Chargino and Neutralino Searches at LEP

Beyond the Standard Searches

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DESY

Outline

- MSSM Particle Spectrum
- Chargino/Neutralino Production at LEP
- Chargino/Neutralino Decays
- Supersymmetry Breaking
- Experimental Results
  - SUGRA
  - GMSB
  - AMSB
- Summary

MSSM Particle Spectrum

SM particle	SUSY particle: weak eigenstates	SUSY particle: mass eigenstates
ν_L	$\tilde{\nu}_L$	$\tilde{\nu}_L$
$\ell^{\pm}_{L,R}$	$\tilde{\ell}^{\pm}_{L,R}$	$\tilde{\ell}^{\pm}_{1,2}$
$\mathrm{q}_{L,R}$	$\tilde{\mathrm{q}}_{L,R}$	$\tilde{\mathrm{q}}_{1,2}$
g	$\tilde{g}$	$\tilde{g}$
$\mathrm{h}, \mathrm{H}, \mathrm{A}$	$\tilde{\mathrm{h}}, \tilde{\mathrm{H}}$	$\tilde{\chi}^0_j$
γ	$\tilde{\gamma}$	
Z^0	$\tilde{\mathrm{Z}}^0$	
$\mathrm{H}^{\pm}$	$\tilde{\mathrm{H}}^{\pm}$	$\tilde{\chi}^{\pm}_i$
$\mathrm{W}^{\pm}$	$\tilde{\mathrm{W}}^{\pm}$	
G	$\tilde{G}$	$\tilde{G}$

Interlude: R-Parity

- as a result of $(B-L)$ invariance, MSSM comes along with a multiplicative R-parity invariance

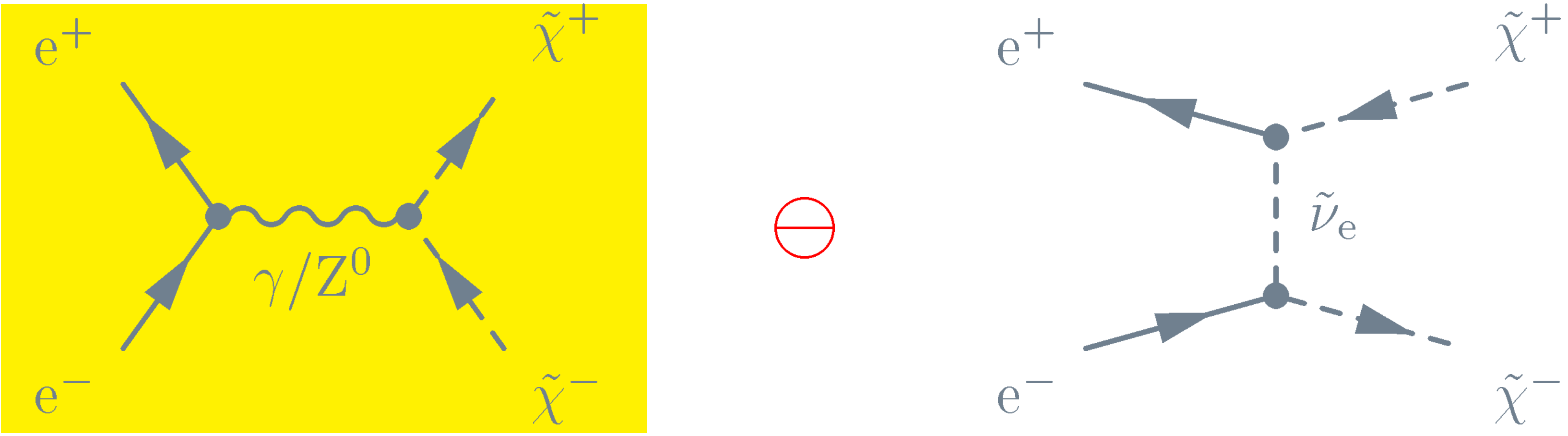
$$R = (-1)^{3(B-L)+2S} \Rightarrow \begin{cases} 1 \,\text{SM particles} \\ -1 \,\text{SUSY particles} \end{cases}$$

- consequences:
  - supersymmetric particles must be produced in pairs
  - the lightest supersymmetric particle (LSP) is
    - absolutely stable
    - terminates the decay chain of every SUSY particle
    - almost certainly electrically and color neutral

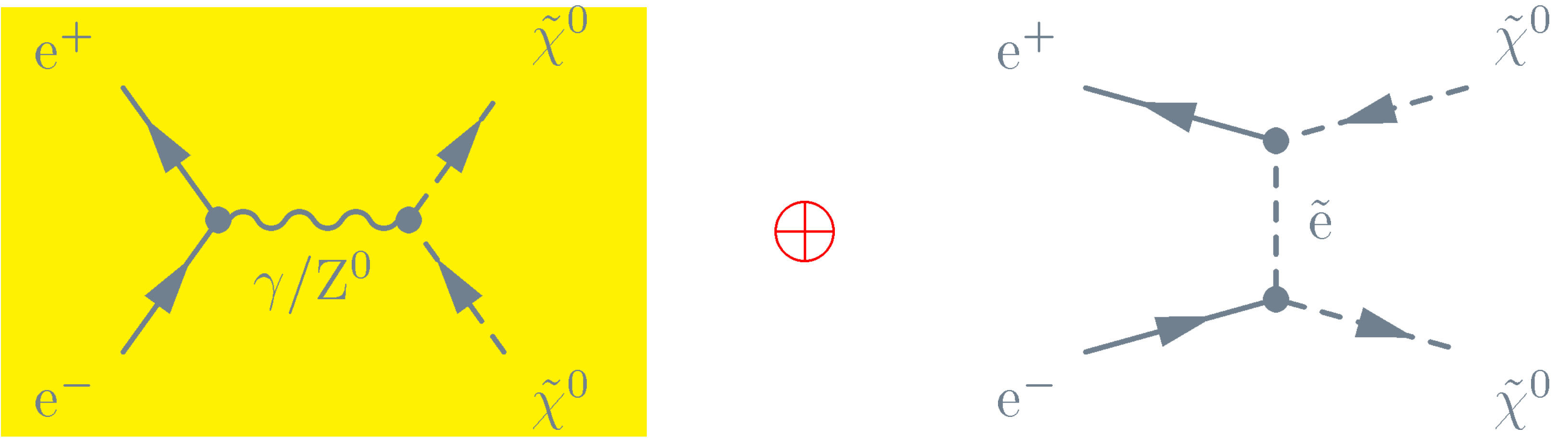
(unless otherwise mentioned R-parity conservation is assumed)

$\tilde{\chi}^{\pm}$ and $\tilde{\chi}^{0}$ Production at LEP

- Chargino Production

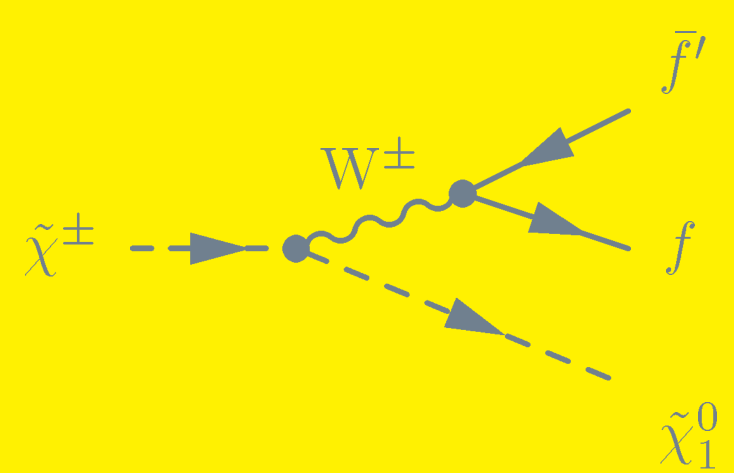


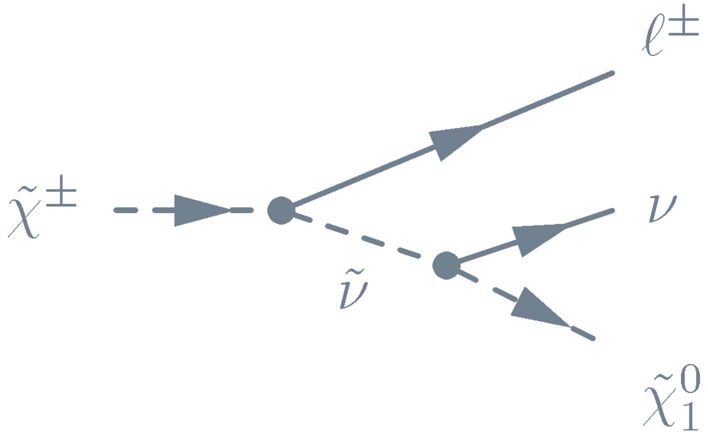
- Neutralino Production



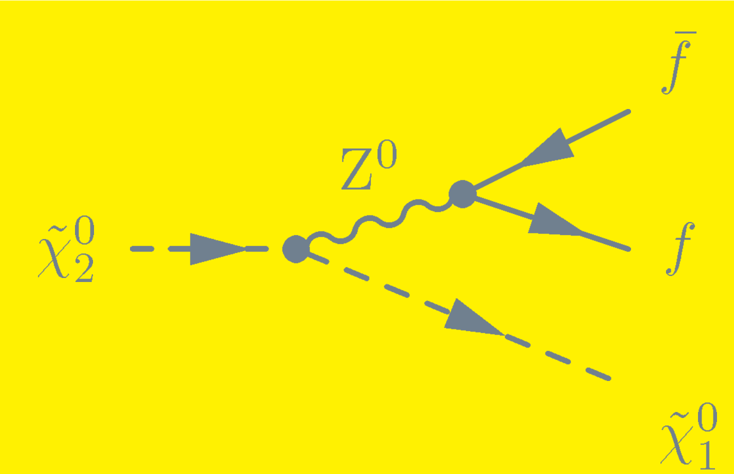
$\tilde{\chi}^\pm$ and $\tilde{\chi}^0$ Decays (Examples)

