SUSY Searches at LEP

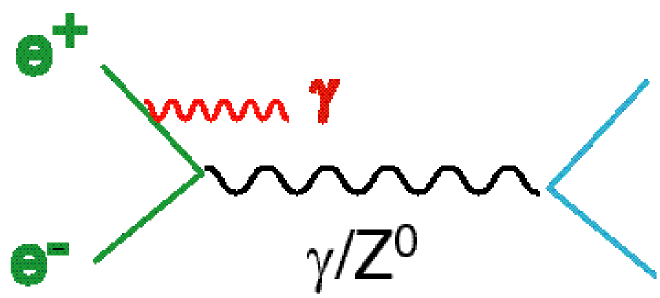
- LEP and experiments
- SUSY parameters
- Physics analyses
- Excluded parameter space

Chicago Personnel

- Senior:
  - Andersen, Merritt, Oreglia, Pilcher
- Postdocs:
  - Bellerive, Teuscher, Torrence (FF)
- Grad Students:
  - Coxe, Hocker
- Undergrads:
  - usually 1/yr on OPAL

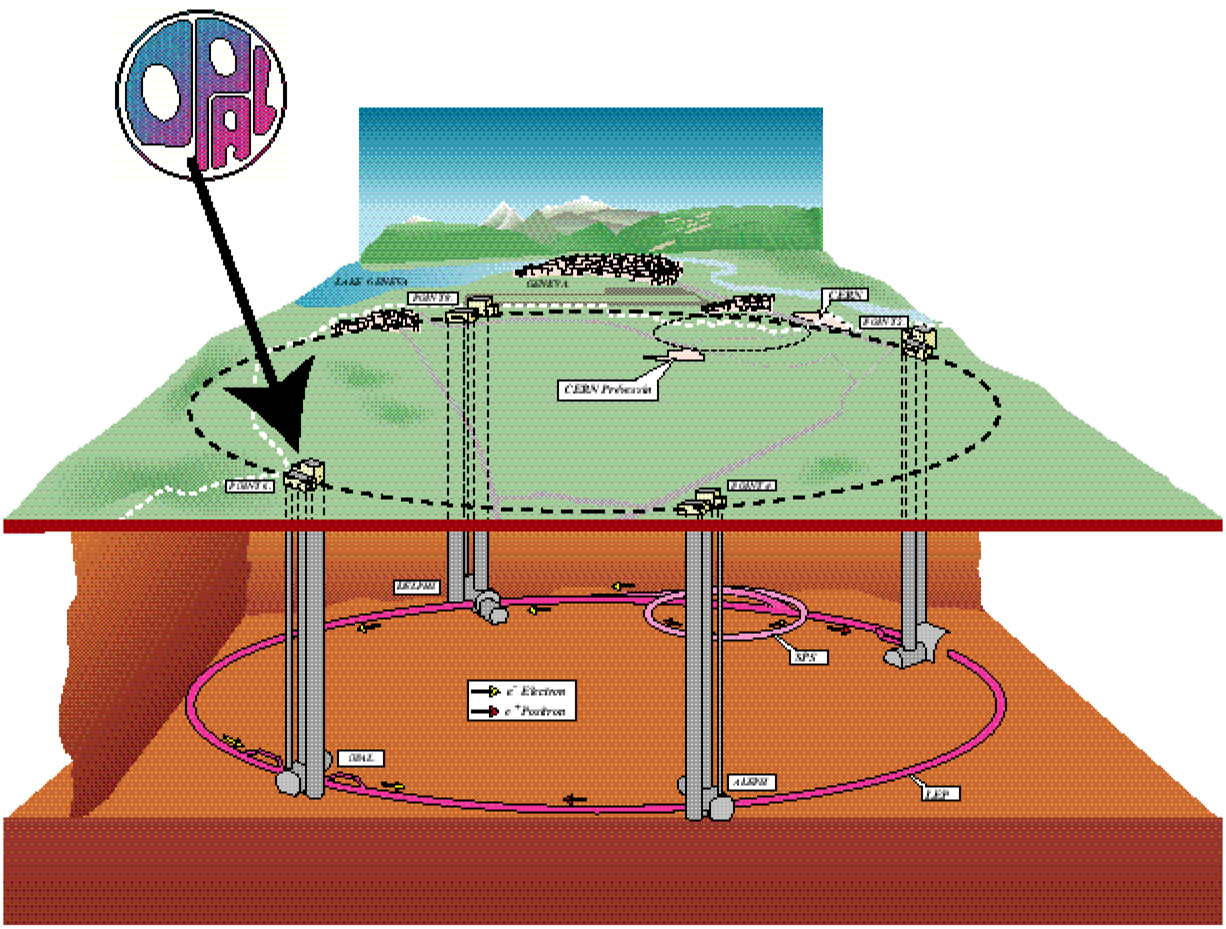
The LEP Accelerator

- e^+e^- collisions
  - no “spectator particles”



- E_{cm} = 88 - 202 GeV
  - this year: all out for 208 GeV !!!
- E_{beam} known to 0.001 %
  - constrains measured E,p -- good measurement of missing E
- Detectors are nearly “hermetic”
  - 4 detectors at LEP
    - allows for combining statistics

The LEP Experiments

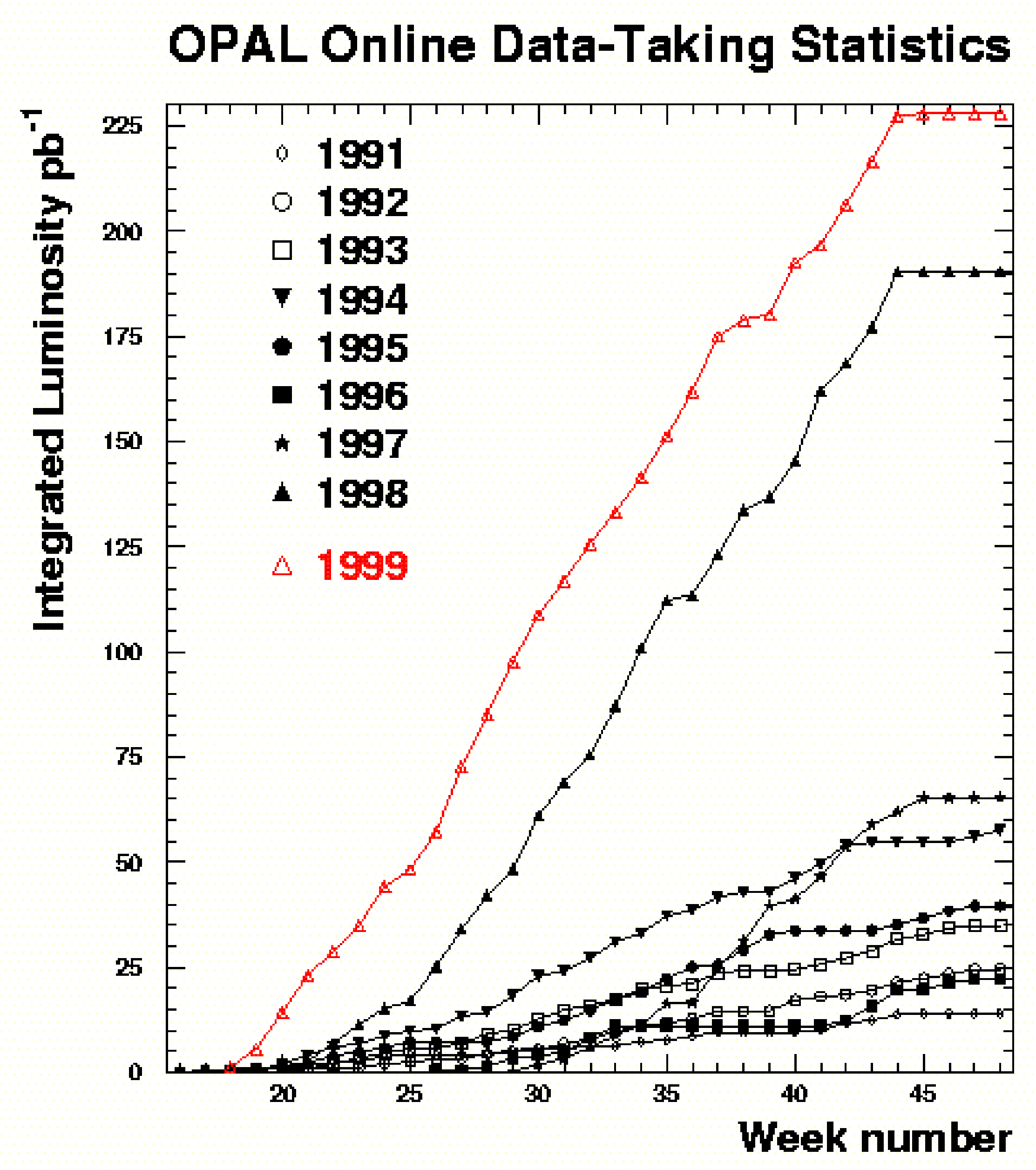


LEP Schedule

- 1989-1995: $E_{cm} = 91 \pm 2$ GeV
  - 1995: + 131-150 GeV
  - precision electroweak
- 1996: 161, 172 GeV
- 1997: 183 GeV
  - M_W, σ_W
- 1998: 189 GeV
- 1999: 192 - 202 GeV
  - Higgs reach > 100 GeV
- 2000: 202 GeV -- 208 GeV !!!
  - last year of running (unless …)

