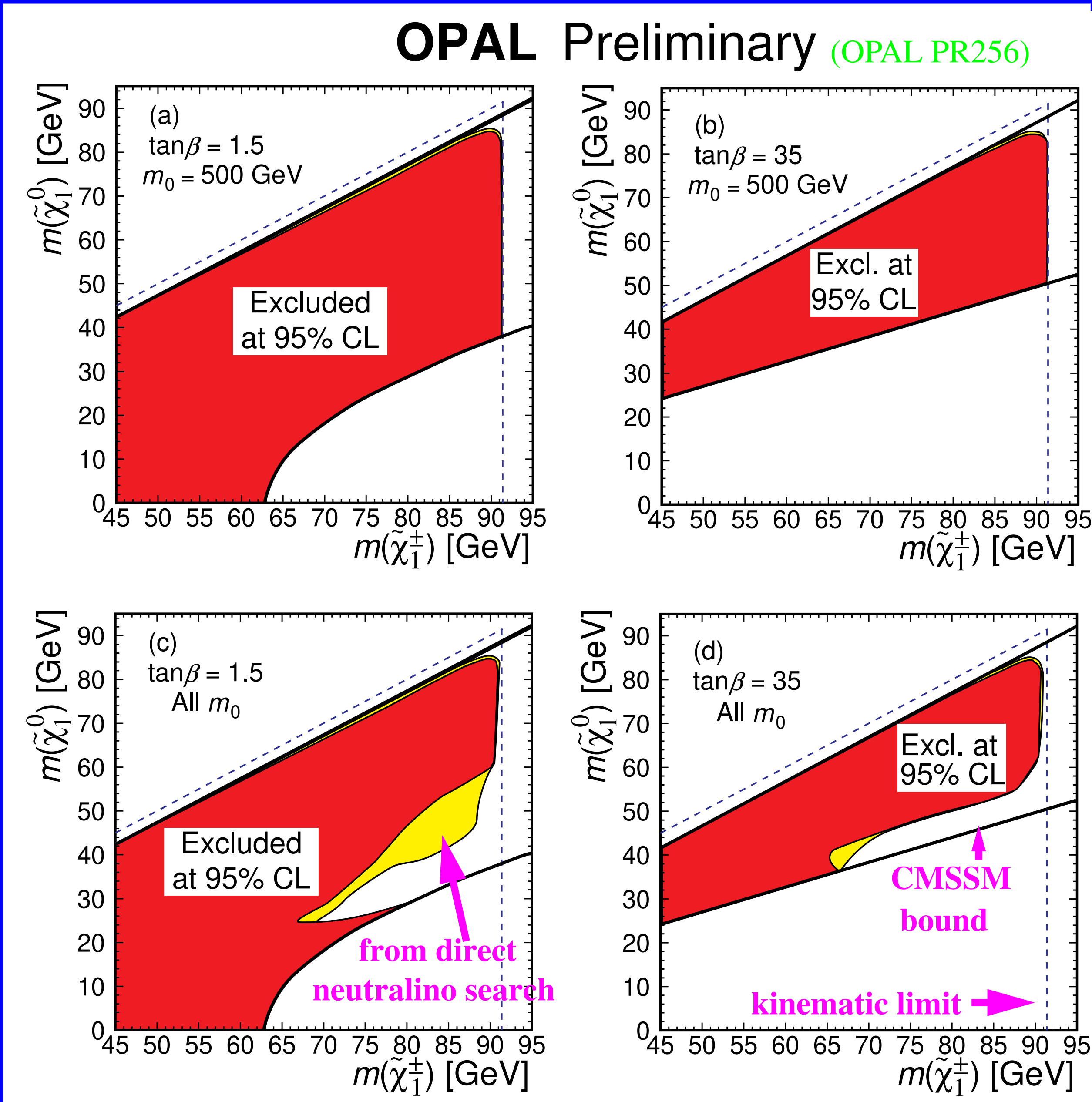


gaugino region

ALEPH 189 GeV Vancouver update

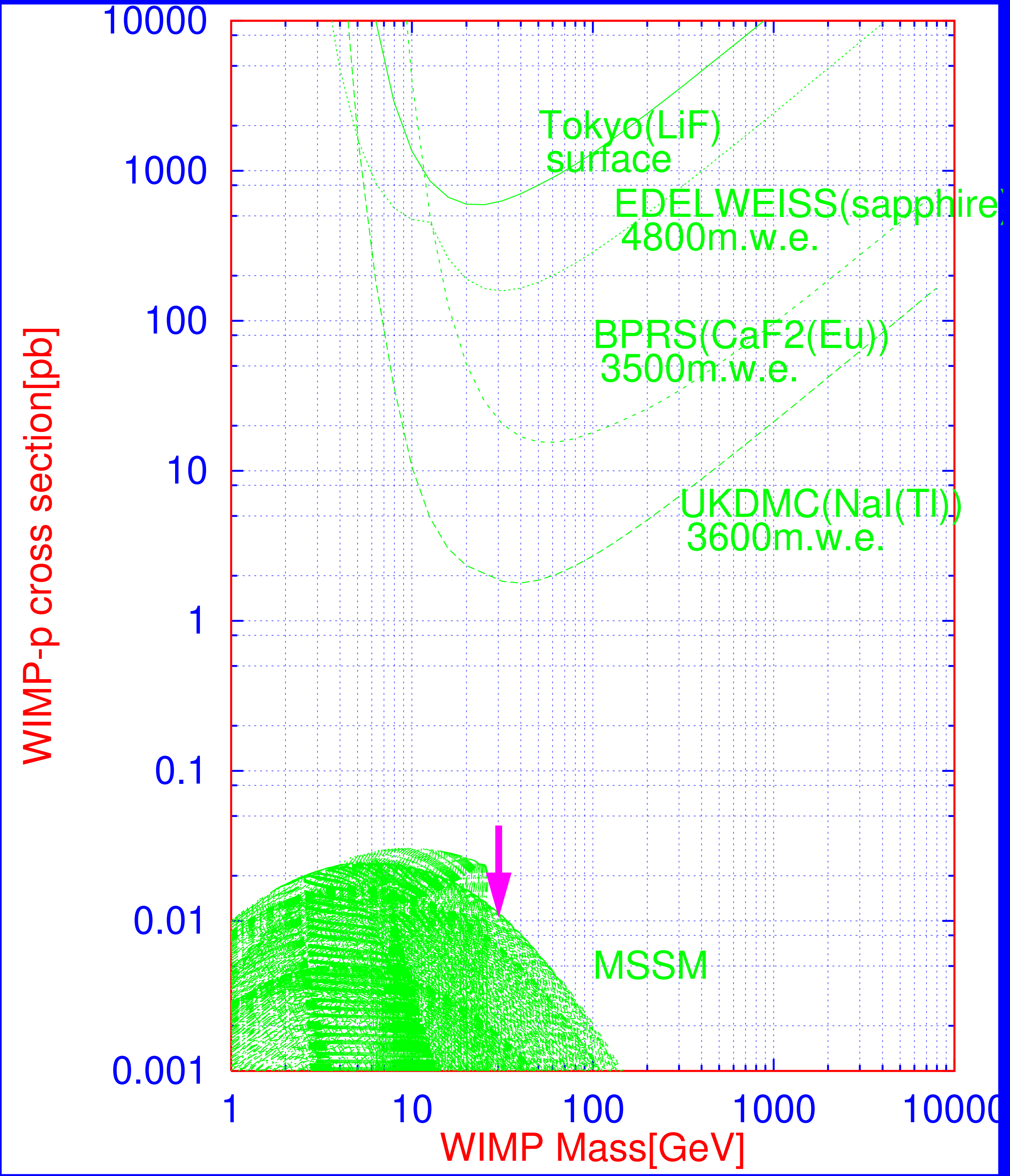
χ^+ search region limited by kinematical limit due to its expected large cross-section

χ^o search limited by integrated luminosity



Neutralino Limits should greatly improve this year.

Implication of the $m_{\tilde{\chi}^0_1}$ limit



Slepton Searches

$$\tilde{l}^+\tilde{l}^- \to l^+\tilde{\chi}^0_1\, l^-\tilde{\chi}^0_1 \to l^+ l^- + E_{miss}$$