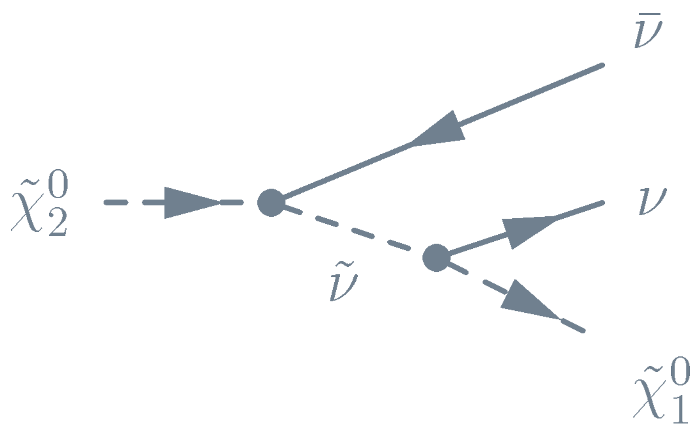
- Chargino Decays





- Neutralino Decays





SUSY Signatures

signature	example	scenario
jets + $\not{E}$	$\tilde{\chi}_1^+\tilde{\chi}_1^- \to q\bar{q}'q''\bar{q}'''\tilde{\chi}_1^0\tilde{\chi}_1^0$	SUGRA
jets + leptons + $\not{E}$	$\tilde{\chi}_1^+\tilde{\chi}_1^- \to q\bar{q}'\ell^+\ell^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	SUGRA
leptons + $\not{E}$	$\tilde{\chi}_1^0\tilde{\chi}_2^0 \to \ell^+\ell^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	SUGRA
γ+ $\not{E}$	$\tilde{\chi}_1^0\tilde{\chi}_2^0 \to \gamma\tilde{\chi}_1^0\tilde{\chi}_1^0$	SUGRA
low momentum pions + $\not{E}$	$\tilde{\chi}_1^+\tilde{\chi}_1^- \to (n\pi)\tilde{\chi}_1^0\tilde{\chi}_1^0\,(n=1,2,3)$	AMSB, SUGRA
$\gamma\gamma$+ $\not{E}$	$\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \gamma\gamma\tilde{G}\tilde{G}$	GMSB
$\tau^+\tau^-$+ $\not{E}$	$\tilde{\chi}_1^+\tilde{\chi}_1^- \to \tau^+\tau^-\nu_\tau\bar{\nu}_\tau\tilde{G}\tilde{G}$	GMSB
stable, heavy, charged particles kinked tracks secondary vertices	long-lived charginos	all
...	...	...

Supersymmetry Breaking

- assume SUSY is realized in nature
- SM particles and SUSY particles are not mass-degenerate
- SUSY is not an exact symmetry of nature
- SUSY must be broken

Hidden Sector
SUSY Breaking

?

Observable Sector
MSSM

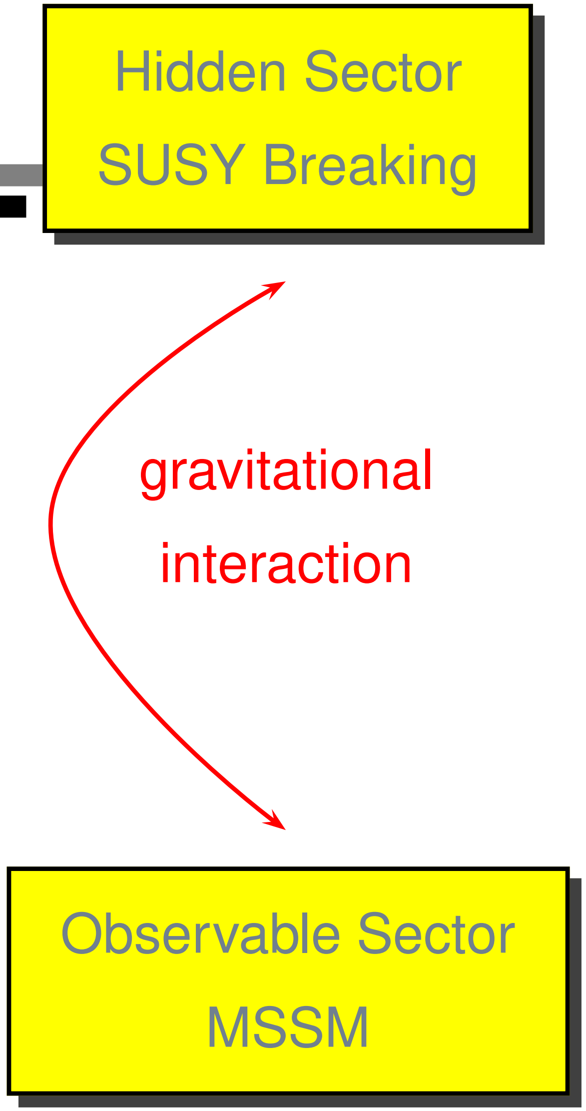
general parameterization leads to more than 100 new parameters

(m)SUGRA

- gauge couplings unify at ultra-high energy scale M_X
- SUSY breaking defined at M_X arises due to gravitational interaction
- SUGRA-inspired Constrained MSSM (CMSSM) defined by 6 parameters

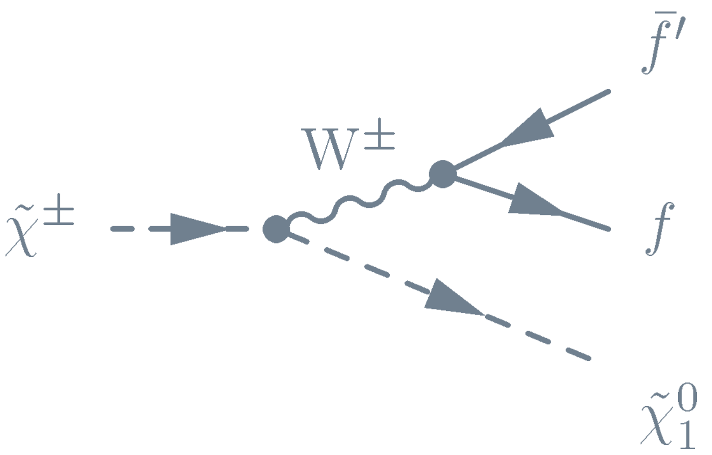
m_0	common scalar mass at M_P
M_2	$SU(2)$ gaugino mass parameter at M_{EW}
$\tan\beta$	v_2/v_1 VEV ratio of two Higgs doublets
μ	mixing parameter of Higgs doublet fields
A_0	trilinear sfermion/Higgs coupling
m_A	pseudoscalar Higgs mass at M_{EW}

- LSP: $\tilde{\chi}_1^0$ ($\tilde{\nu}$)



SUGRA: Decay Topologies

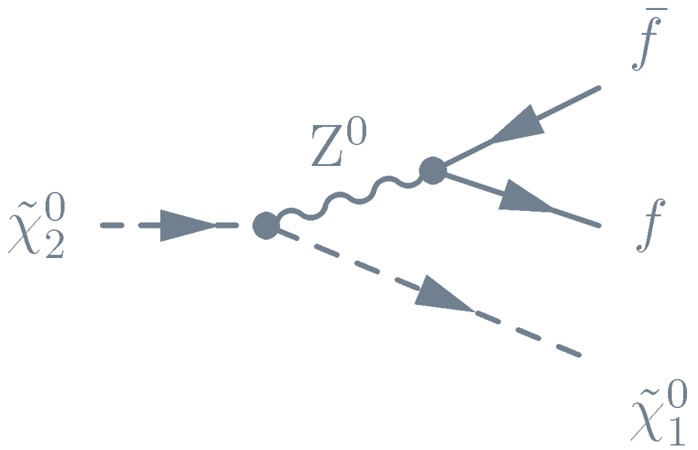
chargino channel: $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^- \to f\bar{f}'f''\bar{f}'''\tilde{\chi}_1^0\tilde{\chi}_1^0$



final states	BR [%]	topology
$q\bar{q}'\,q\bar{q}'$	46	jets+ $\not{E}$
$q\bar{q}'\,\ell^-\bar{\nu}$	44	jets + lepton + $\not{E}$
$\ell^+\nu\,\ell^-\bar{\nu}$	11	leptons + $\not{E}$

neutralino channel: $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0 \to f\,f'\tilde{\chi}_1^0\tilde{\chi}_1^0$