LEP Performance

About 200 events/yr for a 1 picobarn x-section



SUSY Particles

Spin: 0	1/2	1
$\tilde{l}^{\pm}_{1,2} \rightarrow \tilde{l}^{\pm}_{L,R}$	$l^{\pm}_{L,R}$	
$\tilde{n}_{L}$	n_{L}	
$\tilde{q}_{1,2} \rightarrow \tilde{q}_{L,R}$	$q_{L,R}$	
	$\tilde{g}$	g
h^{0}, A^{0}, H^{0}	$\langle g, \tilde{h}, \tilde{H}, \tilde{Z} \rangle = \tilde{c}^{0}_{j}$	g, Z^{0}
$H^{\pm}$	$\langle \tilde{H}^{\pm}, \tilde{W}^{\pm} \rangle = \tilde{c}^{\pm}_{j}$	$W^{\pm}$

SUSY Models, Params

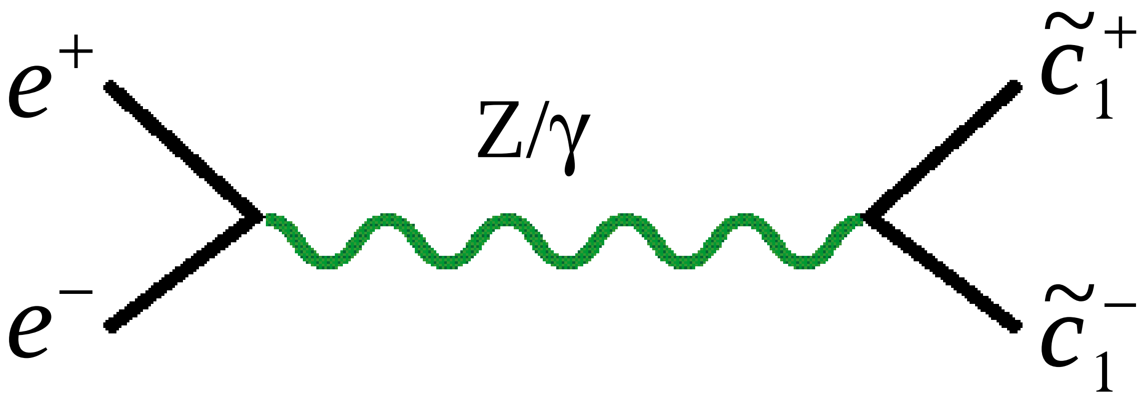
- Minimal Fields: MSSM
  - >100 parameters, including:
  - M_1, M_2, M_3 = U(1),SU(2),SU(3) mass
  - m_f = sfermion masses
  - v, tanβ, m_A,μ = Higgs mass, mixing
  - A_U, A_D, A_L = sfermion-Higgs couplings
- Constraints: CMSSM (5 parm.)
  - SUGRA employed to unify at M_P
  - M_2 = SU(2) mass scale
  - m_0 = GUT-scale mass
  - tanβ = v_2/v_1 (Higgs potential)
  - A_0 = common trilinear coupling
  - μ = a Higgs mass parameter

Search Topology

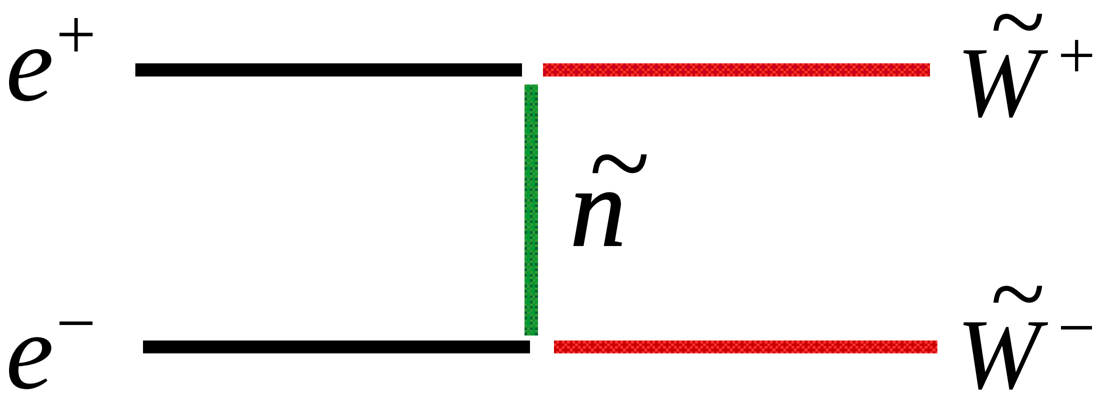
- In all cases, production of SUSY particles ends in a decay chain with the lightest SUSY particle LSP.
  - But there are extended models where this is not the case
- LSP doesn't interact in detector
  - look for events with significant missing energy and momentum
  - the sensitive regions of the parameters are those which can be cut away from Standard Model backgrounds:
    - 4-fermions (esp. WW): miss ν
    - "2-photon" processes: down the pipe

Chargino Production

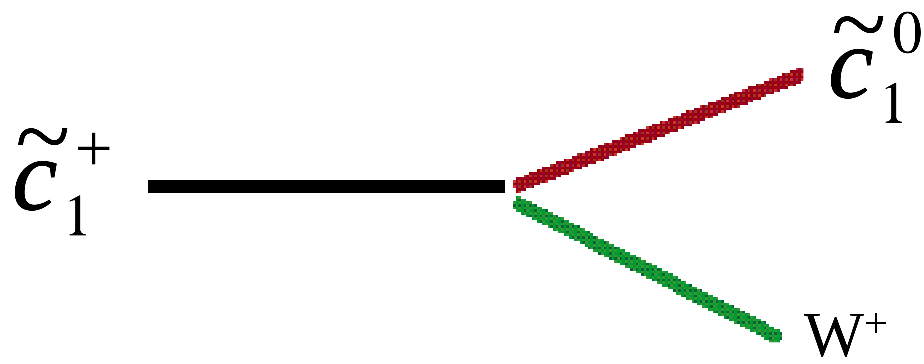
- σ > 4 pb (unless sneutrino is light)



If μ << M_2, interferes destructively with:



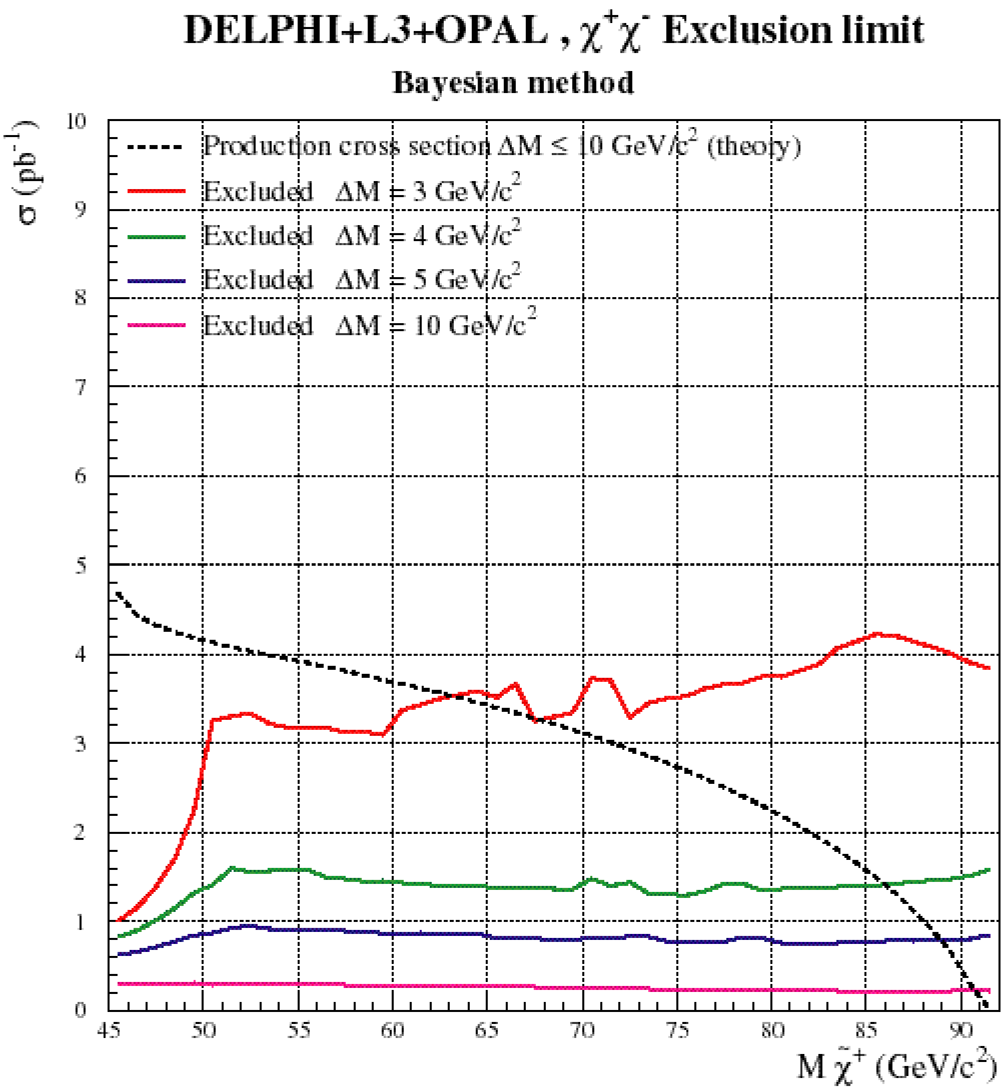
Chargino Decays



$$W \to q\bar{q}, W \to ln$$

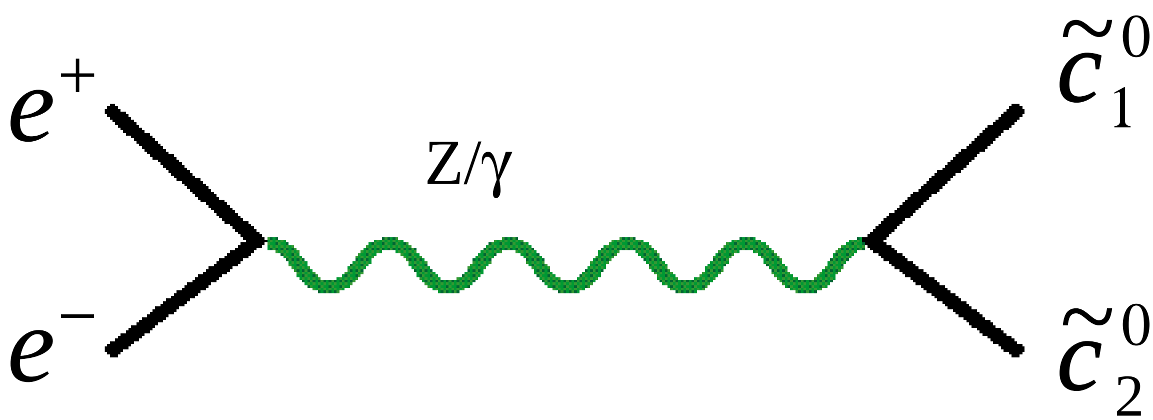
- Topologies all have missing E:
  - 4-jet
  - 2-jet+lepton,
  - 2-lepton
- sensitivity depends on $M_{\tilde{c}_1^+}$- $M_{\tilde{c}_1^0}$
- data consistent with SM bckgds: $M_{\tilde{c}_1^+}$> 89.6 GeV for ΔM > 3 GeV

Chargino σ Limits

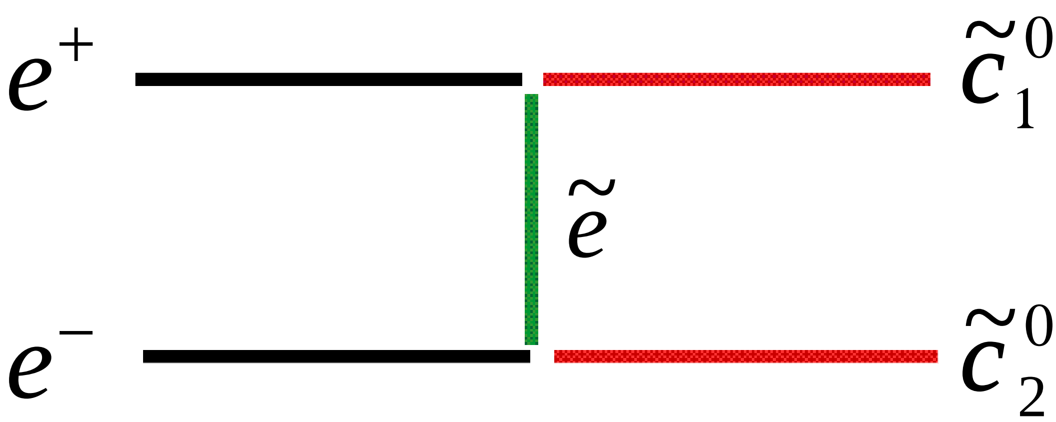


Neutralino Production

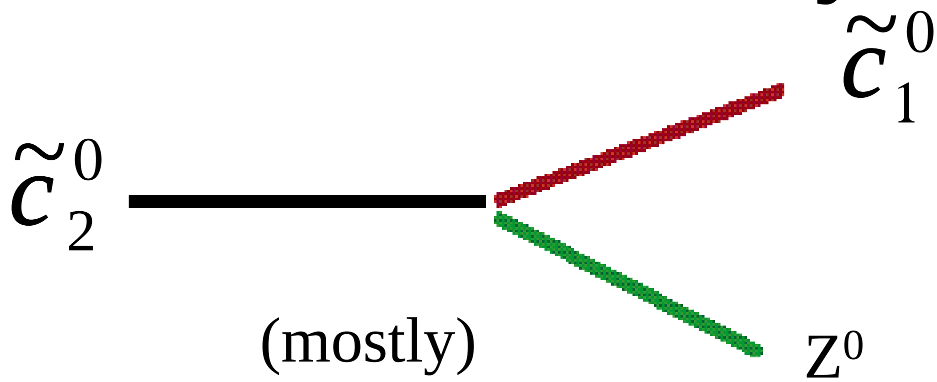
Lower production σ than for chargino:



Interferes constructively with:



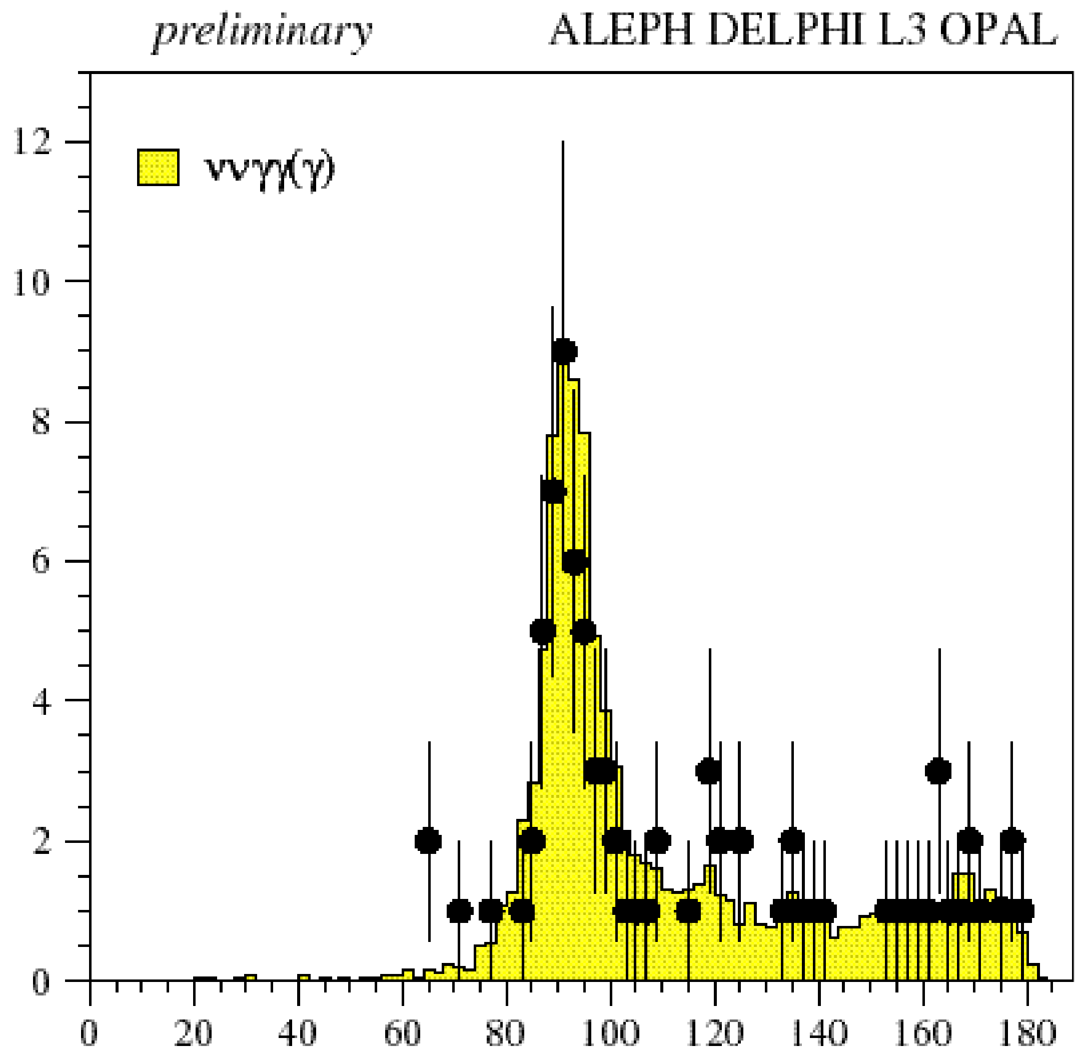
Neutralino Decays



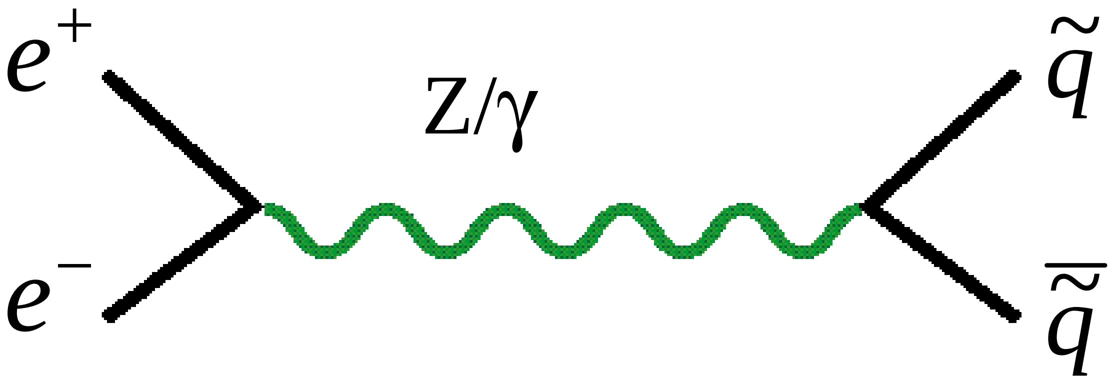
- Topologies:
  - difermions + E_{miss}
  - acoplanar with beam axis

- … but decays into γ instead of Z for some of the parameter space

Recoil Mass for $\gamma\gamma E_{miss}$



Squark Production



- Production cross section is large
- *stop* mass gets large loop corrections
- stop could be the lightest squark!