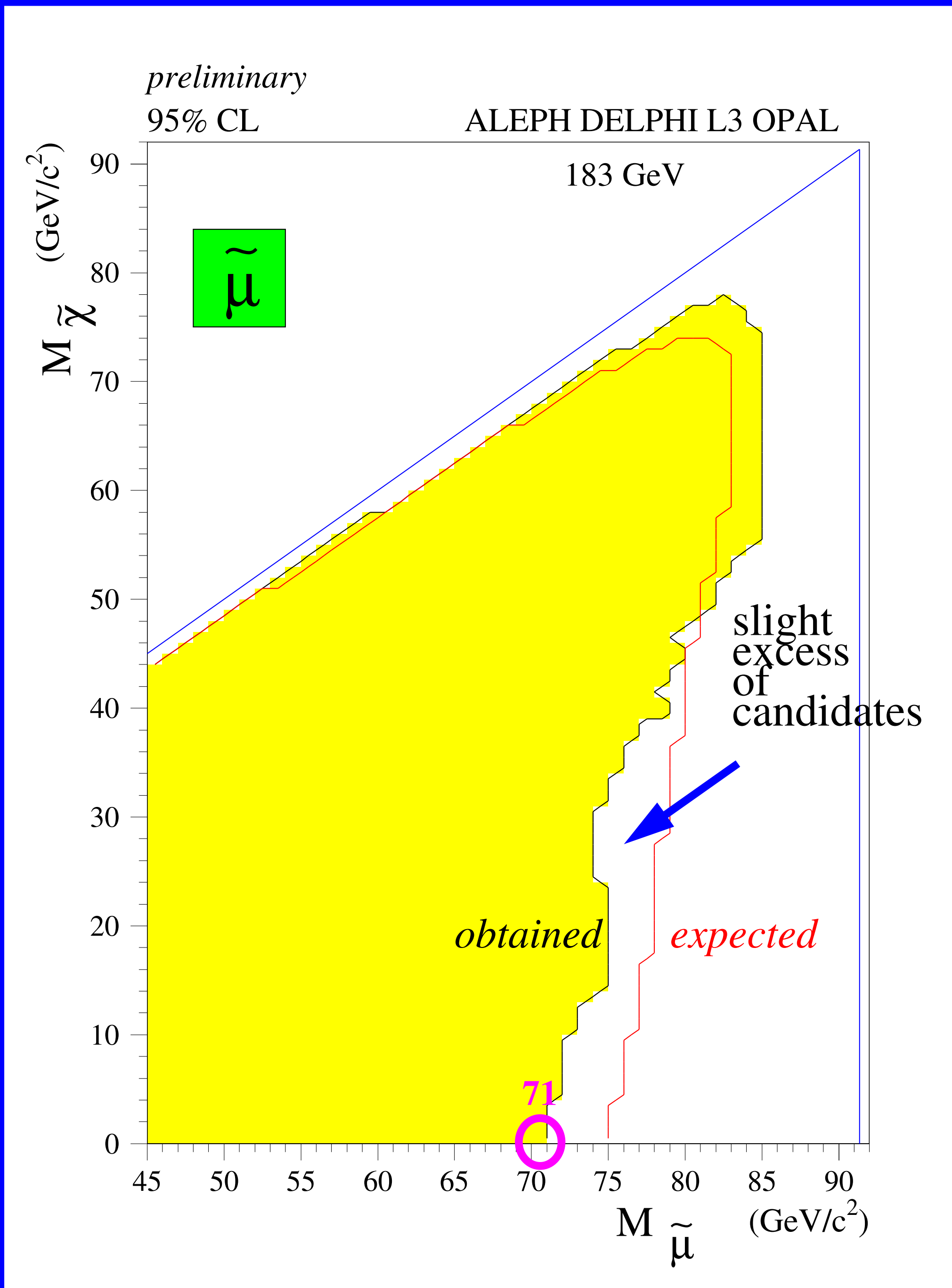
signature used:
acoplanar & missing P_t di-lepton events

Individual and Combined Limits

	ALEPH	DELPHI	L3	OPAL	LEP 183 $\Delta M>$ 15 GeV
$\tilde{e}$	84 $\Delta M>15$ GeV $tg\beta=2$	84.4 $\Delta M>15$ GeV $tg\beta=1.5$	80 $\Delta M>15$ GeV $tg\beta=1.41$	78 $\Delta M>15$ GeV $tg\beta=1.5$	84
$\tilde{\mu}$	78 $\Delta M>15$ GeV	70.3 $\Delta M>35$ GeV	69 $\Delta M>15$ GeV	73 $\Delta M>3$ GeV	71
$\tilde{\tau}$	65 $\Delta M>15$ GeV	70 $\Delta M>15$ GeV		69.4 $\Delta M>10$ GeV	72

Individual results are for sqrt(s)=189 GeV

No Significant Excesses Observed but some Discrepancies Exist



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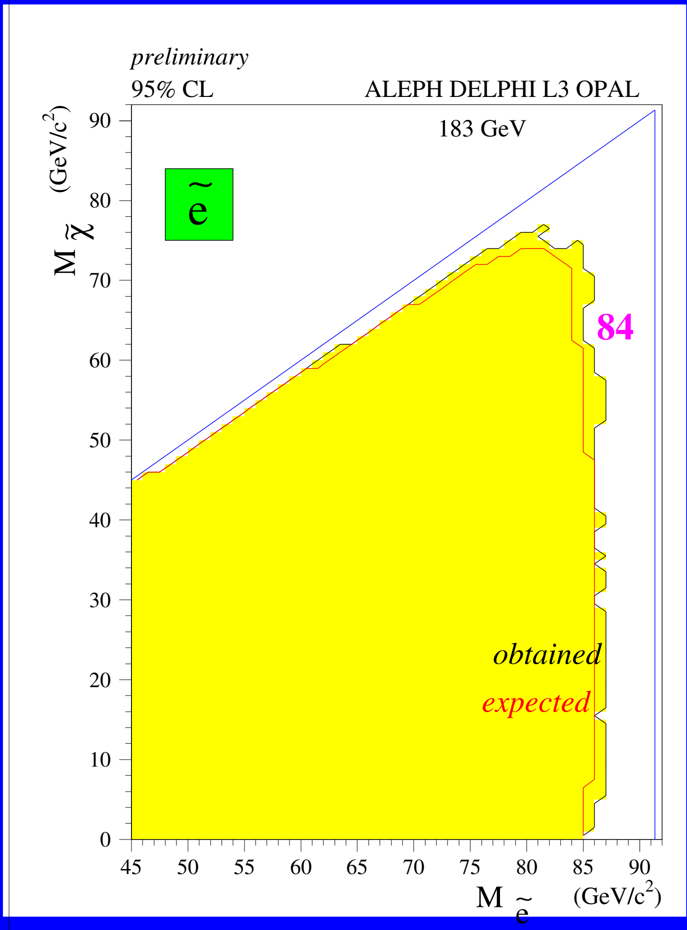
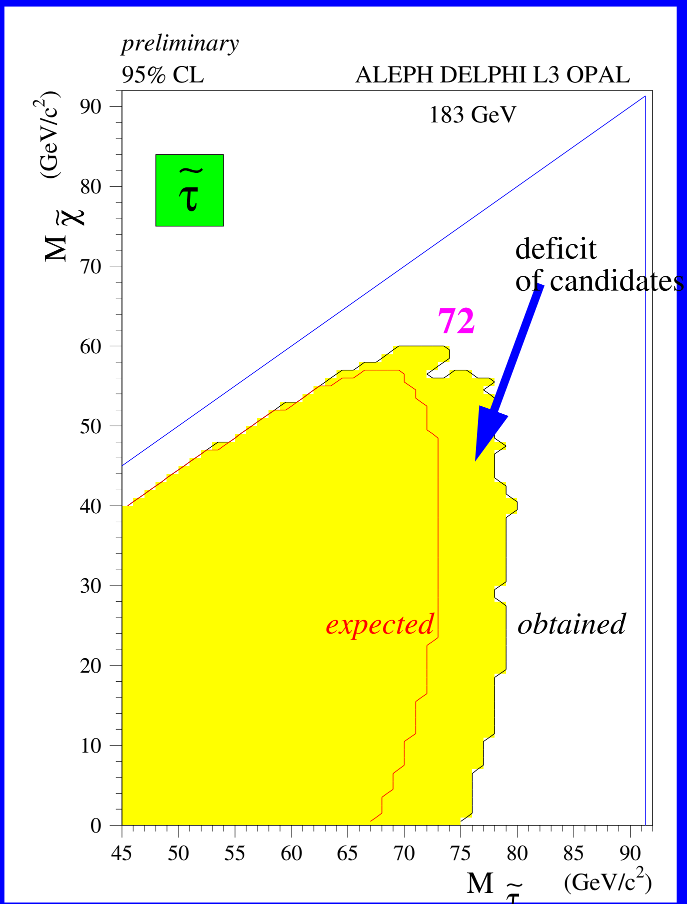

preliminary
95% CL
ALEPH DELPHI L3 OPAL
183 GeV
ẽ
84
obtained
expected
M χ̃ (GeV/c²)
M ẽ (GeV/c²)


preliminary
95% CL
ALEPH DELPHI L3 OPAL
183 GeV
τ̃
deficit
of candidates
72
expected
obtained
M χ̃ (GeV/c²)
M τ̃ (GeV/c²)

Stop and Sbottom

stop mass eigenstates determined by the mixing angle $\theta_{\tilde{t}}$

$$\tilde{t} \to \tilde{t}_L \cos\theta_{\tilde{t}} + \tilde{t}_R \sin\theta_{\tilde{t}}$$

possibly very light due to
large negative corrections from
Higgsino-(s)quark loops
and
a large mass splitting between
the two mass eigenstates