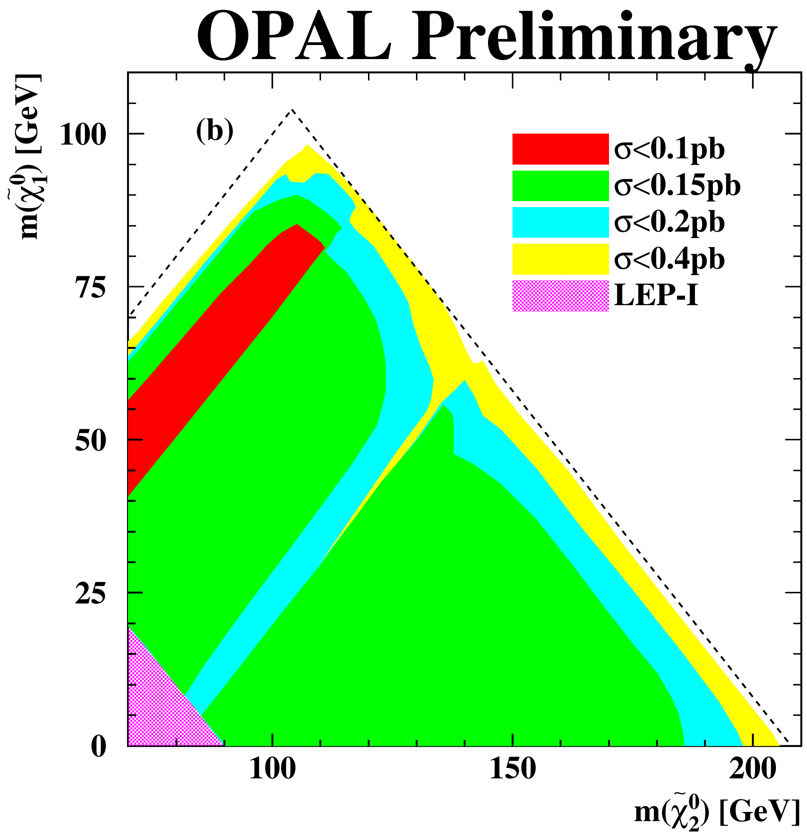
final states	BR [%]	topology
$q\bar{q}'\,q\bar{q}'$	70	jets+ $\not{E}$
$q\bar{q}'\,\ell^-\bar{\nu}$	10	leptons + $\not{E}$
	20	invisible



Cross-section Limits $\tilde{\chi}^0$

$\tilde{\chi}^0_1\tilde{\chi}^0_2 \to Z^{0(\star)}\tilde{\chi}^0_1\tilde{\chi}^0_1$

- OPAL 95% C.L. upper σ limit at $\sqrt{s} = 208$ GeV
- assuming 100% Z^0 BRs
- region $M_{\tilde{\chi}^0_2} + M_{\tilde{\chi}^0_1} < M_{Z^0}$ is not considered
- exclusion to kinematic limit for $\Delta M^0 = M_{\tilde{\chi}^0_2} - M_{\tilde{\chi}^0_1} > 10$ GeV
- $M_{\tilde{\chi}^0_1} > 44.9\,\mathrm{GeV}$
- $M_{\tilde{\chi}^0_2} > 79.6\,\mathrm{GeV}$ (any m_0, $\tan\beta = 1.5$)

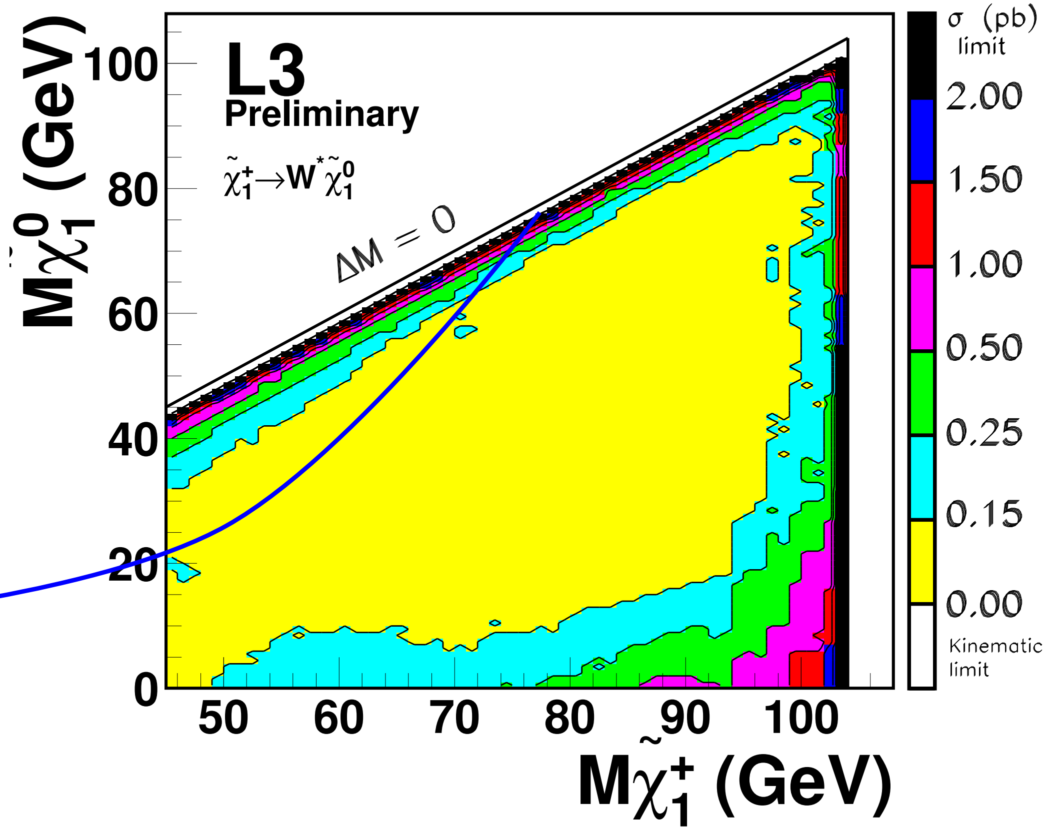


Cross-section Limits $\tilde{\chi}_1^{\pm}$

$$\tilde{\chi}_1^+\tilde{\chi}_1^- \to f\bar{f}'f''\bar{f}'''\tilde{\chi}_1^0\tilde{\chi}_1^0$$

- L3 95% C.L. upper σ limit at $\sqrt{s} = 208$ GeV
- assuming 100% $\mathrm{W}^{\pm}$ BRs
- exclusion to kinematic limit for $\Delta M^{\pm} = M_{\tilde{\chi}_1^{\pm}} - M_{\tilde{\chi}_1^0} > 3$ GeV

small $\Delta M^{\pm}$ region



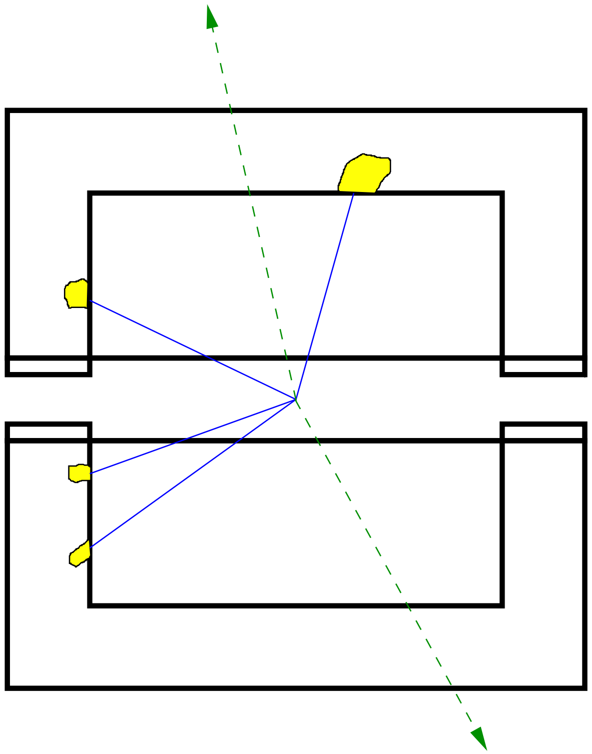
Interlude: Small $\Delta M^{\pm}$ Searches

- small $\Delta M^{\pm}$ implications
  - trigger:
    - Large $\Delta M^{\pm}$: no problem
    - Small $\Delta M^{\pm}$: only little detector activity
  - background:
    - Large $\Delta M^{\pm}$: 4-fermion ($\sigma \sim 20\mathrm{pb}$)
    - Small $\Delta M^{\pm}$: 2-photon ($\sigma \sim \mathcal{O}(\mathrm{nb})$)
- solution:
  - use hard ISR photons in order to
    - increase the trigger efficiency
    - reduce the two-photon background
- tradeoff:
  - small signal efficiency ($\epsilon \sim \mathcal{O}(1\%)$)

  (for more details see talk by S. Paiano)