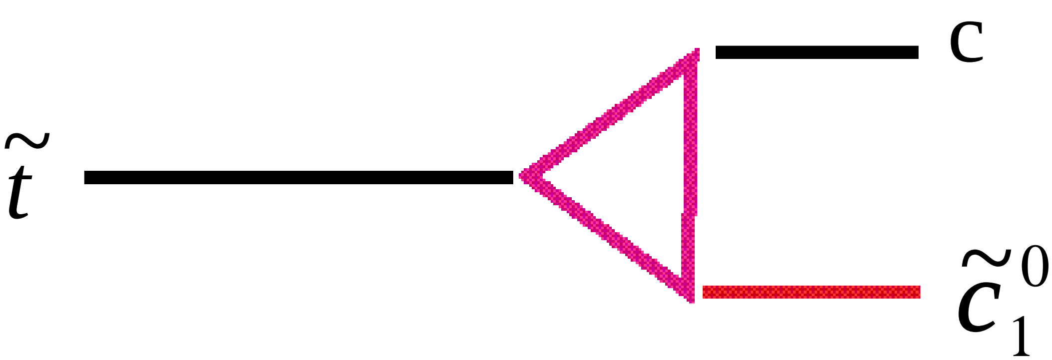
(or even the lightest sfermion)

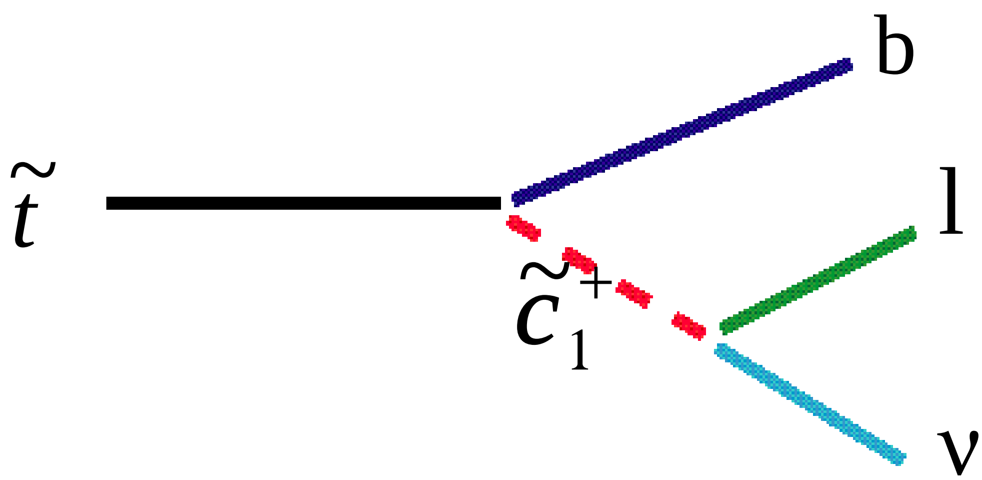
- There is mixing of L and R

components to form the physical mass eigenstate: $\tilde{t}_1 = \cos\theta\ \tilde{t}_L + \sin\theta\ \tilde{t}_R$