similarly
for large $\tan\beta$
the $\tilde{b}$ can be light

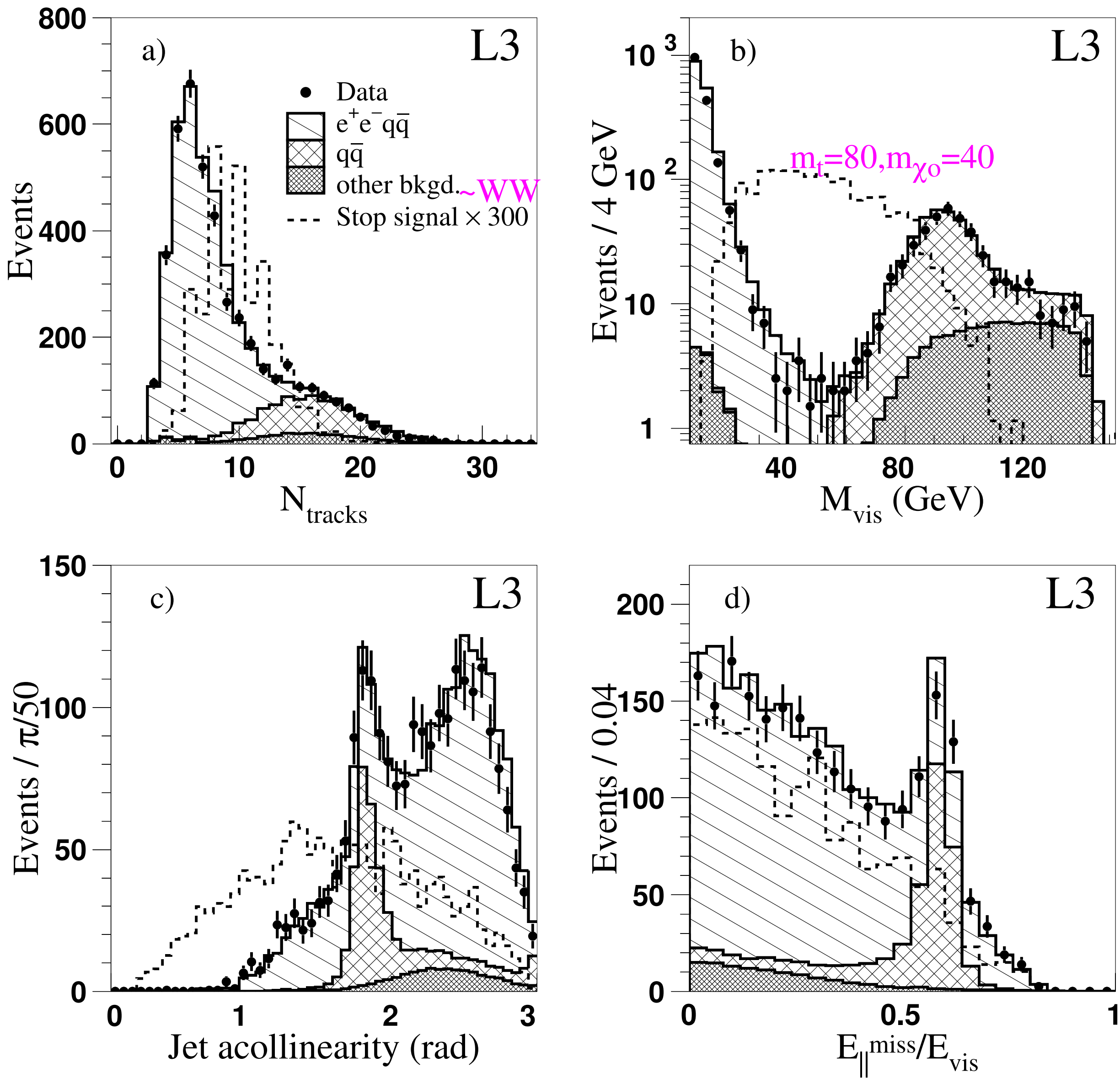
Signatures:

$$\tilde{t}\bar{\tilde{t}} \to c\tilde{\chi}_1^0 c\tilde{\chi}_1^0 \to c\bar{c} + \mathrm{E}_{miss}, \tilde{b}\bar{\tilde{b}} \to b\tilde{\chi}_1^0 \bar{b}\tilde{\chi}_1^0 \to b\bar{b} + \mathrm{E}_{miss}$$

$$\tilde{t}\bar{\tilde{t}} \to bl\tilde{\nu}\bar{b}l\tilde{\nu}'' \to b\bar{b} + ll + \mathrm{E}_{miss}$$

SUSY breaking parameters determined by θ & m

Discrimination Variables for the L3 Stop/Sbottom Search at 183 GeV

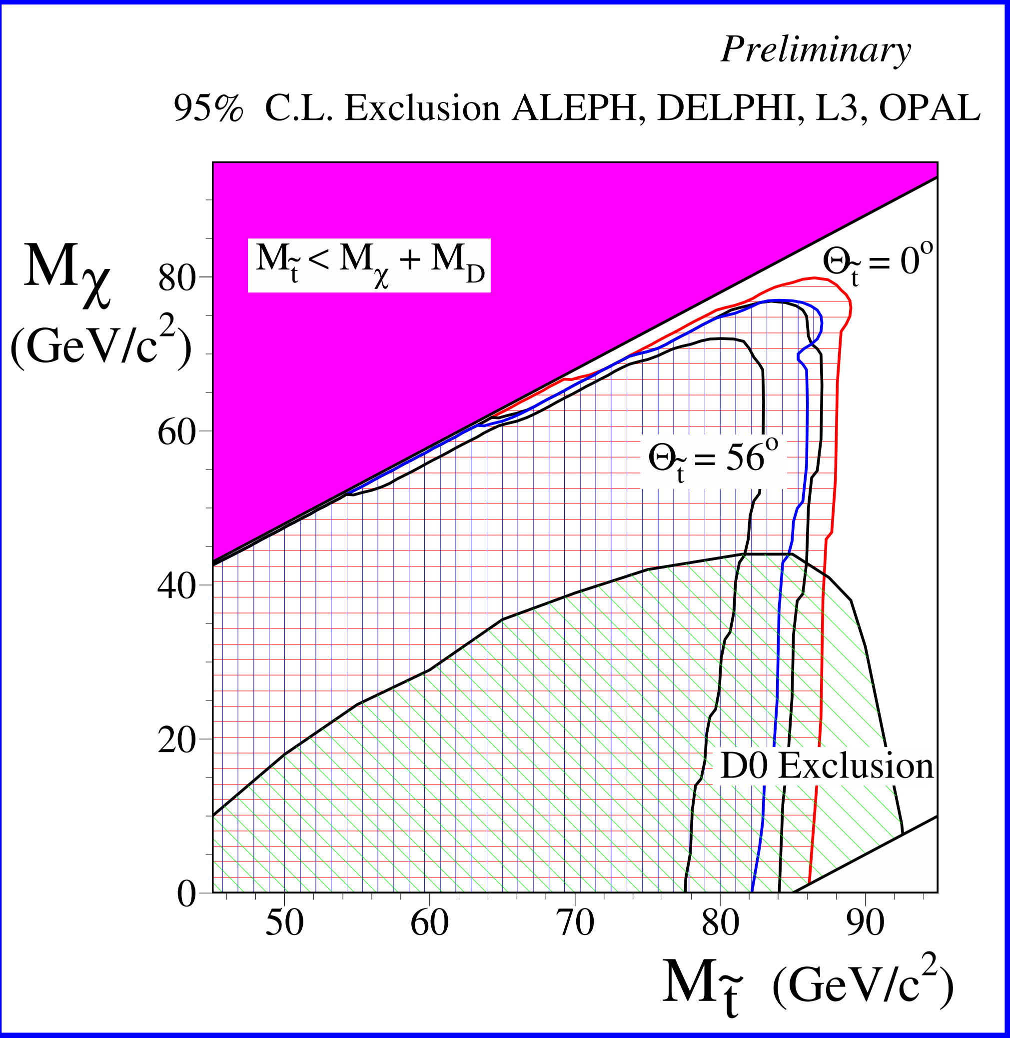


L3 stop/sbottom note submitted to Phys. Lett. B 8/98

by Homer Neal, Jr.

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

$\tilde{t} \rightarrow c\tilde{\chi}_1^0$	ALEPH 189 GeV ΔM>10 GeV	DELPHI 189 GeV ΔM>10 GeV	L3 189 GeV ΔM>10 GeV	OPAL 189 GeV ΔM>10 GeV	LEP **183 GeV** ΔM> 15 GeV
$\theta_t=0^o$	84	78.4	81	88.3	86.5
$\theta_t=56^o$				85.2	83.5