Small $\Delta M^{\pm}$ Topology

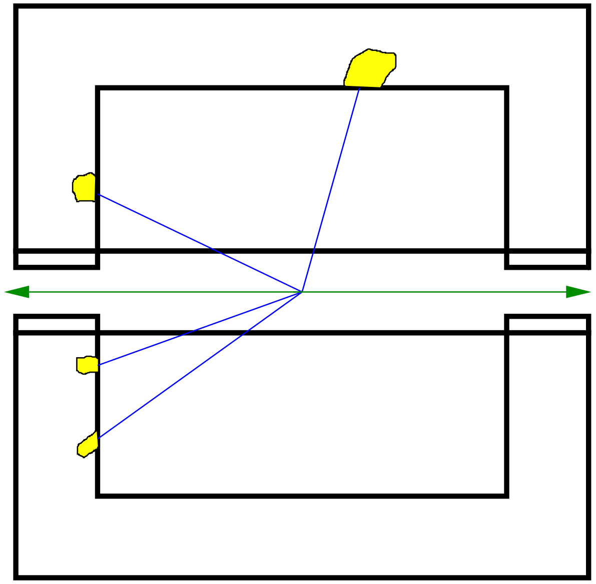
Signal



- $\sigma_{\mathrm{LEP}} \sim \mathcal{O}(\mathrm{pb})$

Two-Photon-Event

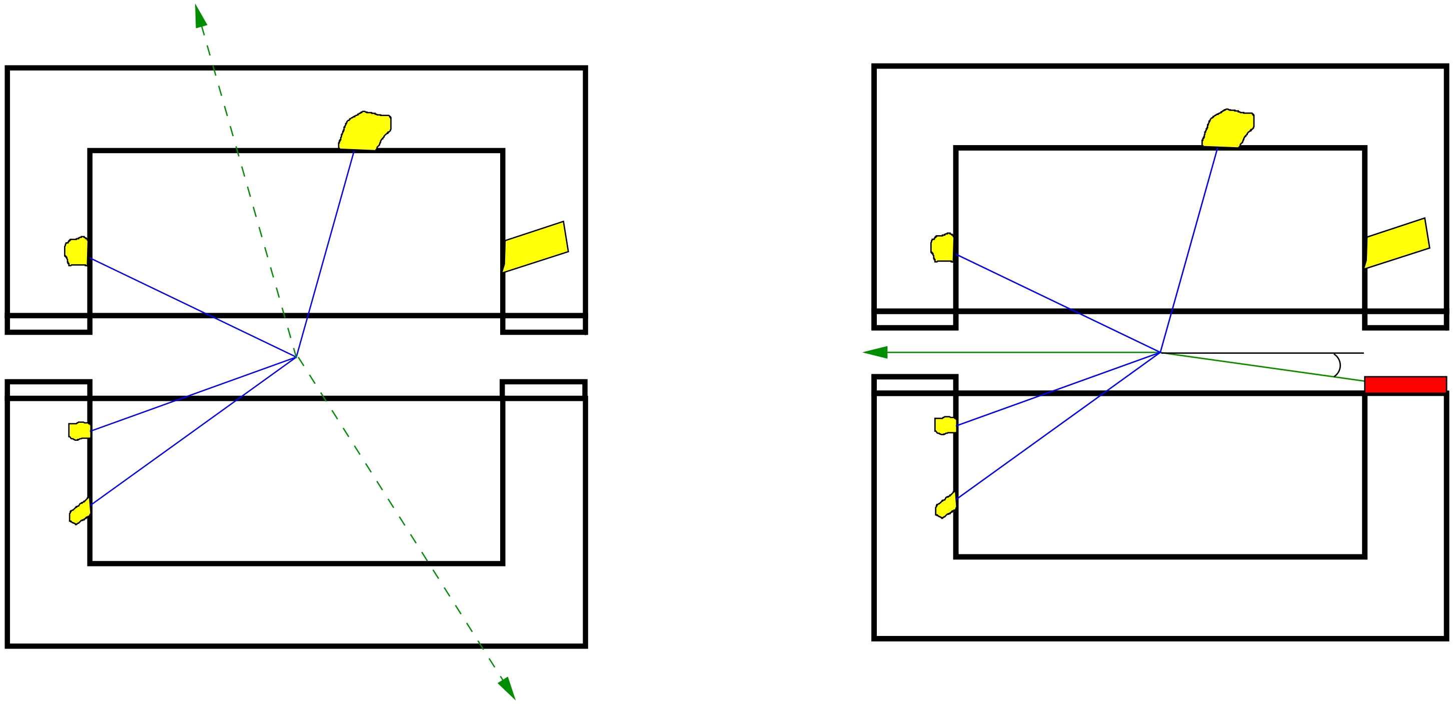
$\mathrm{e}^+\mathrm{e}^- \rightarrow \; \mathrm{e}^+\mathrm{e}^-\gamma^{(\star)}\gamma^{(\star)} \rightarrow \; \mathrm{e}^+\mathrm{e}^- X$



- $\sigma_{\mathrm{LEP}} \sim \mathcal{O}(\mathrm{nb})$

Small $\Delta M^{\pm}$ and ISR

- require ISR-Photon with $E_T > \sqrt{s}\frac{\sin\theta_D}{1+\sin\theta_D}$
  (θ_D: minimal accessible polar angle)

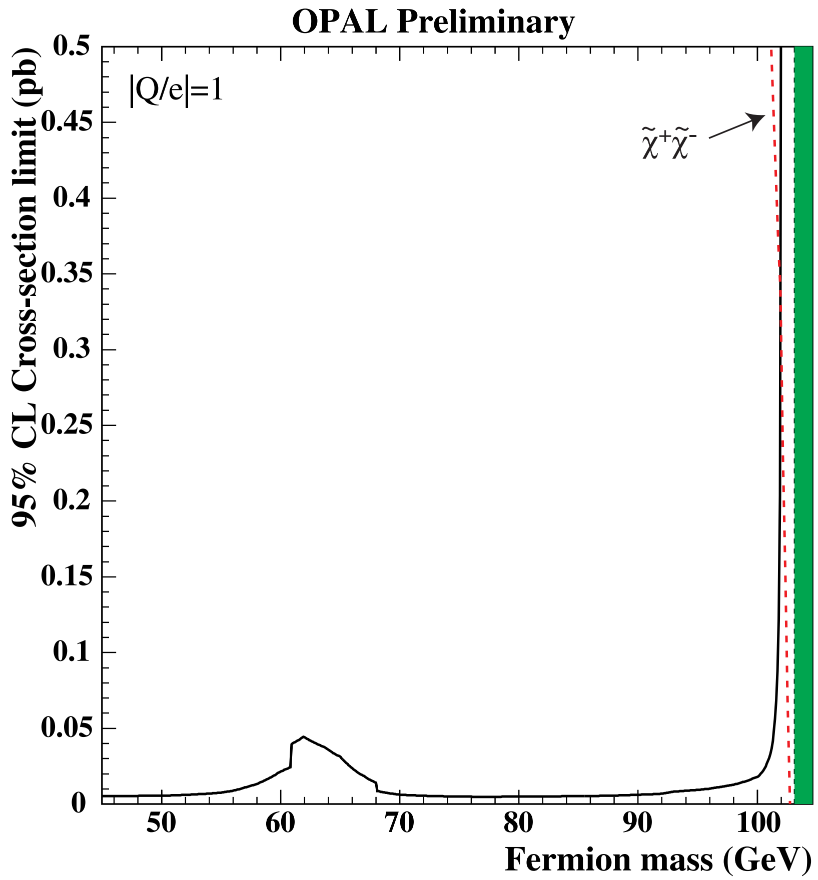


- signal and background events become distinguishable:
  - reject event if beam electron is detected

The Very Small $\Delta M^{\pm}$ Region

- for decreasing $\Delta M^{\pm}$ lifetime effects become important
- depending on expected lifetime search for:
  - secondary vertices
  - impact parameters
  - stable, heavy, charged particles (dE/dx)

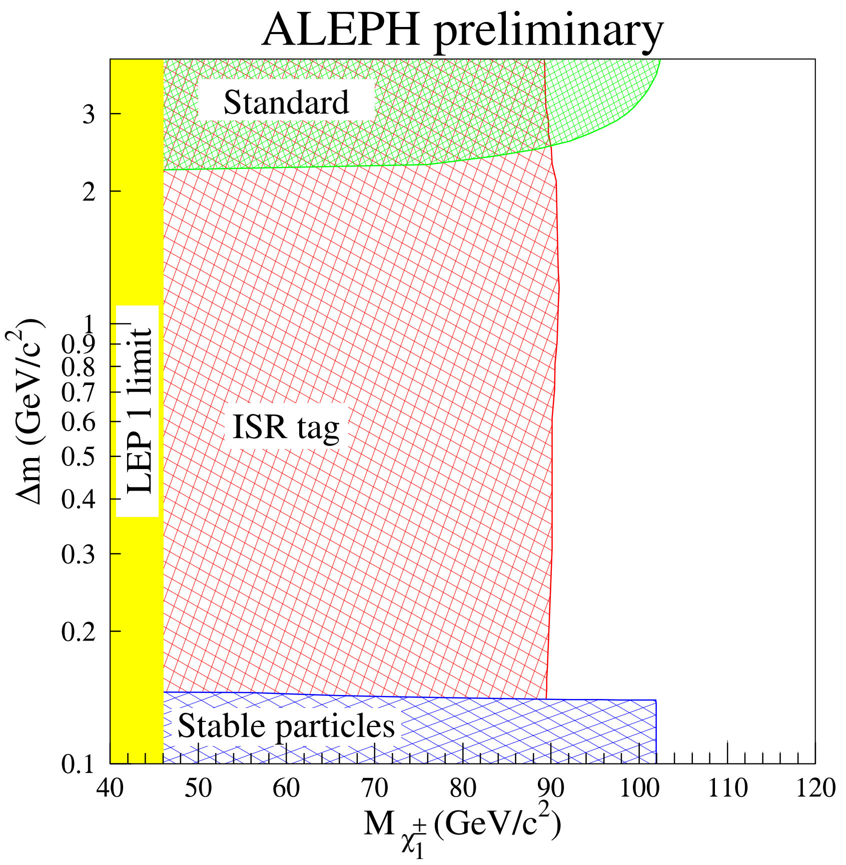
  $\tilde{\chi}_1^{\pm}$ quasi-stable
- OPAL 95% C.L. upper σ limit at $\sqrt{s} = 206.3$ GeV
- $M_{\tilde{\chi}_1^{\pm}} > 102\,\mathrm{GeV}$ (for $\tau_{\tilde{\chi}_1^{\pm}} > 1\mu$s)