- For large enough θ, decouples from Z

Squark Decays

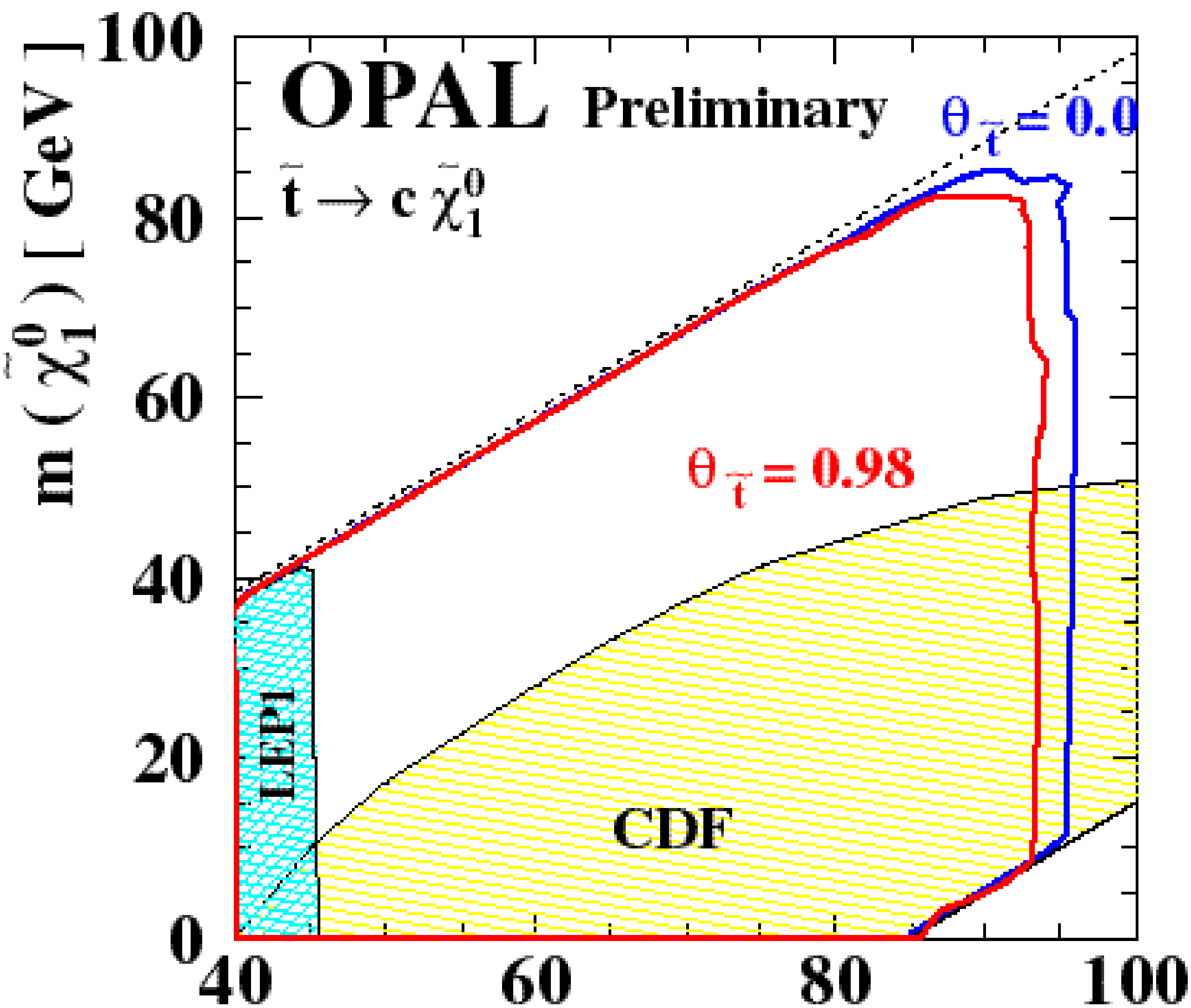




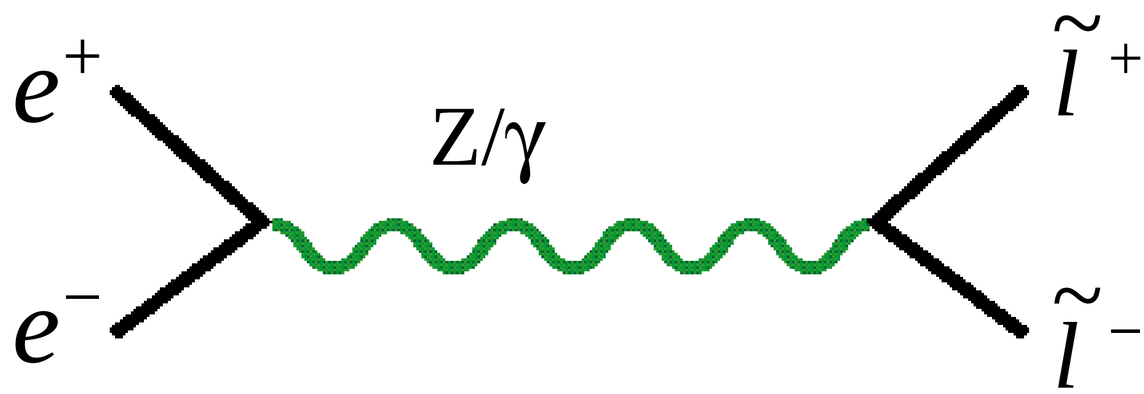
- …depends on how light *stop* is

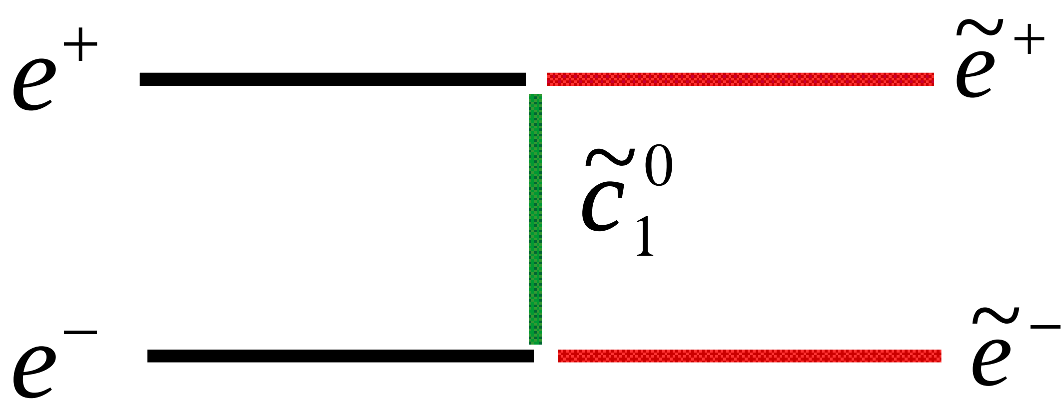
stop Limits

CDF: out to larger masses; LEP: better at low mass

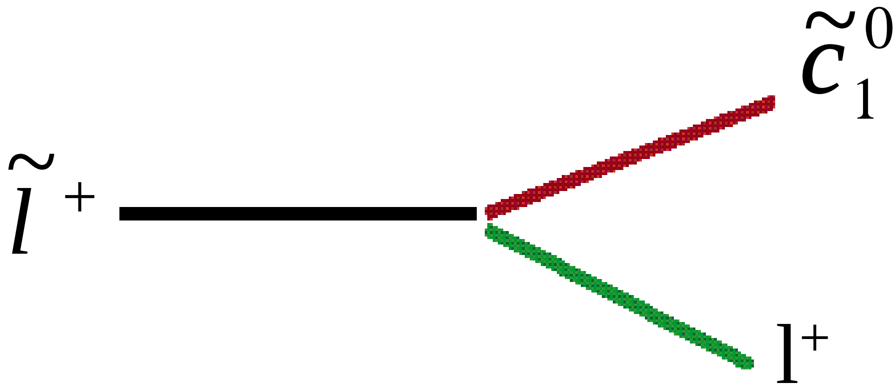


Slepton Production



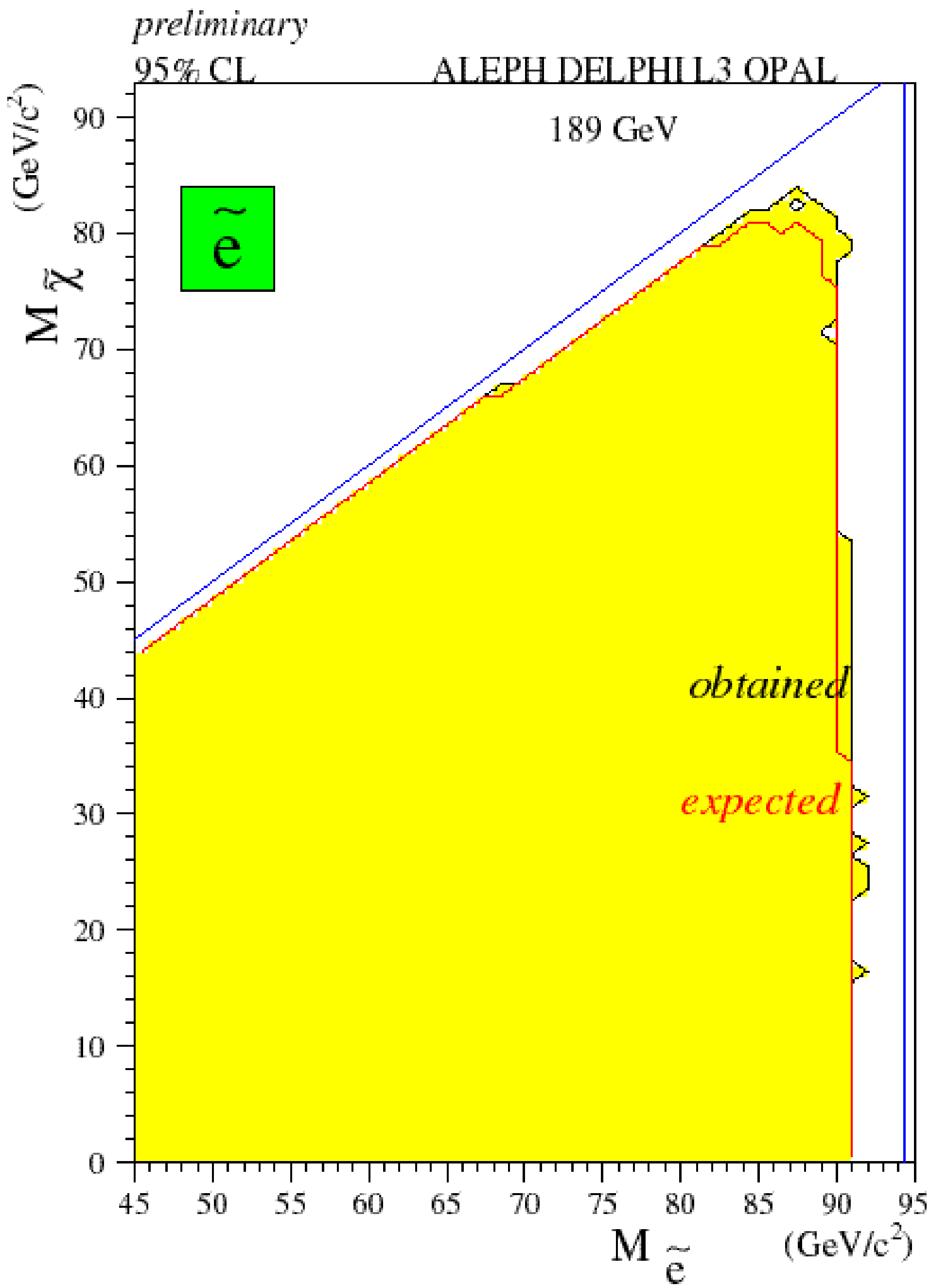


Slepton Decays



- Topology: 2 acoplanar leptons
- again, efficiency depends on mass difference, but …
- the small ΔM region is recovered by the t-channel production

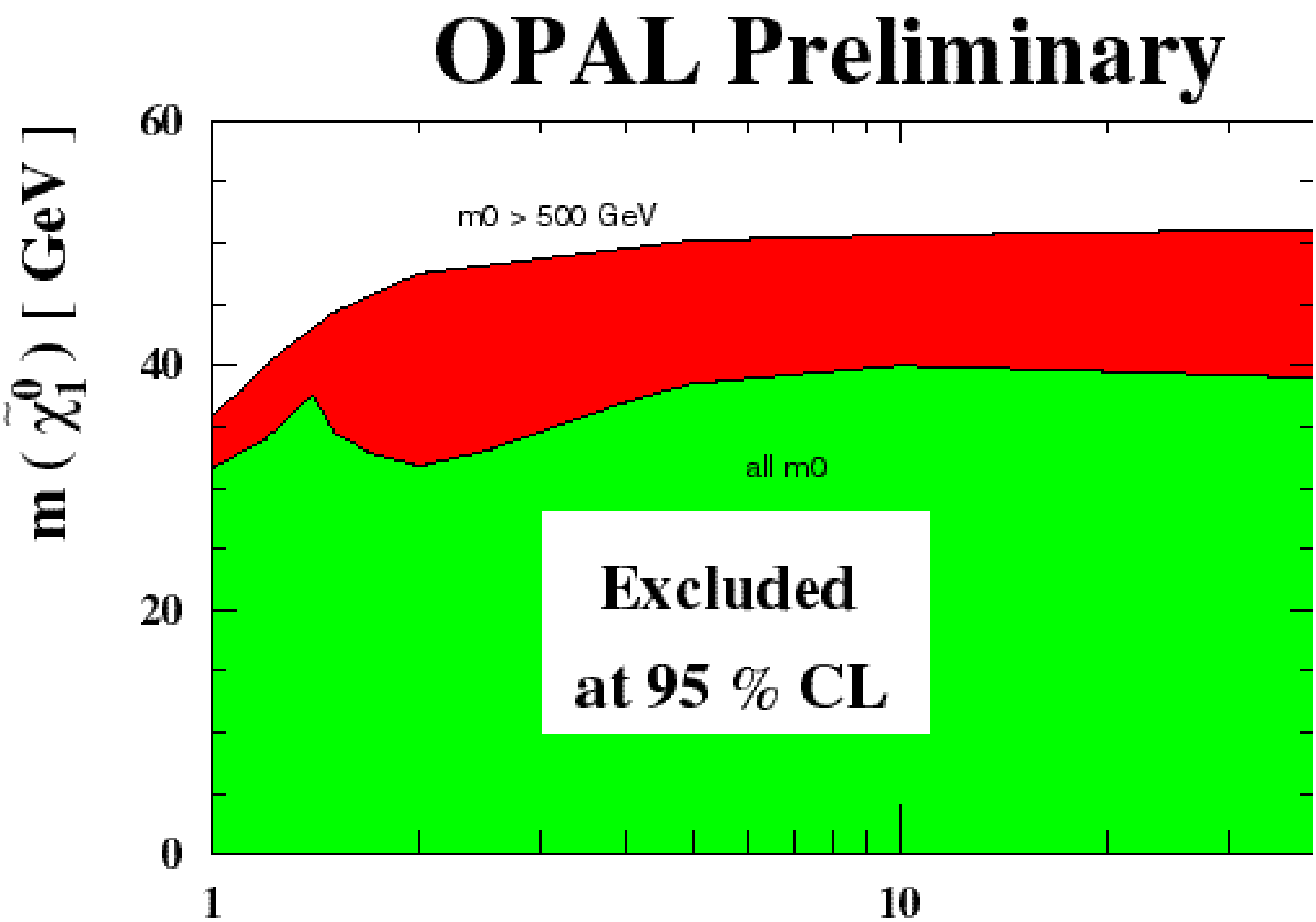
Selectron Limits



Combine Measurements for a Grand SUGRA Limit

- Use limits from:
  - selectron, stau, chargino production
  - MSSM Higgs search
  - Precision EW parameters
- Scan 4 of the 5 parameters in the SUGRA model
  - get limit on LSP production cross section as function of LSP mass
  - compare to predictions
    - depend on ΔM
- In general, have many such exclusion plots!