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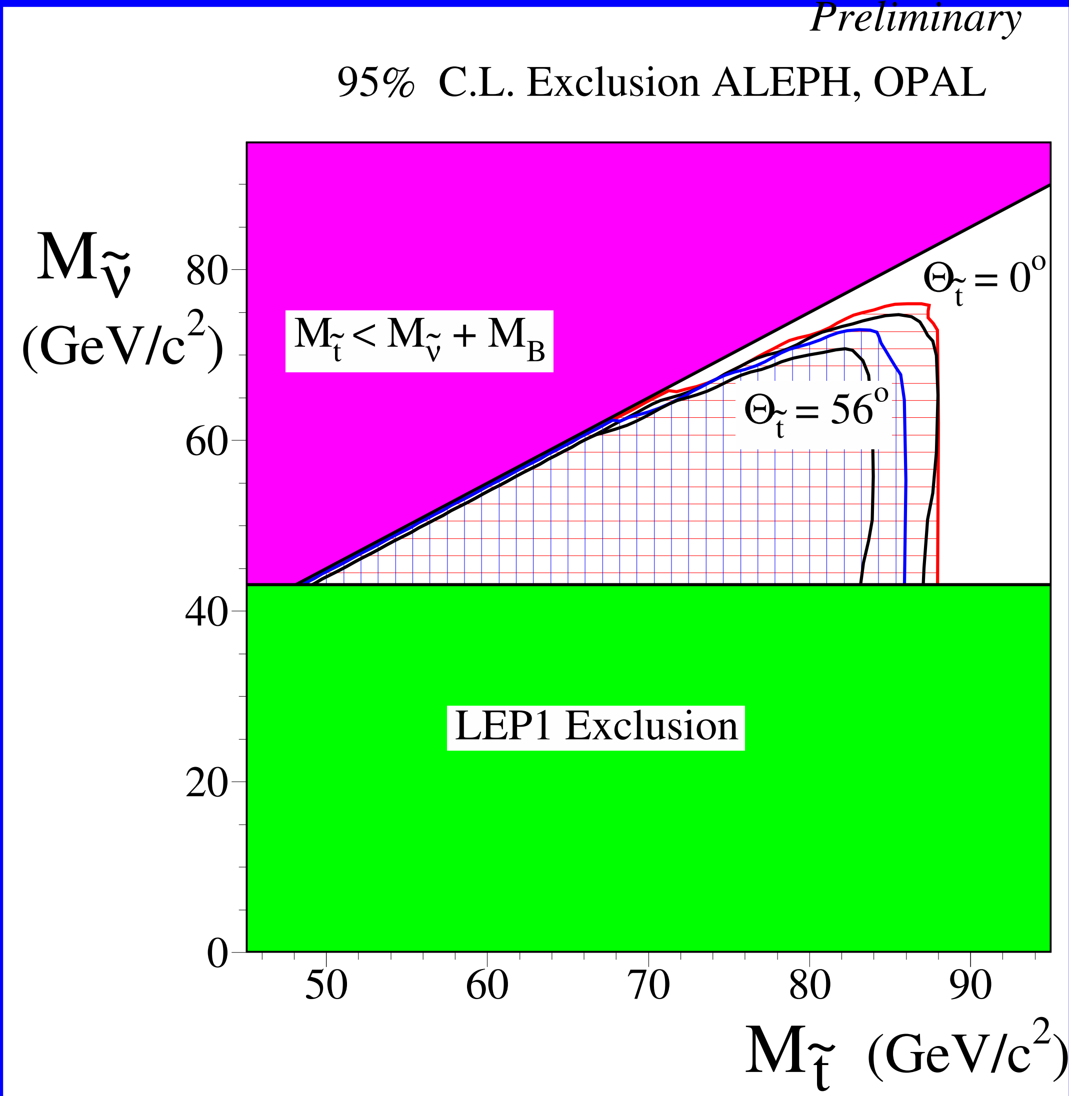
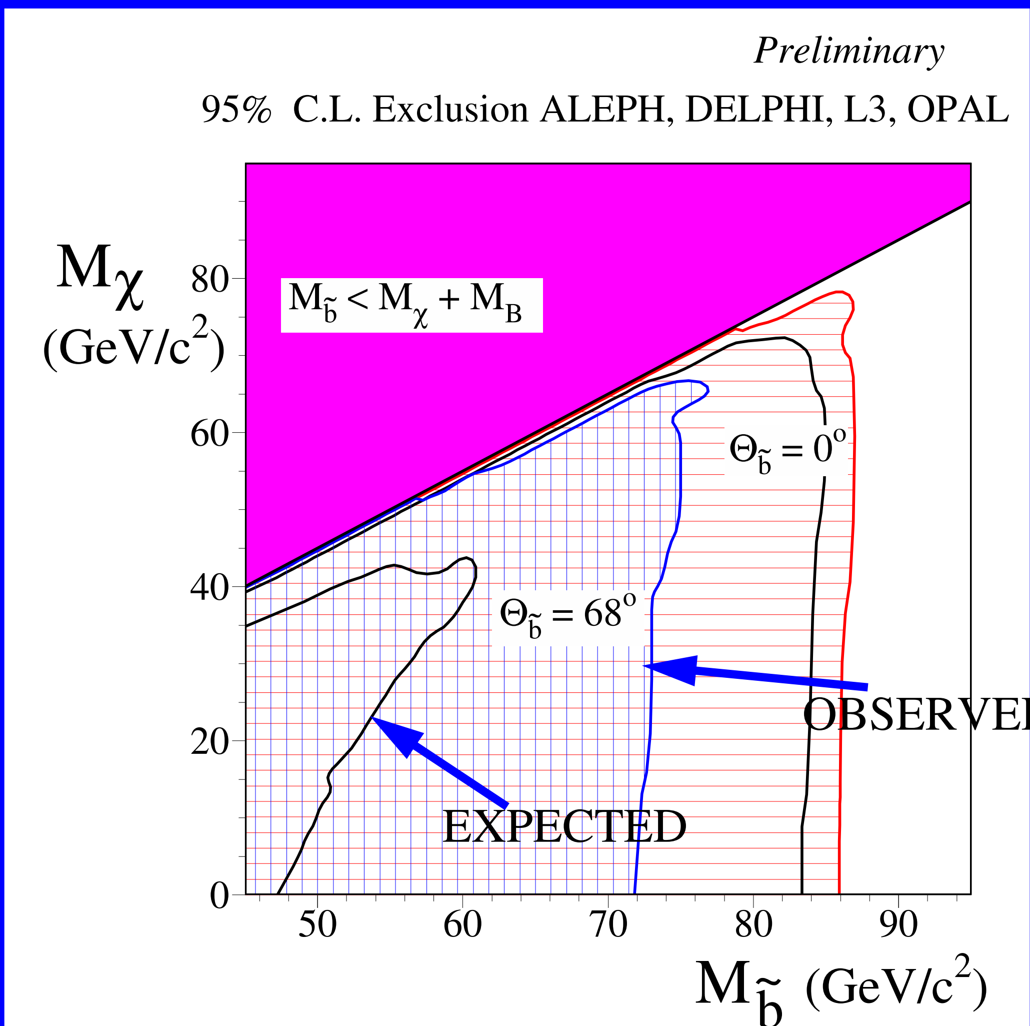
$\tilde{t} \to bl\nu$ Stop Searches

$\tilde{t} \to bl\nu$	ALEPH 189 GeV $\Delta M>10$ GeV	DELPHI 189 GeV $\Delta M>15$ GeV	L3 189 GeV $\Delta M>10$ GeV	OPAL 189 GeV $\Delta M>10$ GeV	LEP **183 GeV** $\Delta M>$ 15 GeV
$\theta_t=0^o$	88	82.0		87.3	87.5
$\theta_t=56^o$				83.5	84.5



Sbottom Searches

$\tilde{b} \to b\tilde{\chi}_1^0$	ALEPH 189 GeV ΔM>10 GeV	DELPHI 189 GeV ΔM>10 GeV	L3 189 GeV ΔM>20 GeV	OPAL 189 GeV ΔM>10 GeV	LEP 183 ΔM> 15 GeV
$\theta_b=0^o$	84	78.6	80	85.5	85.5
$\theta_b=68^o$				63.3	75.5



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Acoplanar Photons

Signature of neutralinos in the MSSM:

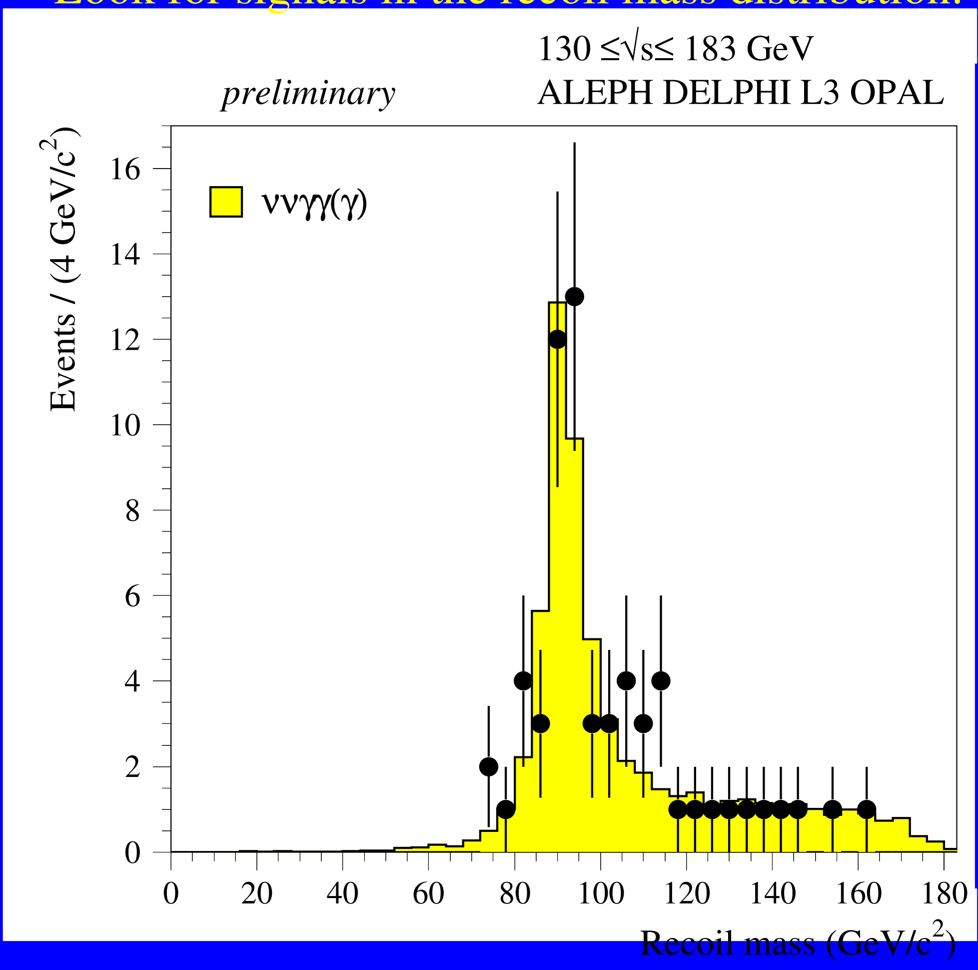
$$\tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow \gamma\tilde{\chi}_1^0\gamma\tilde{\chi}_1^0 \rightarrow \gamma\gamma + E_{miss}$$

Signature of gravitinos in the GMSB:

$$\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}\gamma\tilde{G} \rightarrow \gamma\gamma + E_{miss}$$

Select a pure set of events with only acoplanar photons pairs

Look for signals in the recoil mass distribution:



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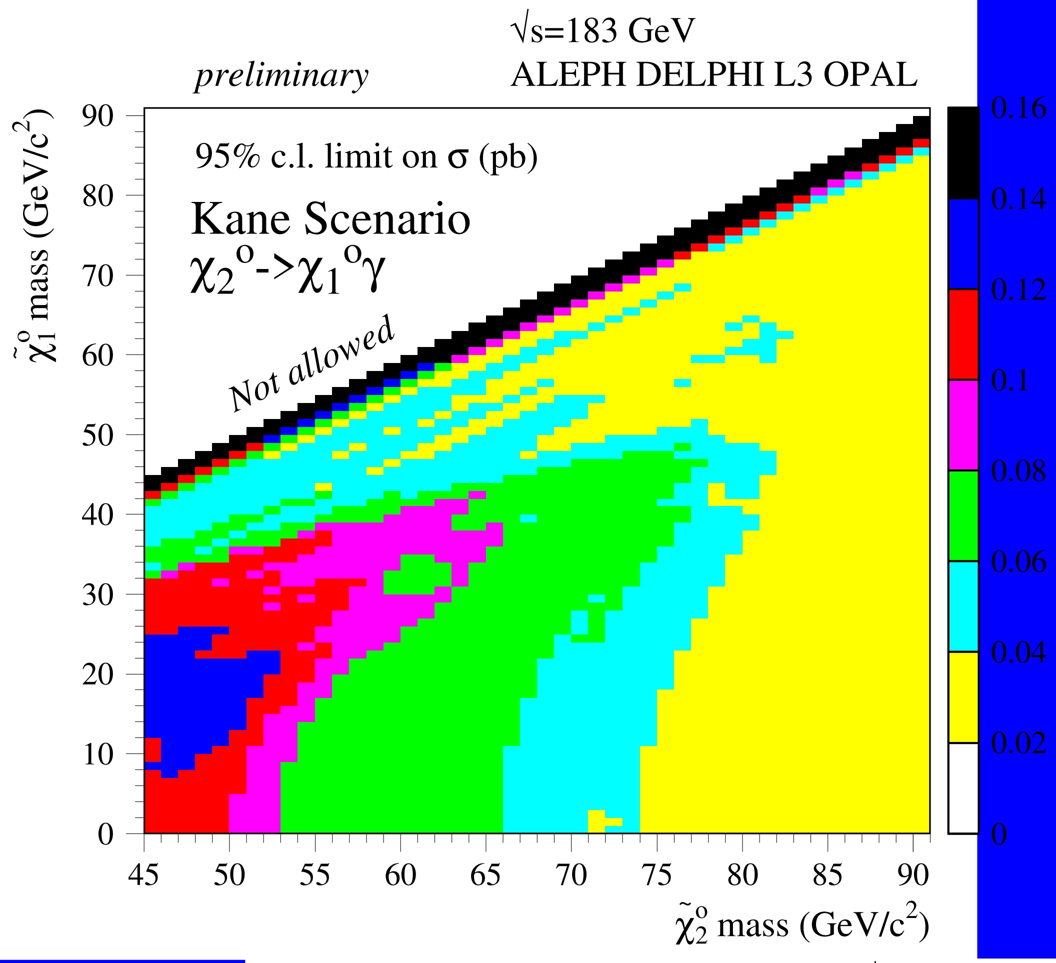

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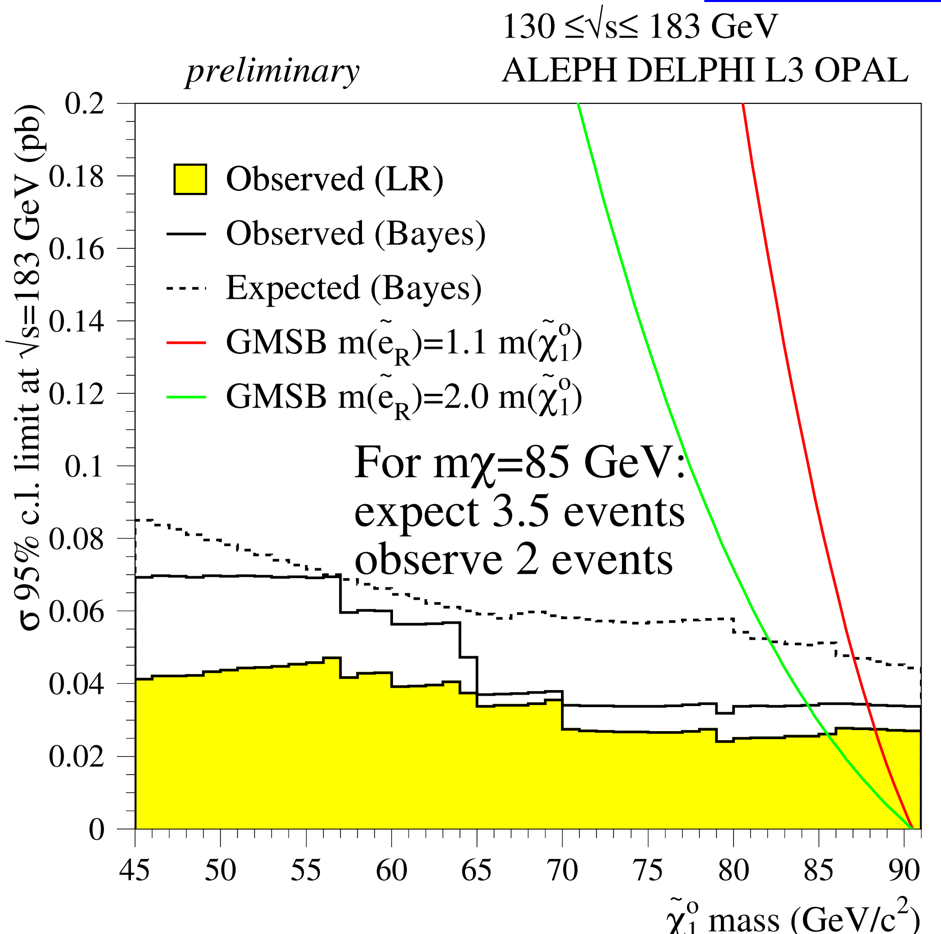


Single Photon Events

Signature of neutralinos in the MSSM:

$$\tilde{\chi}_2^0\tilde{\chi}_1^0 \rightarrow \gamma\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow \gamma + E_{miss}$$

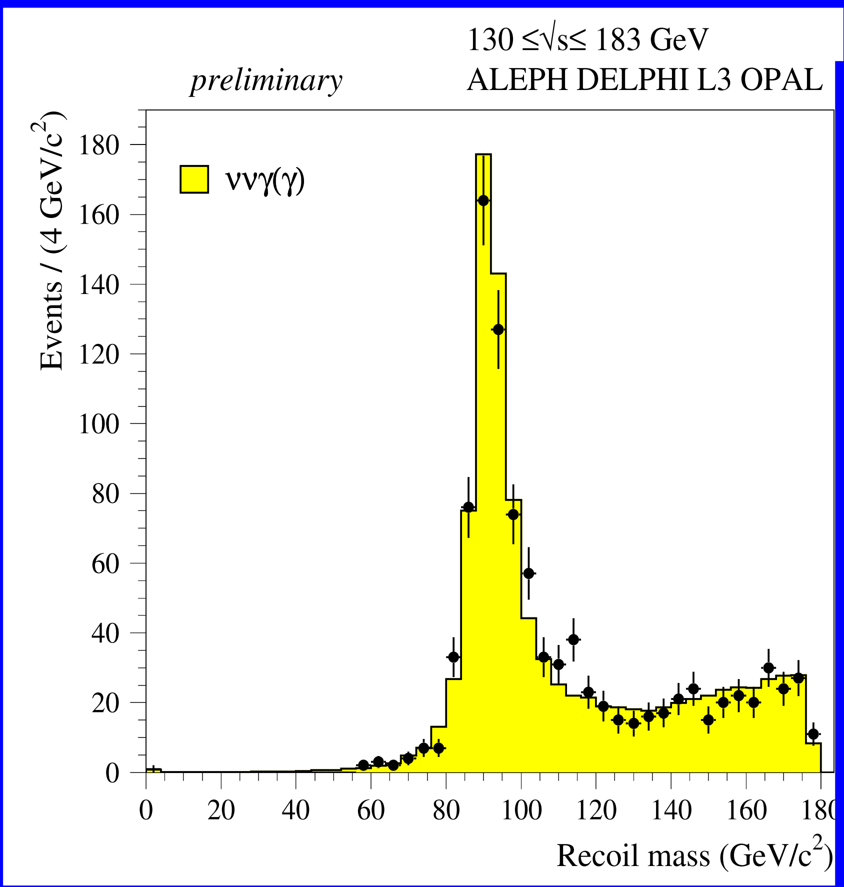
Signature of gravitinos in the GMSB:

$$\tilde{\chi}_1^0\tilde{G} \rightarrow \gamma\tilde{G}\tilde{G} \rightarrow \gamma + E_{miss}$$

$$\gamma\tilde{G}\tilde{G} \rightarrow \gamma + E_{miss}$$

Select a pure set of events with only one photon

Look for signals in the missing mass distribution:



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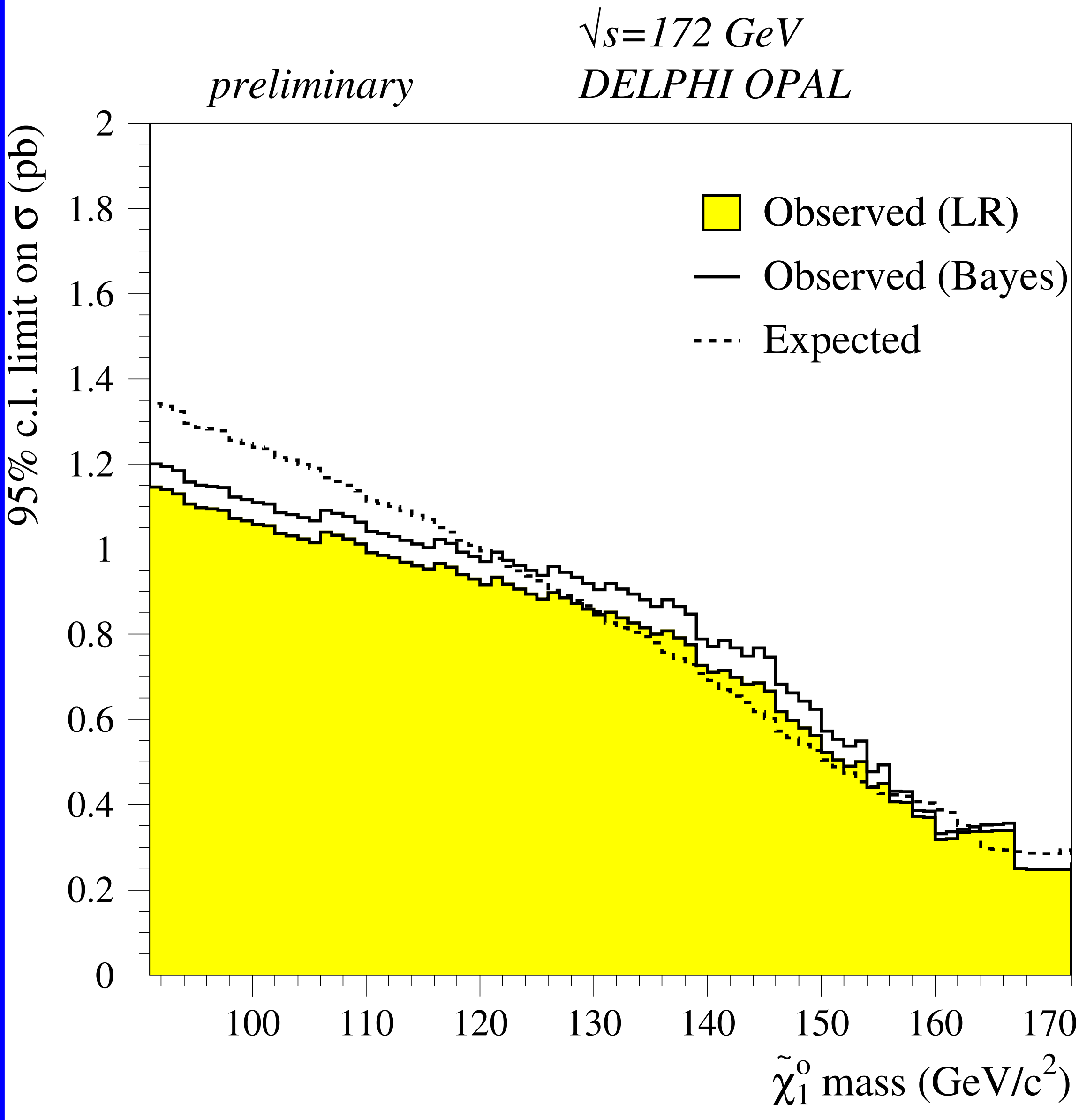

√s=172 GeV
preliminary
DELPHI OPAL
Observed (LR)
Observed (Bayes)
Expected
95% c.l. limit on σ (pb)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
100
110
120
130
140
150
160
170
$\tilde{\chi}^o_1$ mass (GeV/c^2)

Search for Stable Heavy Charged Particles

Example of possible signals:

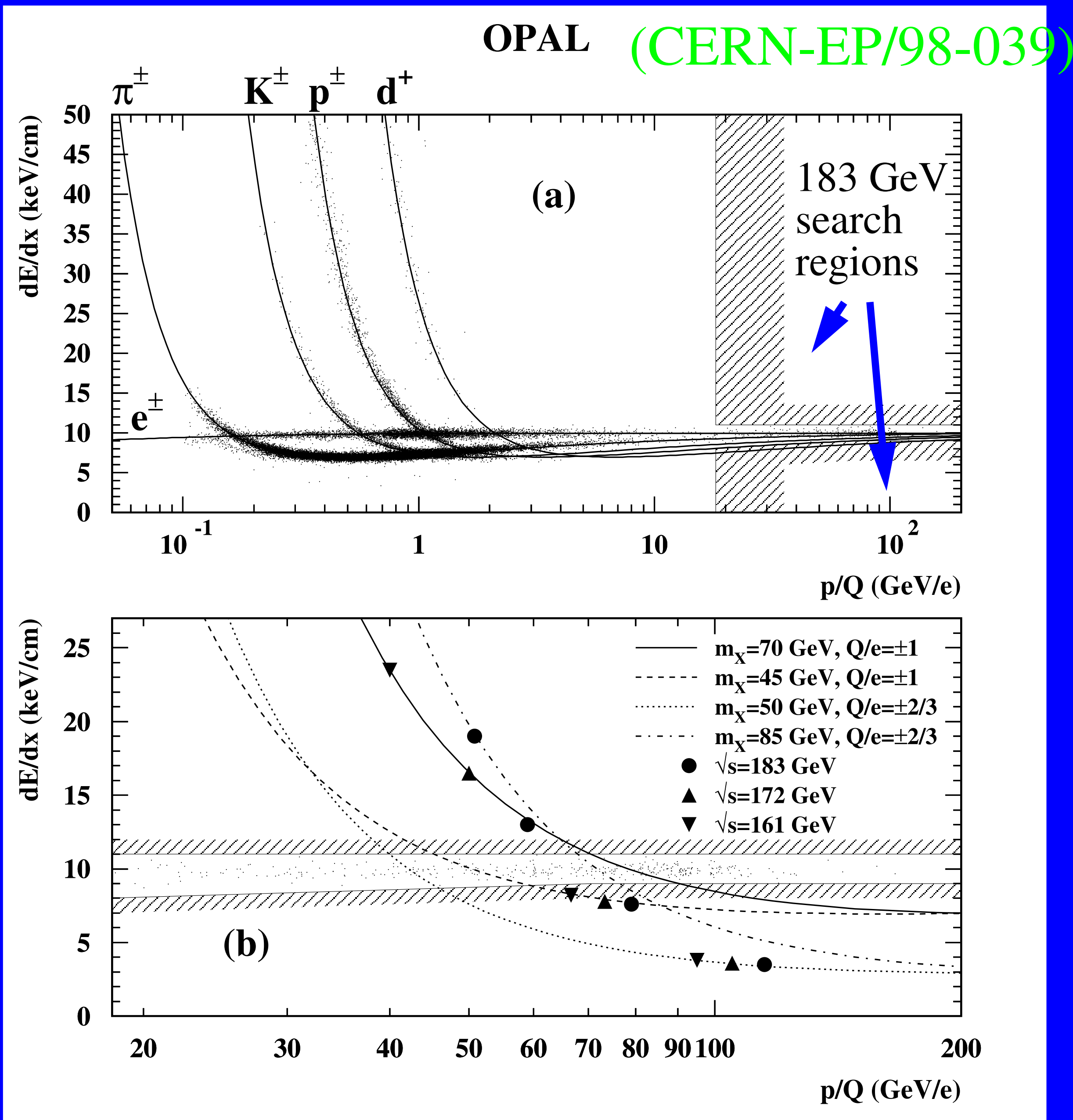
sleptons

stable charginos

Identification methods:

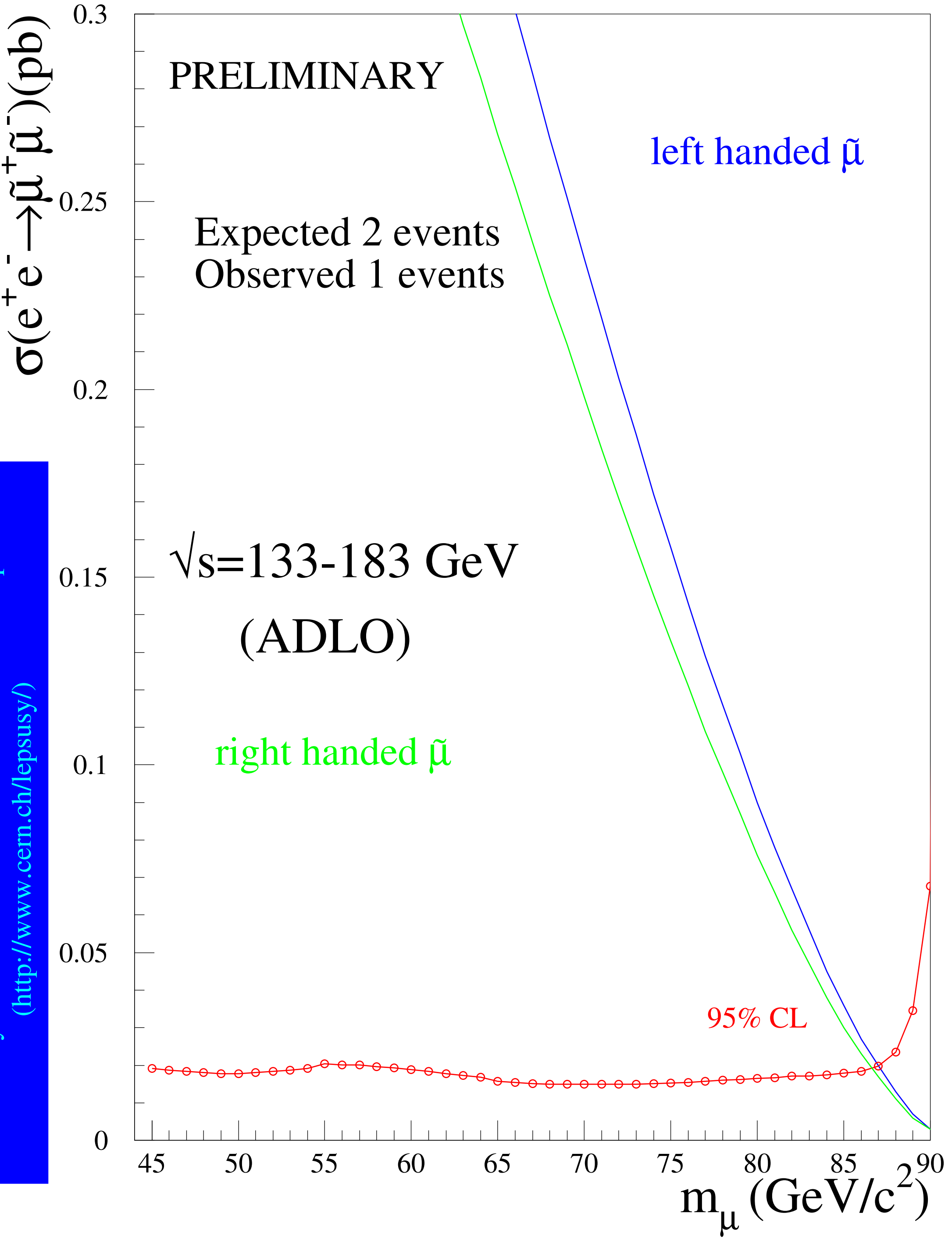
dE/dx

Cherenkov Chambers



	Right	Left
ADLO Combined	45-86.5 GeV	45-87.0 GeV

ADLO limits stable sleptons



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GMSB Searches

Gauge-Mediated SUSY Breaking
SUSY broken in hidden sector with
energy scale down to 10^4 GeV

hidden sector → messenger sector →
normal SM gauge interactions → visible sector

==>automatically no flavor changing neutral currents

$\overline{G}$ is the lightest sparticle (<1 GeV)
only its spin 1/2 component interacts