Mass Limits $\tilde{\chi}_1^\pm$

$\tilde{\chi}_1^+\tilde{\chi}_1^- \to X\tilde{\chi}_1^0\tilde{\chi}_1^0$

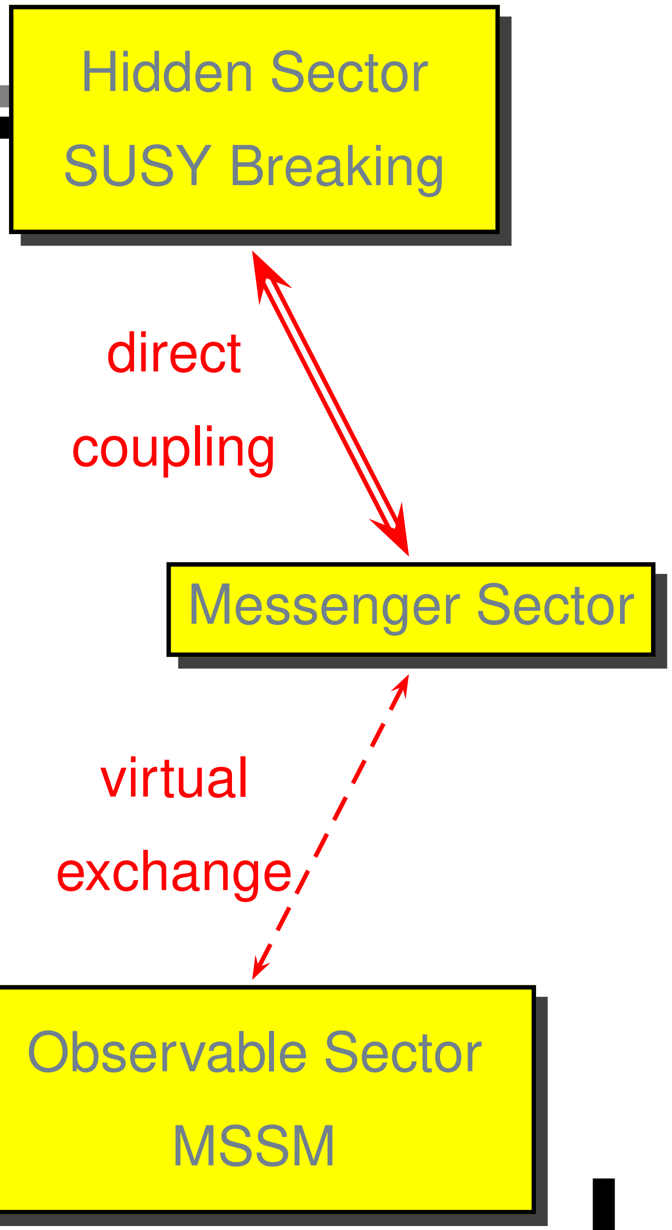
- Aleph 95% C.L. excluded $M_{\tilde{\chi}_1^\pm}$ region $(\sqrt{s} = 189\text{-}209\,\mathrm{GeV})$
- $M_{\tilde{\chi}_1^\pm} > 89\,\mathrm{GeV}$ $(m_0 > 500\mathrm{GeV})$
- many analyses not shown
- mass limits translate into limits on
  - μ
  - M_2
  - $\tan\beta$
  - $\ldots$



(for more details see talk by B. Tellili)

GMSB

- poor man's GMSB construction kit
  - hidden sector with broken SUSY
  - messenger sector: particles with $SU(3) \times SU(2) \times U(1)$ quantum numbers
  - observable sector with MSSM
- free parameters
  - Λ universal mass scale of SUSY particles
  - N number of messenger pairs
  - M_m messenger mass scale
  - $\tan\beta$ VEV ratio of two Higgs doublets
  - $\mathrm{sign}(\mu)$ sign of Higgs mixing parameter fields
  - $\sqrt{F}$ SUSY breaking scale
- implications
  - LSP: gravitino $\tilde{G}$, $(M_{\tilde{G}} \sim \mathrm{eV} - \mathrm{keV})$
  - NLSP determines topology



GMSB: NLSP and Signal Topologies

scenario	sparticle production	final state $(+\tilde{G}\tilde{G})$
neutralino NLSP	$\tilde{\chi}_1^0\tilde{\chi}_1^0$	$\gamma\gamma$
	$\tilde{\ell}_R\tilde{\ell}_R$	$\gamma\gamma\ell\ell$
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$	$\gamma\gamma W^{+(\star)}W^{-(\star)}$
	$\tilde{\chi}_1^0\tilde{\chi}_2^0$	$\gamma\gamma Z^{0(\star)}$
slepton co-NLSP	$\tilde{\chi}_1^0\tilde{\chi}_1^0$	$\ell\ell'\ell\ell'$
$(M_{\tilde{\ell}_R} < \min[M_{\tilde{\chi}_1^0}, M_{\tilde{\tau}_1} + M_\tau])$	$\tilde{\ell}_R\tilde{\ell}_R$	$\ell\ell$
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$	$\tau\nu_\tau\tau\bar{\nu}_\tau$
stau NLSP	$\tilde{\ell}_R\tilde{\ell}_R$	$\tau\tau\ell\ell\tau\tau$
	$\tilde{\tau}_1\tilde{\tau}_1$	$\tau\tau$
neutralino-stau co-NLSP	$\tilde{\chi}_1^0\tilde{\chi}_1^0$	$\gamma\gamma$
$(\lvert M_{\tilde{\tau}_1} - M_{\tilde{\chi}_1^0}\rvert < M_\tau)$	$\tilde{\tau}_1\tilde{\tau}_1$	$\tau\tau$

GMSB: The NLSP Lifetime

- NLSP lifetime depends on gravitino mass $(M_{\tilde{G}} \propto (\sqrt{F})^2)$:

$$c\tau_{NLSP} \simeq \frac{1}{100} \left(\frac{\sqrt{F}}{100\mathrm{TeV}} \right)^4 \left(\frac{M_{NLSP}}{100\mathrm{GeV}} \right)^{-5} \mathrm{cm}$$

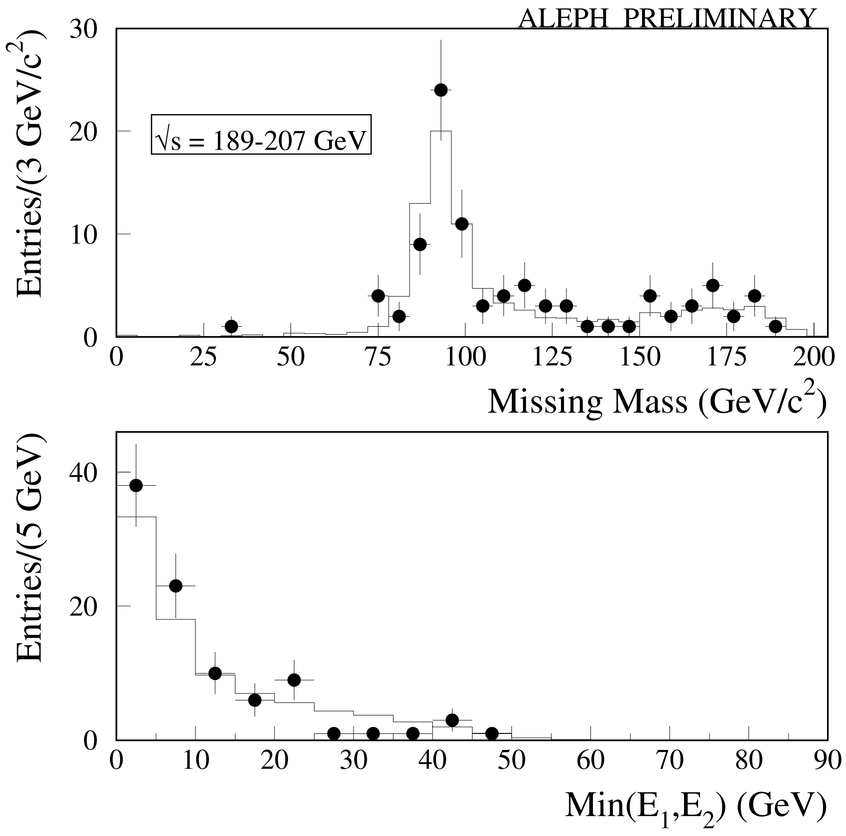
- $c\tau_{NLSP} = \mathcal{O}(1\,\mu\mathrm{m})$-$\mathcal{O}(10\mathrm{m}) \Leftrightarrow 30\,\mathrm{TeV} < \sqrt{F} < 1800\,\mathrm{TeV}$
- each final state may have one out of three possible topologies:
  - prompt decays
  - decays within the detector but separated from primary vertex
  - decays outside of the detector
- only a few examples of analyses can be shown . . .