Limits on Lightest Neutralino



$M_{\tilde{c}_1^0} > 31.6$ GeV (CMSSM)

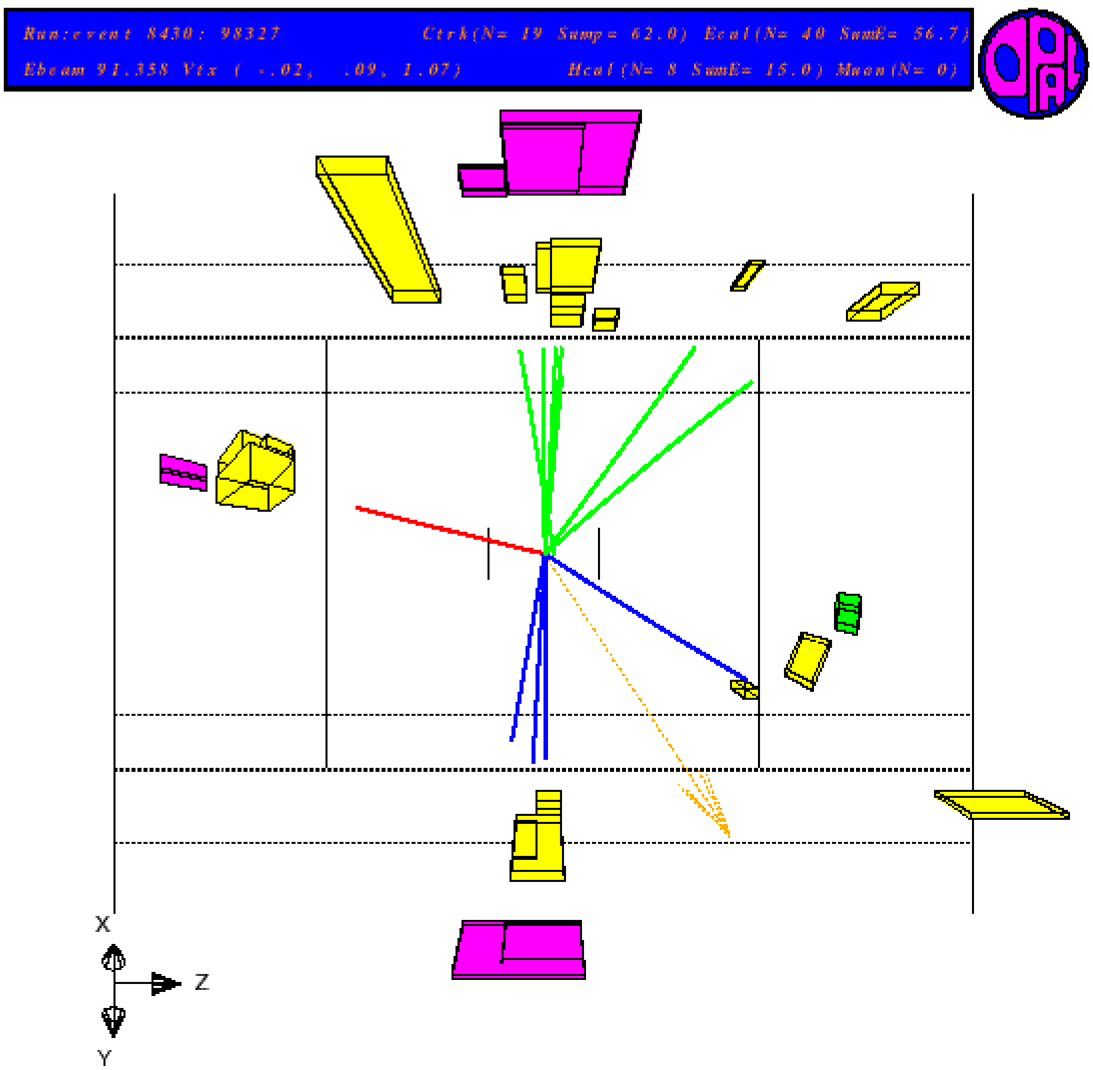
Alternative to SUGRA

- Gauge-Mediated SUSY Breaking (GMSB):
  - sector of SU(5) “messengers” mediate the symmetry breaking at EW scale
  - 5 parameters in popular model
- Main difference from SUGRA: LSP is $\tilde{G}$
  - this leads us to treat $\tilde{\chi}_1^0$ as the NLSP
  - final decay chain is: $\tilde{\chi}_1^0 \rightarrow \tilde{G}g$
  - and $\tilde{l} \rightarrow \tilde{G}l$
  - lifetime of NLSP important!

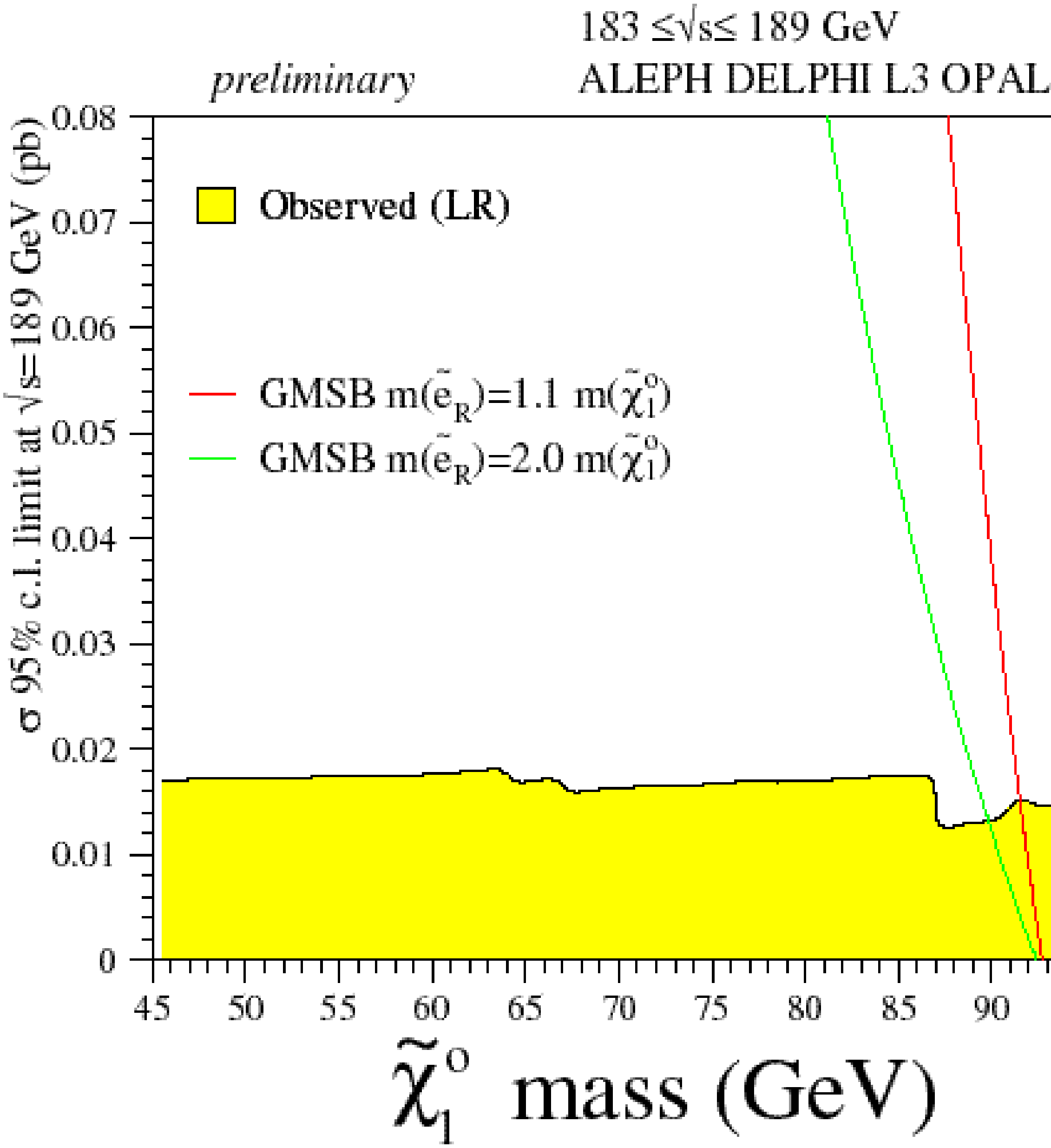
An OPAL Candidate

This could be: $\tilde{c}_1^+ \tilde{c}_1^- \rightarrow q\bar{q}\, tn\, \tilde{c}_1^0 (\tilde{c}_1^0 \rightarrow \tilde{G} g)$

(but number of events consistent with SM bkgd!)