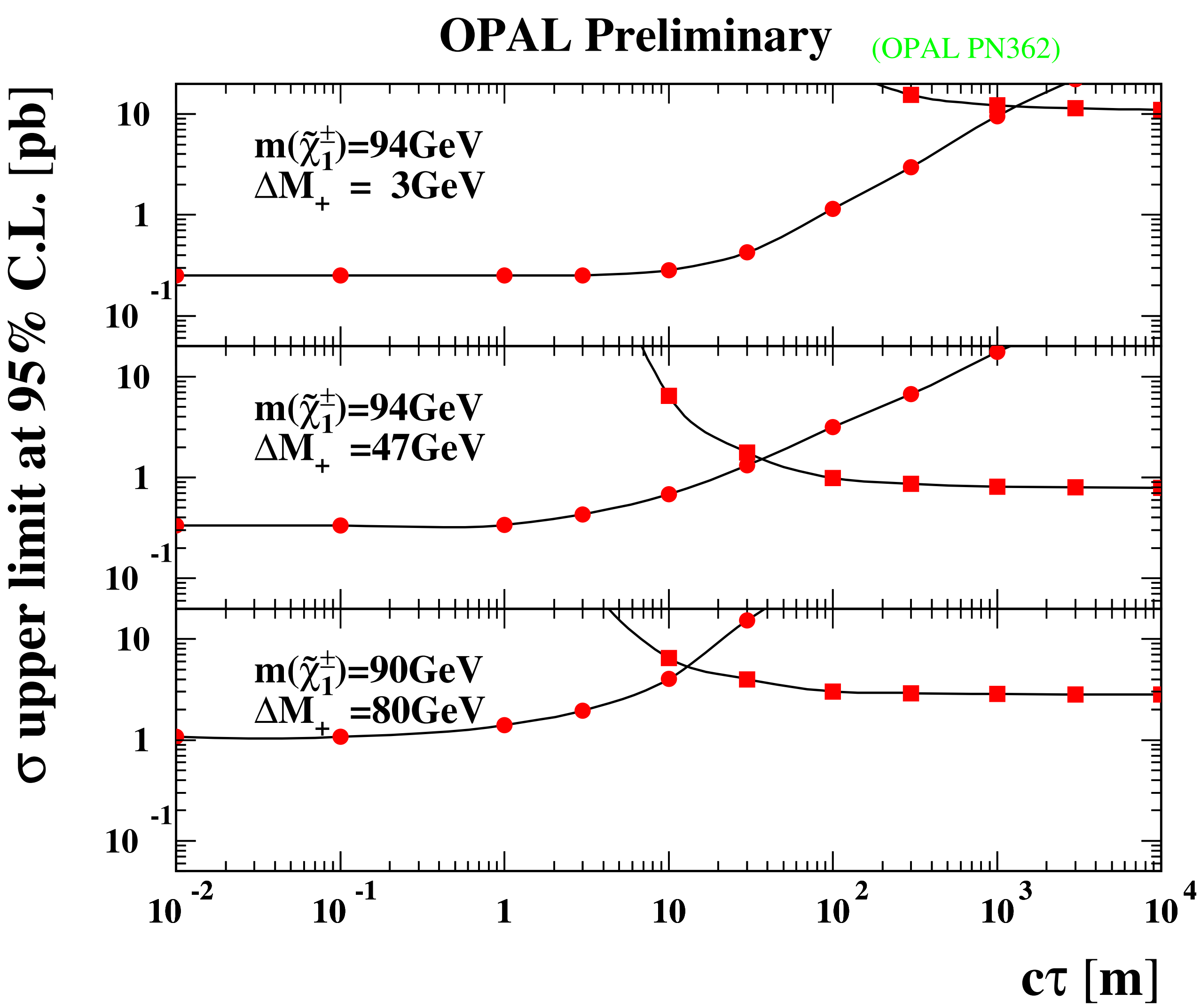
Signatures with GMSB:

$$\tilde{\chi}_1^+\tilde{\chi}_1^- \to W^{+*}\tilde{\chi}_1^o W^{-*}\tilde{\chi}_1^o \to W^{+*}\gamma\tilde{G}W^{-*}\gamma\tilde{G} \to f\bar{f}f\bar{f} + \gamma\gamma + E_{mis}$$

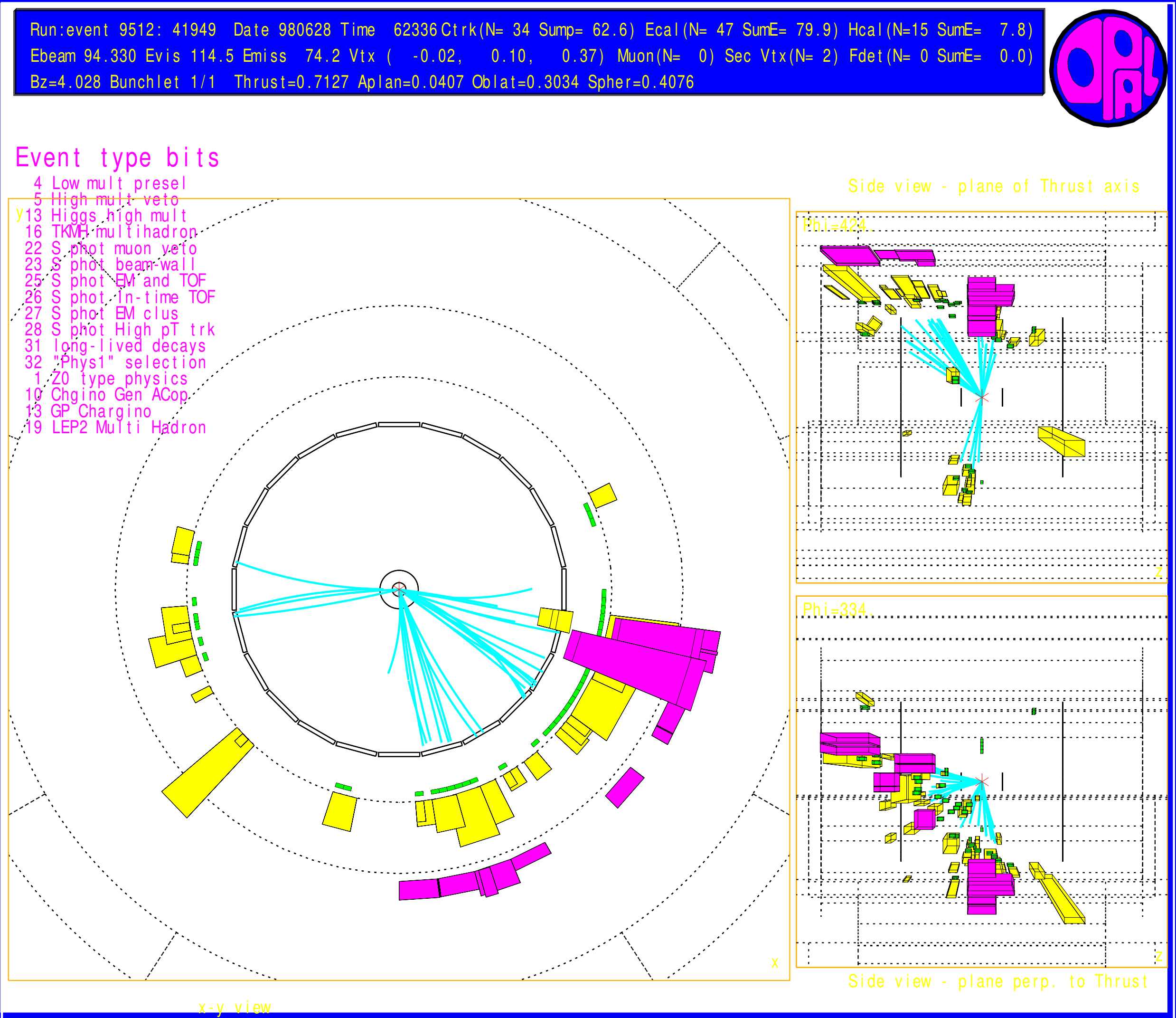
$$\tilde{\chi}_2^0\tilde{\chi}_1^0 \to Z^*\tilde{\chi}_1^0\tilde{\chi}_1^0 \to Z^*\gamma\tilde{G}\gamma\tilde{G} \to f\bar{f} + \gamma\gamma + E_{miss}$$

Like gravity mediated signals but
with photons added.