A Selection of GMSB Scenarios

- Minimal Gauge Mediated SUSY Breaking Scenario
  - constraints on slepton and gaugino masses
    - $\tilde{\chi}_1^0$ is NLSP
      channel: $\mathrm{e}^+\mathrm{e}^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 \to \gamma\gamma\tilde{G}\tilde{G}$
      signature: $\gamma\gamma$+$\not{E}$
    - $\tilde{\tau}_1$ is NLSP
      channel: $\mathrm{e}^+\mathrm{e}^- \to \tilde{\chi}_1^+\tilde{\chi}_1^- \to \tau^+\tau^-\nu_\tau\bar{\nu}_\tau\tilde{G}\tilde{G}$
      signature: $\tau^+\tau^-$+$\not{E}$
- Extended Gauge Mediated SUSY Breaking Scenario
  - no severe constraints on slepton and gaugino masses
  - search for classic SUSY signatures (+ photons)
    - $\tilde{\chi}_1^0$ is NLSP
      channel:$\mathrm{e}^+\mathrm{e}^- \to \tilde{\chi}_2^0\tilde{\chi}_1^0 \to \mathrm{Z}^{0(\star)}\gamma\gamma\tilde{G}\tilde{G}$
      signature: $f\bar{f}\gamma\gamma$+$\not{E}$

GMSB: $\gamma\gamma + \not{E}$

- $e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 \to \gamma\gamma\tilde{G}\tilde{G}$
- main background $e^+e^- \to \nu\bar{\nu}\gamma\gamma(\gamma)$

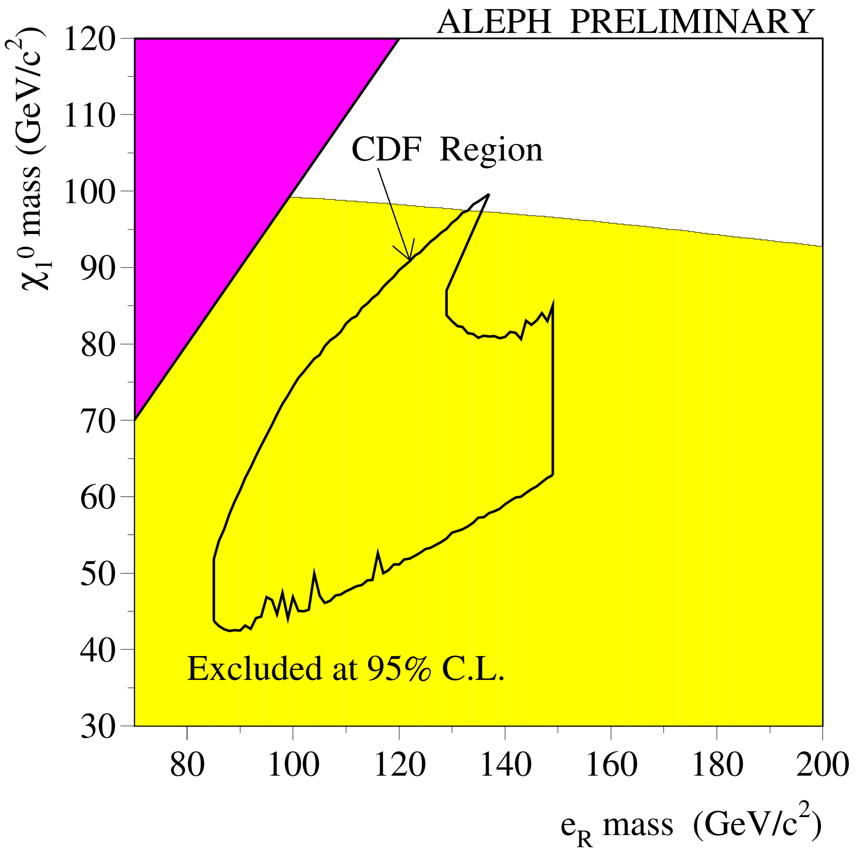


- Aleph analysis:
  - after two-photon selection 93 candidates remain while 88 events expected
  - cuts are optimized using the 'Minimal Gauge Mediated SUSY Breaking Model'

    (e.g. $\min(E_1^\gamma, E_2^\gamma) > 37$ GeV)
  - $\tilde{\chi}_1^0$ mass limits $\Rightarrow$

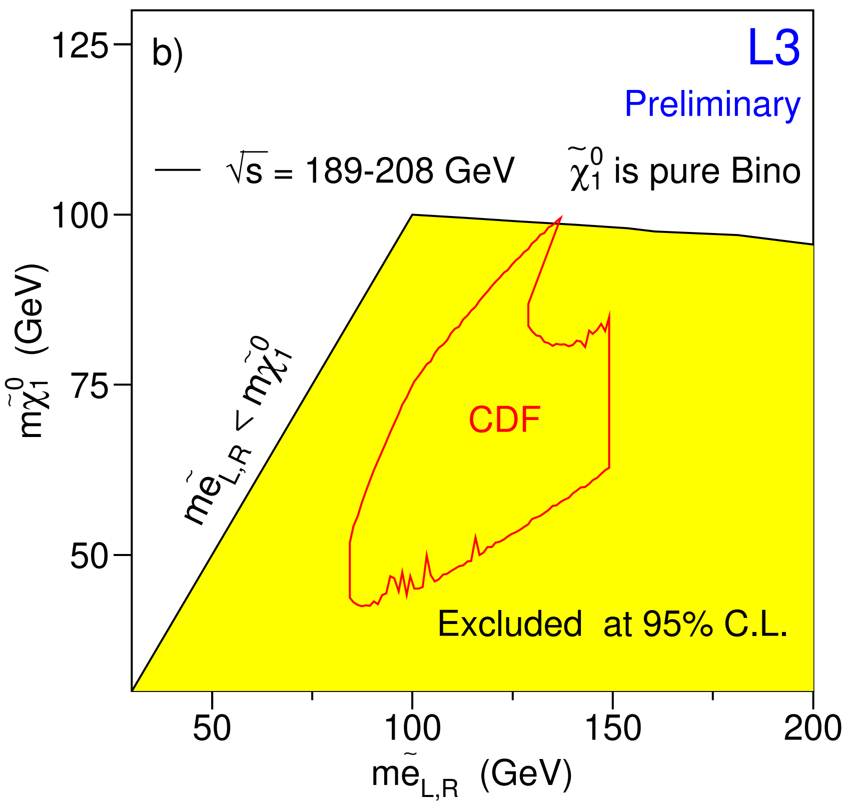
GMSB: $\gamma\gamma + \not{E}$, Mass Limits

- $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 \to \gamma\gamma\tilde{G}\tilde{G}$
- cross-section $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0$ depends strongly on $M_{\tilde{e}_R^\pm}$
- 'CDF region' corresponding to $q\bar{q} \to \tilde{e}_R\tilde{e}_R \to ee\tilde{\chi}_1^0\tilde{\chi}_1^0 \to ee\gamma\gamma\tilde{G}\tilde{G}$
- mass limits calculated for $\tilde{\chi}_1^0$ lifetime smaller than 3 ns
- Aleph lower mass limit: $M_{\tilde{\chi}_1^0} \geq 99\,\mathrm{GeV}$ at 95% C.L. $(\sqrt{s} = 189\text{-}208\,\mathrm{GeV})$