Compare acoplanar $\sigma_{\gamma\gamma}$ with GMSB

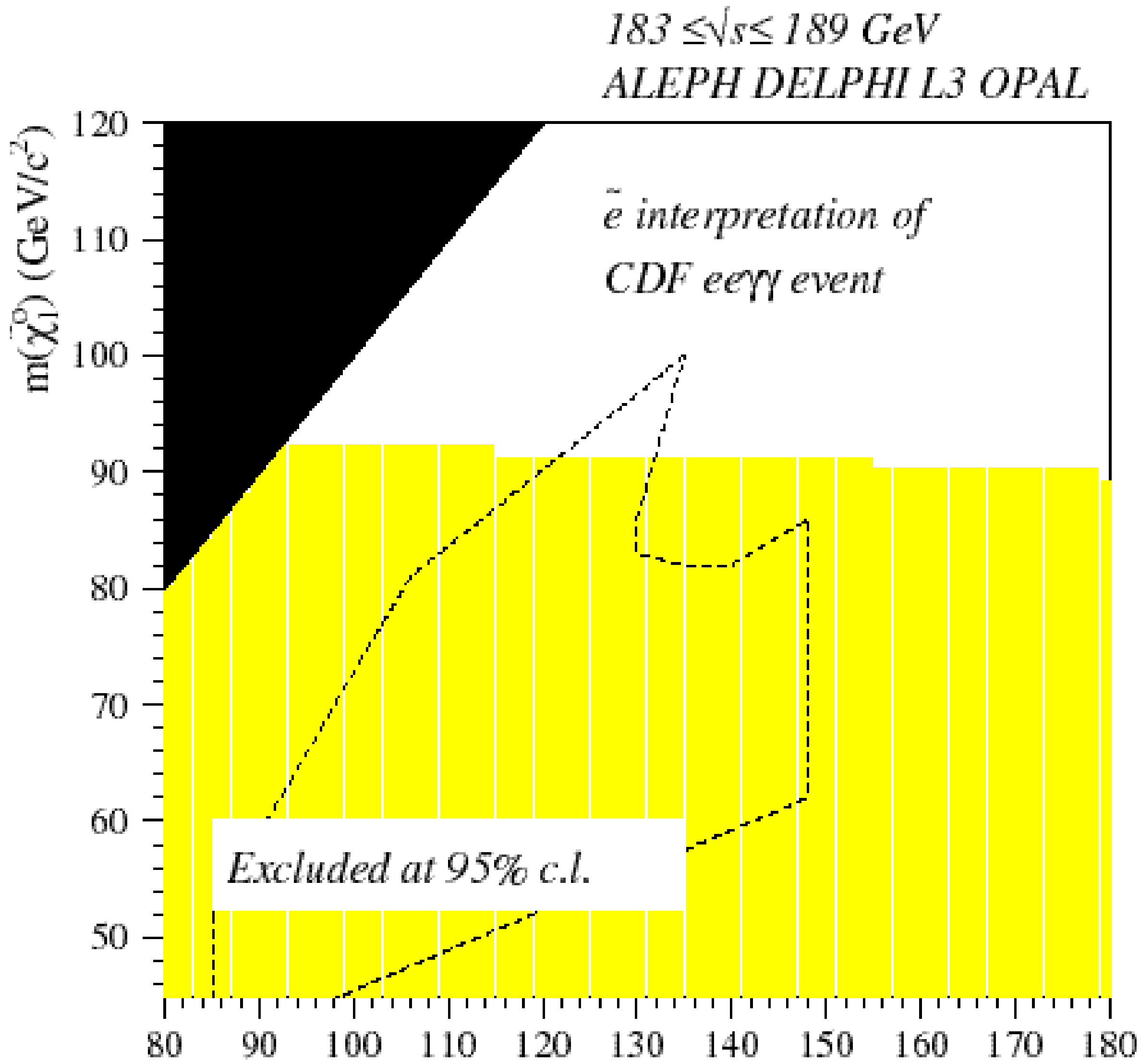


CDF has THE event!

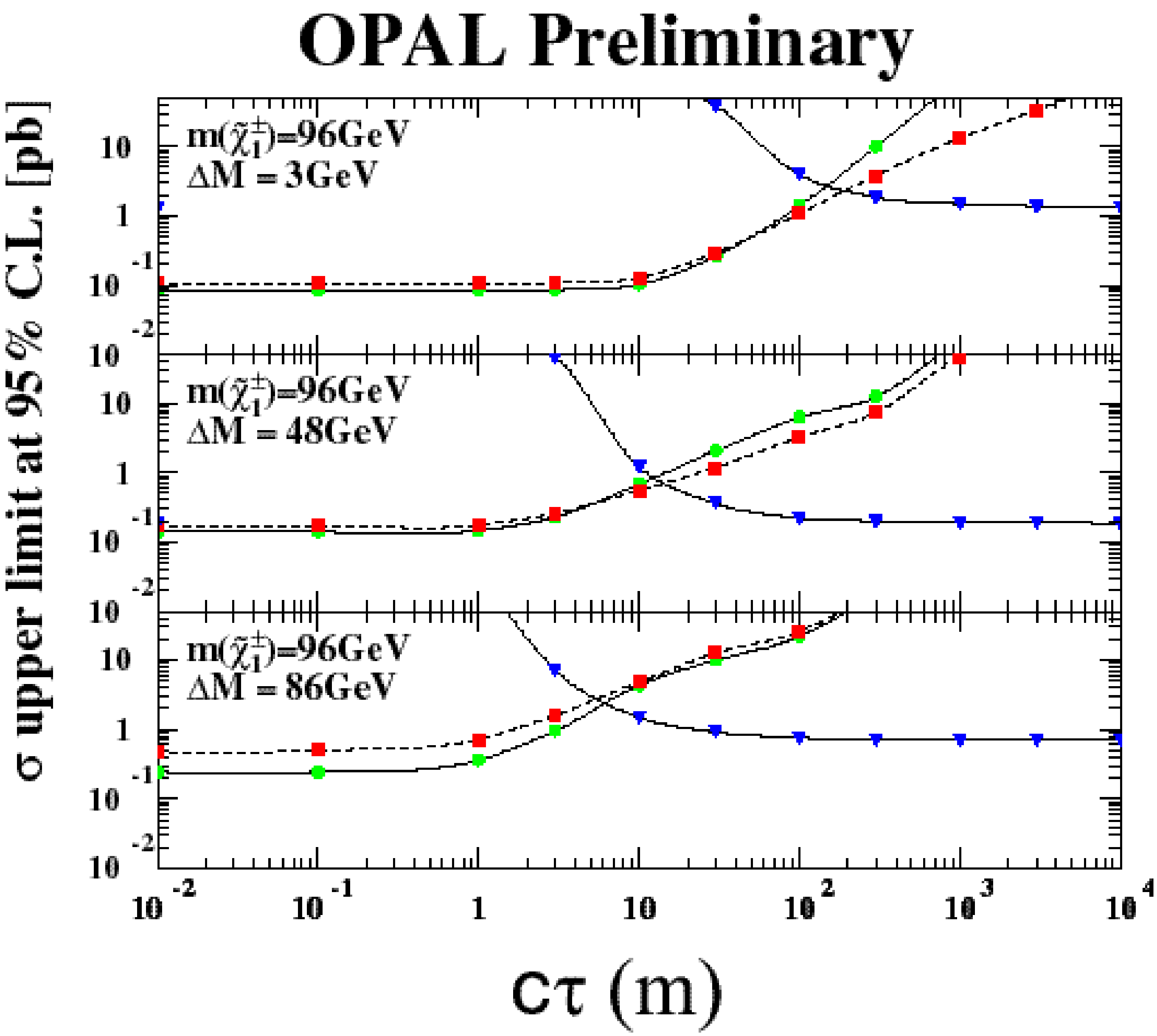
- CDF reported 1 ee$\gamma\gamma$ candidate,

$$e^+e^- \rightarrow \tilde{e}^+\tilde{e}^-, \tilde{e} \rightarrow e\tilde{c}_1^0, \tilde{c}_1^0 \rightarrow g\tilde{G}$$

- which LEP cannot rule out…completely!