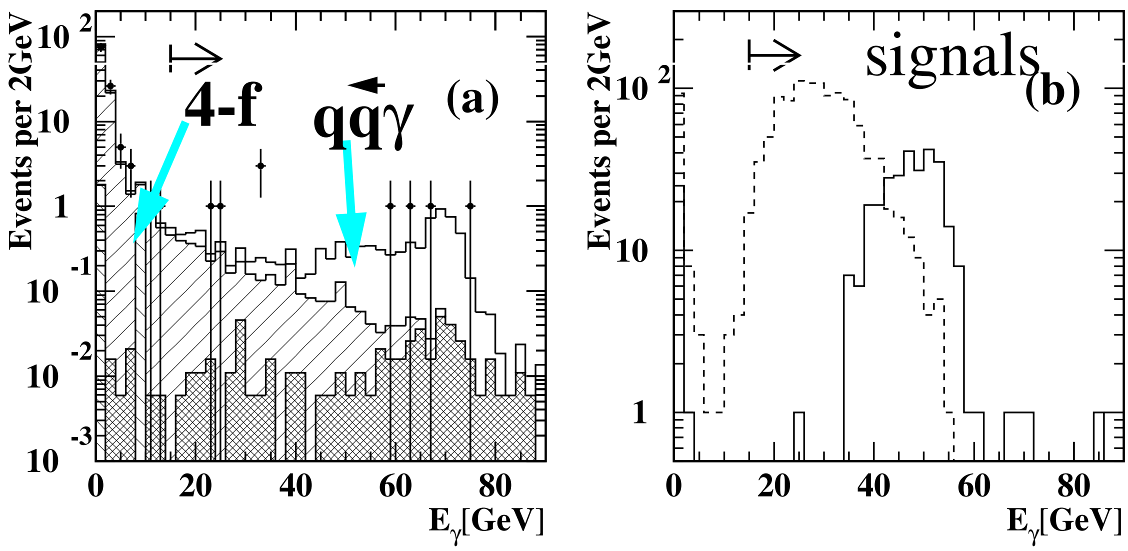
GMSB Search for Charginos



GMSB Chargino Candidate w/20 GeV Isolated Photon



OPAL Preliminary PN-332



by Homer Neal, Jr.

R-Parity Violating Searches

R Parity violation is possible

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

Implications of R Parity violation:

❋lepton and baryon number violation

❋sparticles can decay directly to SM particles

❋any sparticle could be the LSP

indirect decays:

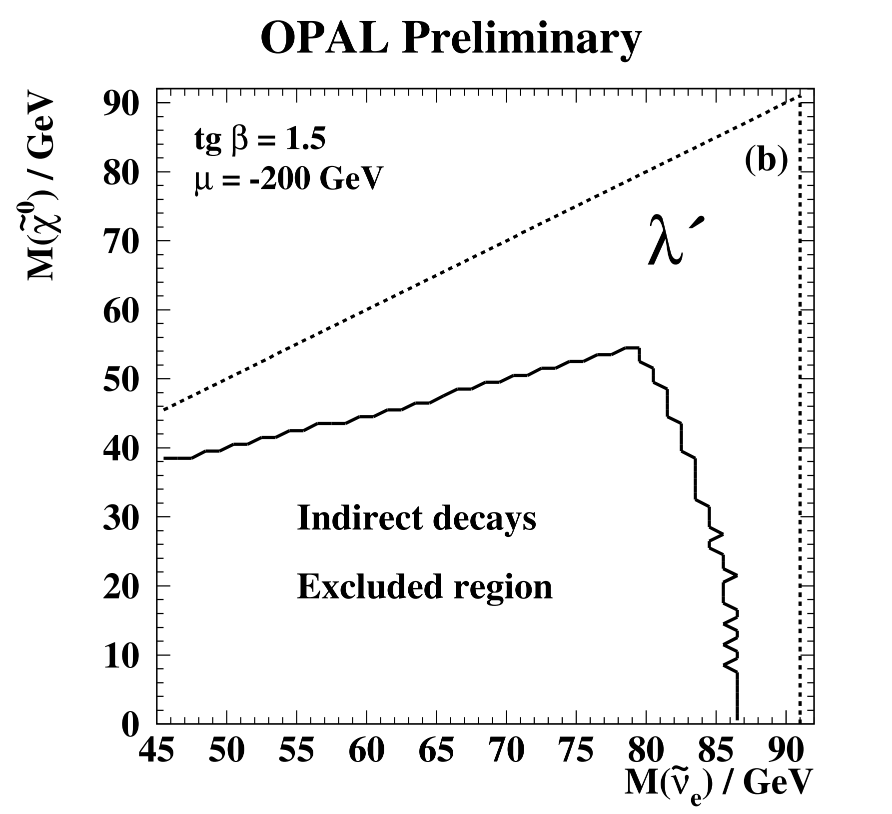
decays of sfermions via the $\tilde{\chi}_1^0$

direct decays:

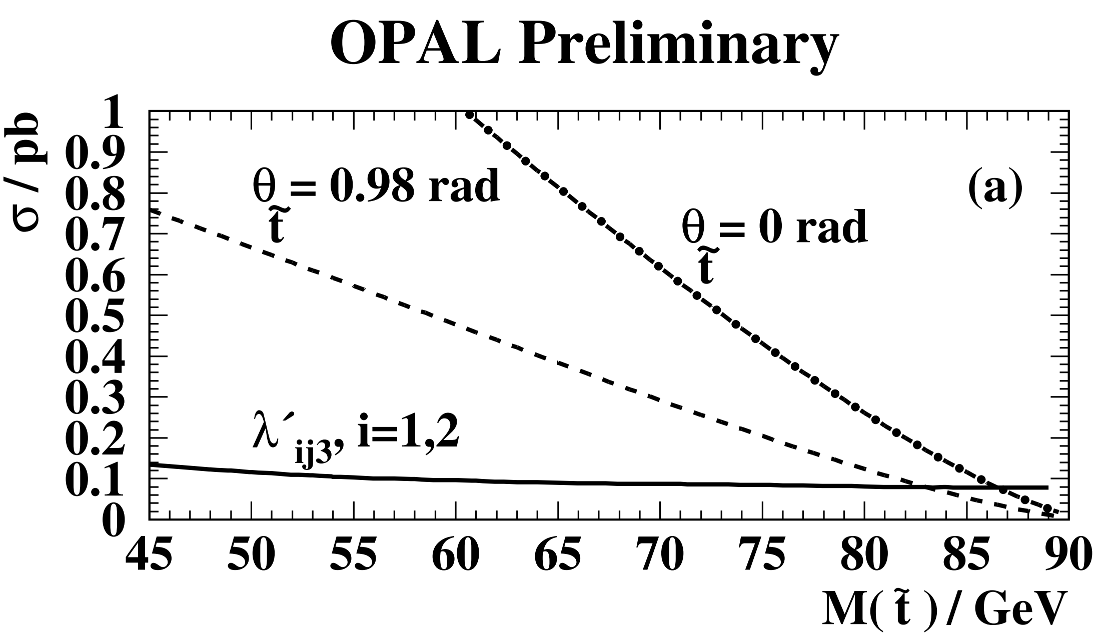
sparticle considered is assumed to be the LSP

Some of the Many Possible R-Parity Violating Decays	
$\tilde{l}^+\tilde{l}^- \rightarrow \nu l \nu l$	2 leptons+E_{miss}
$\tilde{\nu}\tilde{\nu} \rightarrow \nu\tilde{\chi}_1^0\nu\tilde{\chi}_1^0 \rightarrow \nu\nu l^+ l^- \nu l^+ l^-$	4 leptons+E_{miss}
$\tilde{\nu}\tilde{\nu} \rightarrow l^+ l^- l^+ l^-$	4 leptons
$\tilde{l}^+\tilde{l}^- \rightarrow l^+\tilde{\chi}_1^0 l^-\tilde{\chi}_1^0 \rightarrow l^+\nu l^+ l^- l^- \nu l^+ l^-$	6 leptons+E_{miss}
$\tilde{t}_1\bar{\tilde{t}}_1 \rightarrow l^+ q l^- q$	2 leptons + 2 jets
$\tilde{l}^+\tilde{l}^- \rightarrow l^+\tilde{\chi}_1^0 l^-\tilde{\chi}_1^0 \rightarrow l^+ l^+ lqqlqq$	leptons + jets

R-Parity Violating Sfermion Limits



(OPAL PN359)



Summary of LEP2 SUSY Searches

	LEP 2 Combined Mass Limit	Reach
$m_{\chi o}$ any m_o	25.9 (L3)	~50 GeV
$m_{\chi o}$ large m_o	32.8 (OPAL) m_o>500 GeV	~50 GeV
$m_{\chi +}$	93.7 GeV(L3) large m_ν, tanβ=1.41 μ=-200 GeV	E_{beam}
$\tilde{e}$	84 GeV* ΔM>15 GeV	E_{beam} -10 GeV
$\tilde{\mu}$	71 GeV* ΔM>15 GeV	E_{beam}-10 GeV
$\tilde{\tau}$	72 GeV ΔM>15 GeV	E_{beam}-10 GeV
$\tilde{t} \rightarrow c\tilde{\chi}_1^0$	86.5 GeV ΔM>15 GeV	E_{beam}-5 GeV(exc) exclusion E_{beam}-10 GeV(dis) discovery
$\tilde{t} \rightarrow bl\nu$	87.5 GeV ΔM>15 GeV	E_{beam}-5 GeV(exc) E_{beam}-10 GeV(dis)
$\tilde{b}$	85.5 GeV ΔM>15 GeV	E_{beam}-5 GeV(exc) E_{beam}-10 GeV(dis)

Where possible, the LEP 2 combined number is given unless otherwise indicated.

Conclusions:

All LEP combined results are preliminary and use data up to 183 GeV only

For large cross-section processes the new individual experiment results at 189 GeV exceed the combined results

GMSB and R-parity violation searches are the new games at LEP 2

Much effort still required to get combined R-parity violation results

Great progress expected this year due to the high integrated luminosity

Hope still exists for a discovery at LEP 2

A discovered sparticle could only be fully studied with a higher energy e^+e^- collider (=> a linear collider)