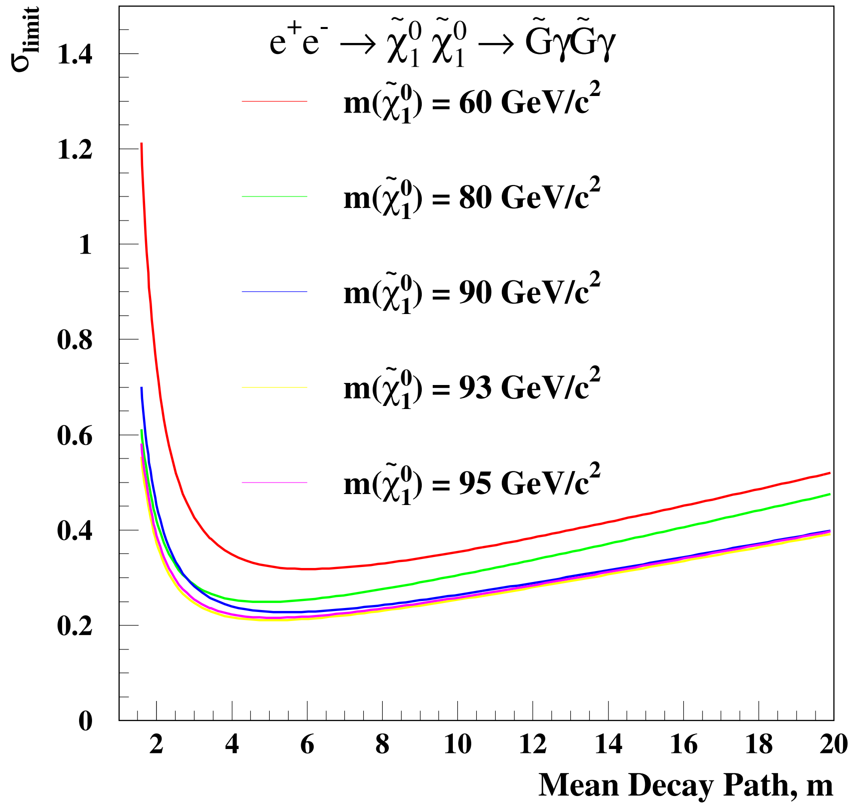


GMSB: $\gamma\gamma+\not{E}$, More Limits

L3, assuming prompt decays



DELPHI preliminary, $\sqrt{s} = 192 - 209$ GeV



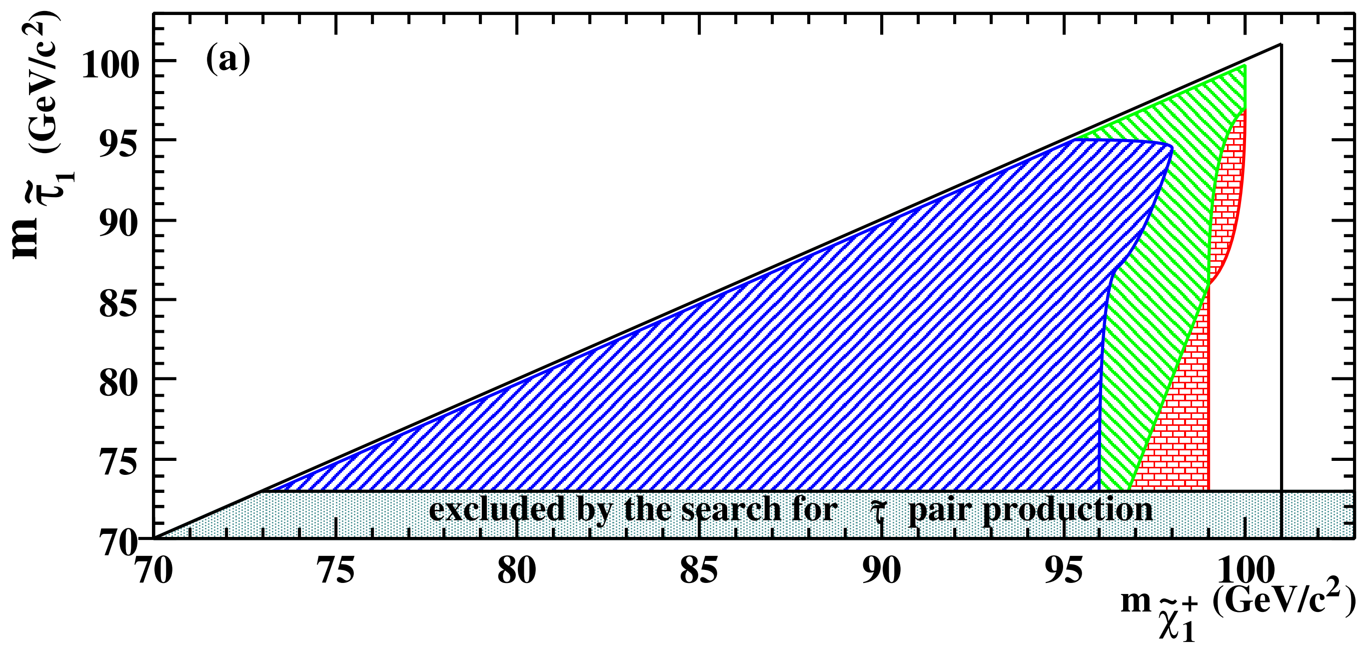
GMSB: $\tau^+\tau^-$+$\not{E}$

- sensitive to $\mathrm{e}^+\mathrm{e}^- \to \tilde{\chi}_1^+\tilde{\chi}_1^- \to \tau^+\tau^-\nu_\tau\bar{\nu}_\tau\tilde{G}\tilde{G}$
- search strategy depends on NLSP ($\tilde{\tau}_1$) lifetime (DELPHI approach):
  - $M_{\tilde{G}} \lesssim 1\mathrm{eV}$
    $\tilde{\chi}_1^\pm$ decays at vertex $\Rightarrow$ apply 'standard' SUGRA search
  - $1\mathrm{eV} \lesssim M_{\tilde{G}} \lesssim 1000\mathrm{eV}$
    $\tilde{\chi}_1^\pm$ has intermediate mean decay length
  - $1000\mathrm{eV} < M_{\tilde{G}}$
    $\tilde{\chi}_1^\pm$ is quasi-stable $\Rightarrow$ apply search for stable, heavy, charged particles

GMSB: $\tau^+\tau^-$+$\not\!\!E$, Mass Limits

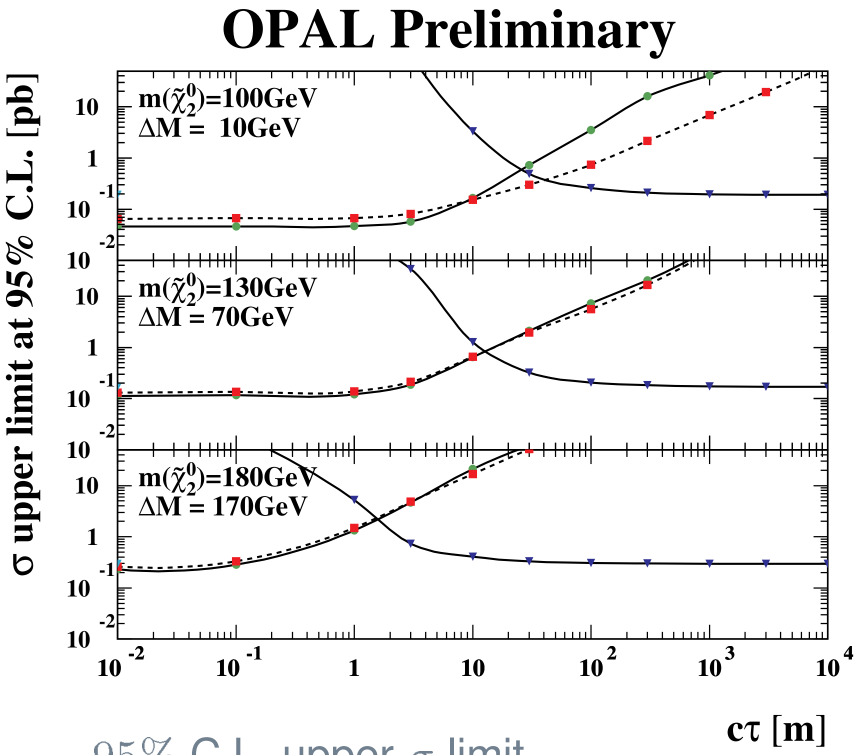
DELPHI, published, $\sqrt{s} = 183 - 202\,\mathrm{GeV}$

	all $M_{\tilde{G}}$	$M_{\tilde{G}}$>100 eV	$M_{\tilde{G}}$>1000 eV
$M_{\tilde{\chi}_1^\pm}$ limit at 95% C.L. ($\Delta M > 0.3\,\mathrm{GeV}$)	95.2 GeV	96.8 GeV	99.0 GeV



GMSB: $f\bar{f}\gamma\gamma + \not{E}$

- sensitive to
  $e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_1^0 \to Z^{0(\star)}\gamma\gamma\tilde{G}\tilde{G}$
- OPAL procedure:
  - low- and high multiplicity selection
  - $\Delta M^0 = M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0}$ dependent selection
  - consider nonzero $\tilde{\chi}_1^0$ lifetime
    - two-photon selection
    - one-photon selection
    - zero-photon selection (SUGRA)



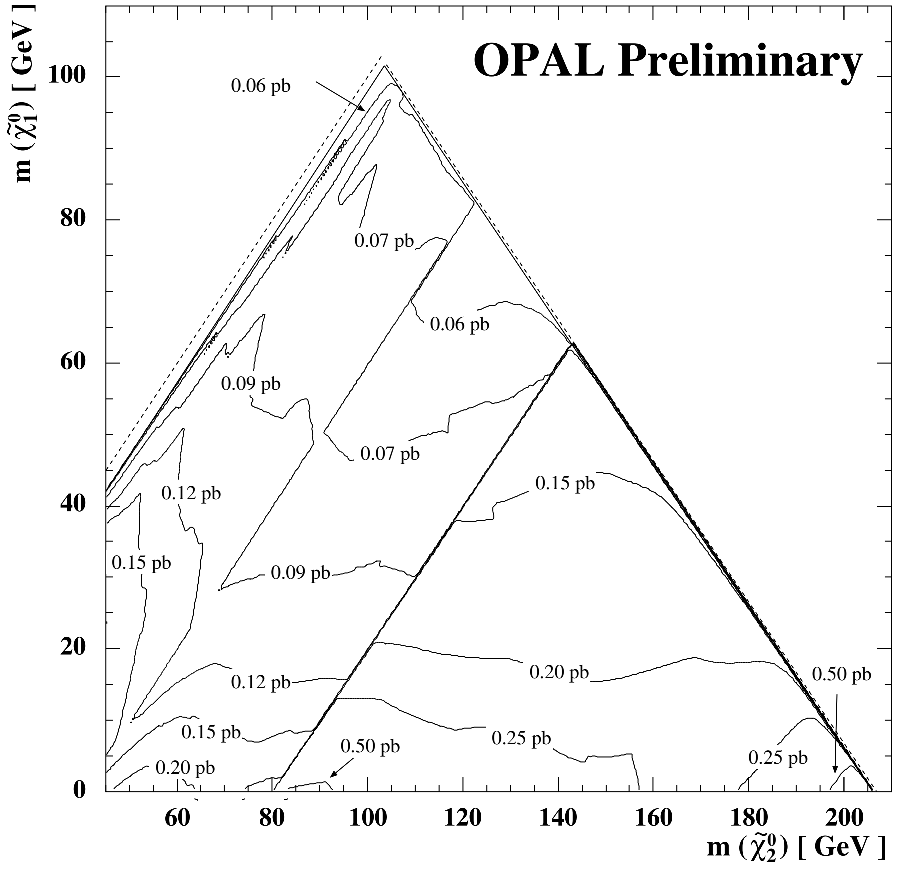
95% C.L. upper σ limit

at $\sqrt{s} = 202$ GeV

GMSB: $f\bar{f}\gamma\gamma+\not{E}$, Cross-section Limit

$$e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_1^0 \to Z^{0(\star)}\gamma\gamma\tilde{G}\tilde{G}$$

- limits at 95% C.L. for $e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_1^0$ at $\sqrt{s} = 206.1\,\mathrm{GeV}$
- assuming $\tilde{\chi}_2^0 \to Z^{0(\star)}\tilde{\chi}_1^0$ decays
- followed by prompt $\tilde{\chi}_1^0 \to \gamma\tilde{G}$ decay



AMSB

Hidden Sector

SUSY Breaking

- anomalous mediated SUSY breaking: SUSY particle masses are generated at loops
  - gaugino masses at one loop
  - scalar masses at two loops
- free parameters

m_0	common scalar mass
$m_{3/2}$	gravitino mass
$\tan\beta$	VEV ratio of two Higgs doublets
$\mathrm{sign}(\mu)$	sign of Higgs mixing parameter

- LSP: $\tilde{\chi}_1^0$

Observable Sector

MSSM

(masses via loops)

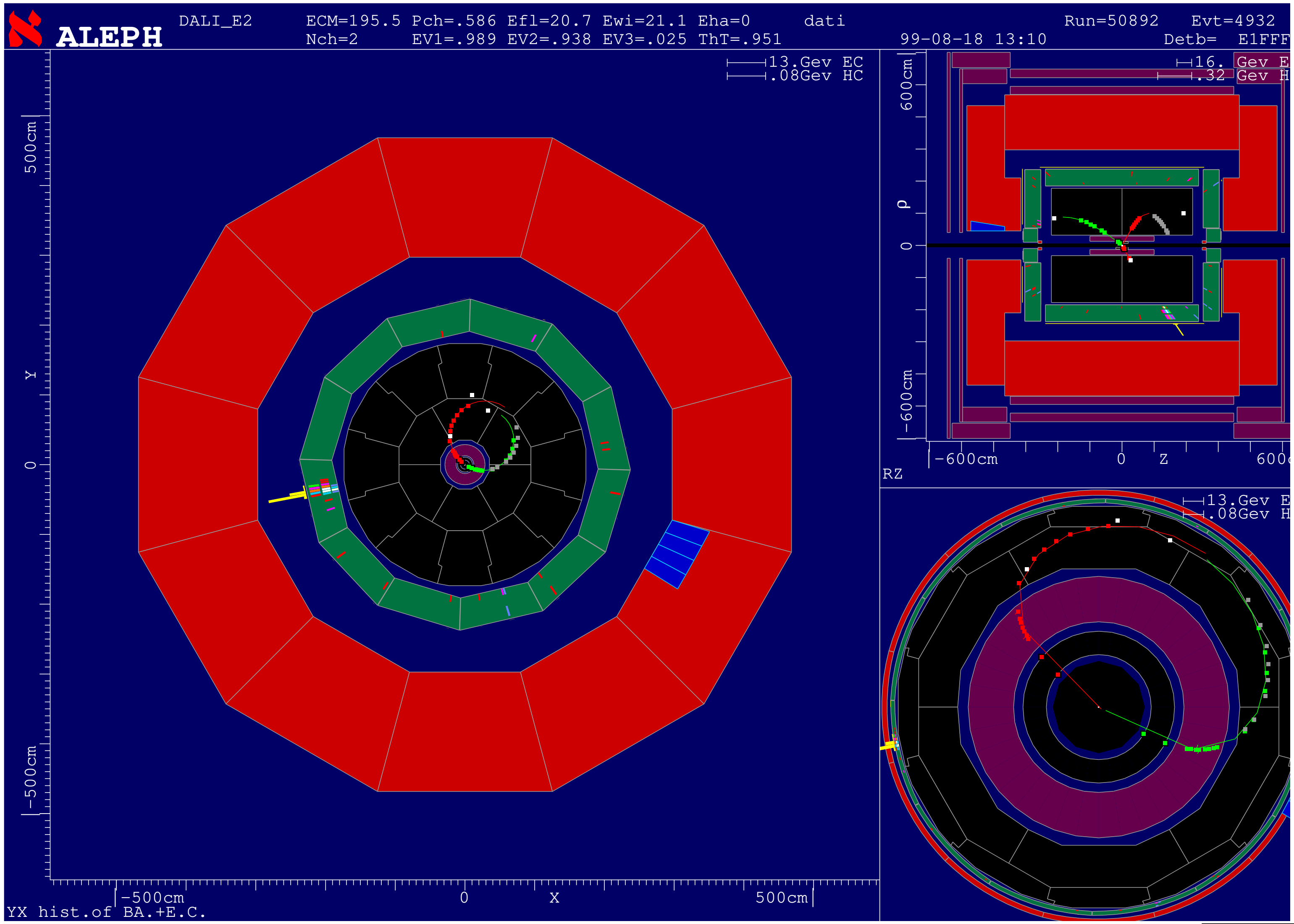
AMSB: Implications

- $\tilde{\chi}_1^0$ is LSP
- small mass splitting $\Delta M^{\pm} \sim 1$ GeV between $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_1^0$
- $\mathrm{e}^+\mathrm{e}^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow (n\pi)\tilde{\chi}_1^0 \tilde{\chi}_1^0$
  - typical signature: $\not{E} +$ little detector activity
  - use ISR Method
  - no mass limits available yet
  - but analyses are underway
- still help needed from theory community
  - cross-sections
  - branching ratios
  - ...

  lack of software that can do the calculations and produce measurable quantities

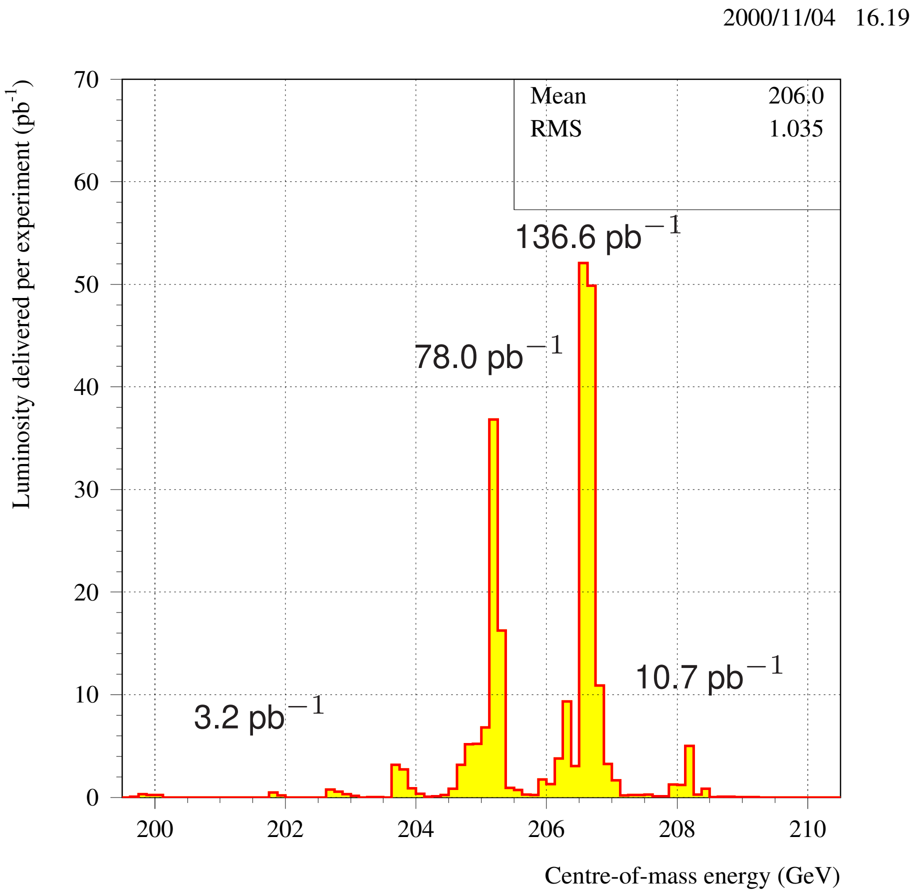
AMSB: Small $\Delta M^{\pm}$ Candidate

ALEPH, $\sqrt{s} = 195.4$ GeV, $E_\gamma \approx 21$ GeV, $M_{\tilde{\chi}_1^\pm} < 84\,\mathrm{GeV}$



Prospects

- most results are preliminary
- more general results are expected for the next months
- LEP combinations will complete the searches
- Y2k data:
  - $220 \mathrm{pb}^{-1}$ per experiment with $\sqrt{s} \geq 200.0\,\mathrm{GeV}$
  - $9 \mathrm{pb}^{-1}$ per experiment with $\sqrt{s} \geq 207.5\,\mathrm{GeV}$



Summary

- Aleph, Delphi, L3, OPAL considered a huge variety of SUSY scenarios respectively search channels (R-parity violating scenarios not even mentioned)
- $\tilde{\chi}_1^{\pm}$ excluded at 95% C.L. in almost full kinematically accessible region at LEP2
- still unexcluded parameter space
- final analyses will be more general
- LEP combined analyses will be base and benchmark for the following years