σ vs. NLSP Lifetime



Summary of the Limits

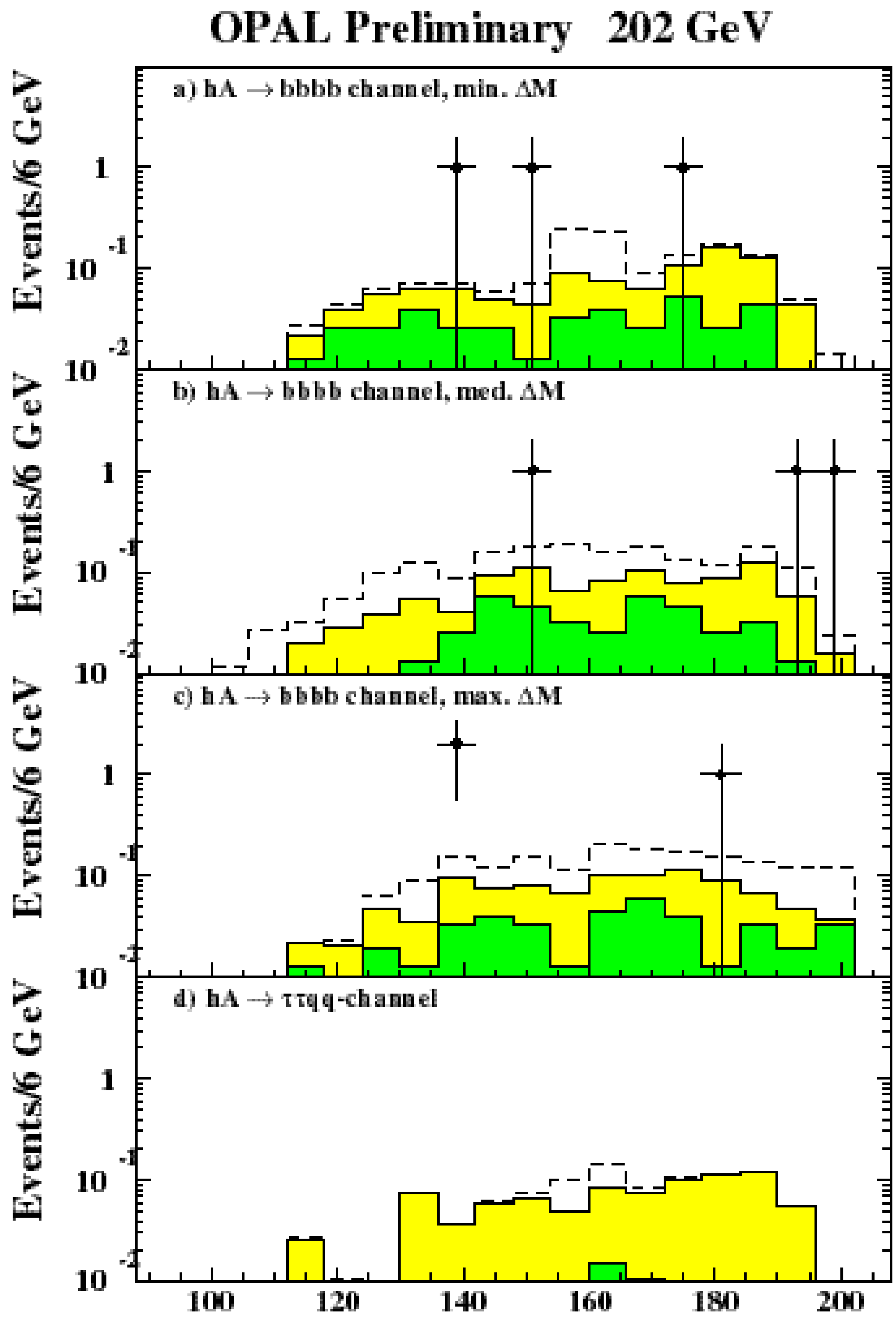
- For the SUGRA CMSSM model
- mass limits from combined searches
- we see NO interesting activity!

  - LSP mass > 30 GeV (SUGRA models)
  - Charginos are heavier than 90 GeV
  - Stop heavier than 88 GeV
  - Sbottom heavier than 75 GeV
  - Sleptons heavier than 70-88 GeV

And Finally: the Higgs

- Our ongoing search for the Higgs in the MSSM sector also leads to limits on the CMSSM parameters
- This Higgs sector has 5 Higgs particle
- we concentrate our searches for
  - h, the lightest neutral
  - A, the CP-odd neutral
  - $H^{\pm}$, the charged Higgs'

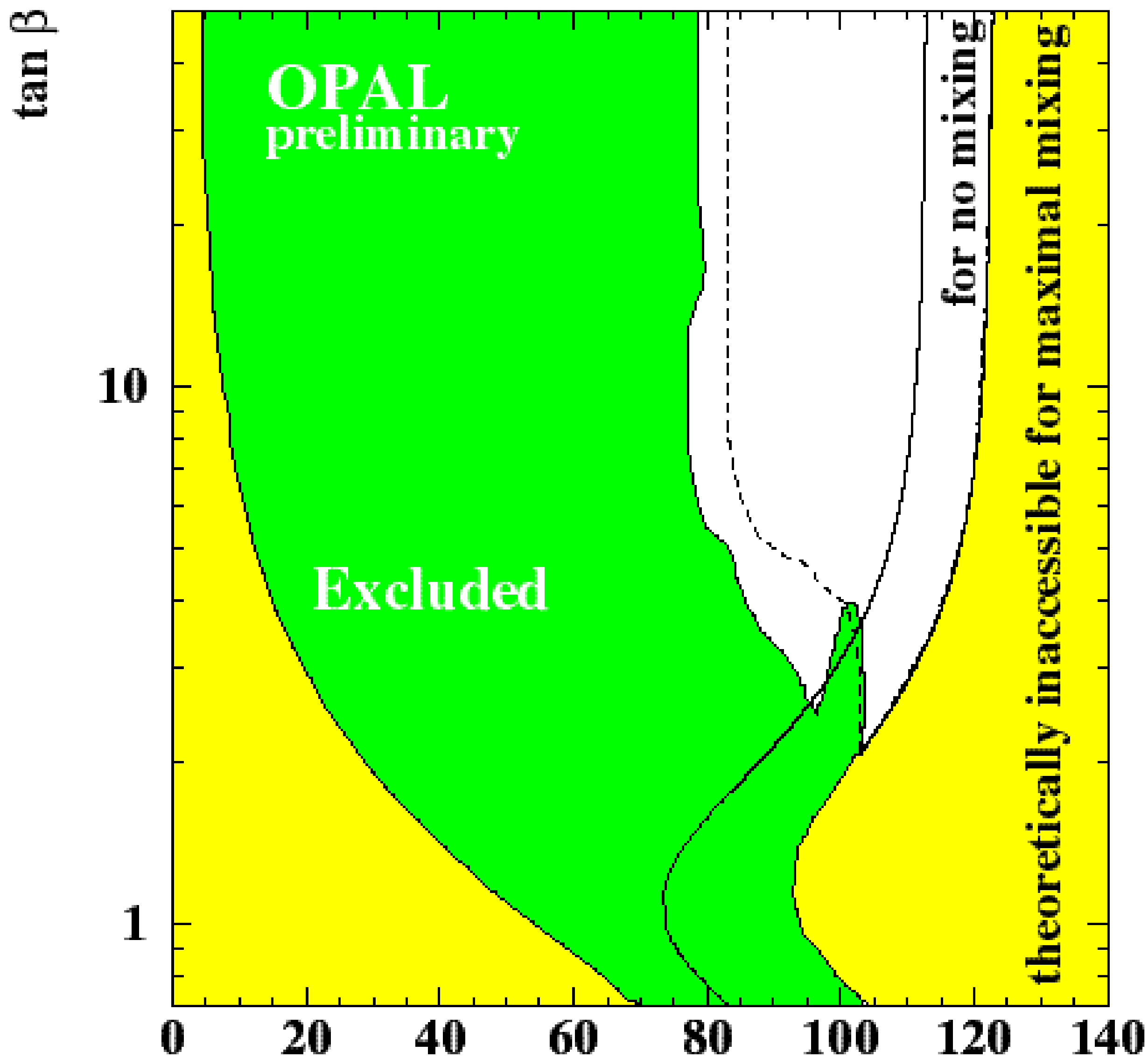
MSSM Higgs Search



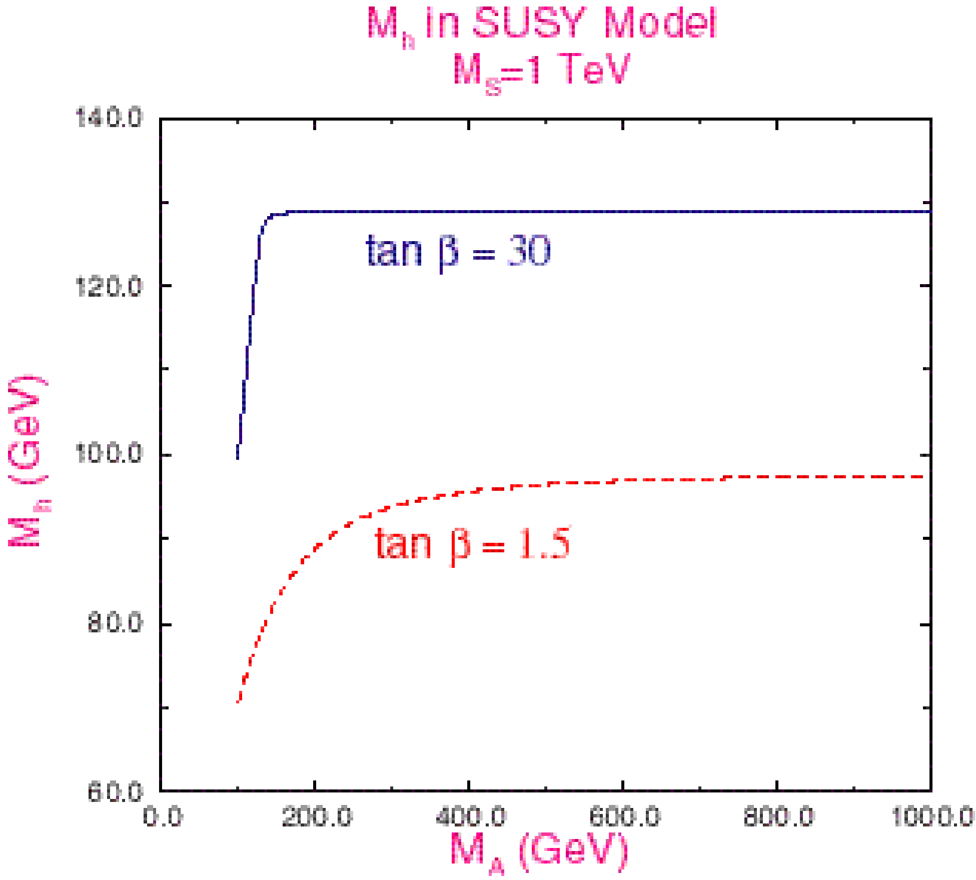
Parameter Space

- Since:
  - $e^+e^- \rightarrow Zh \sim \sin^2(\beta-\alpha)$, and
  - $e^+e^- \rightarrow ZA \sim \cos^2(\beta-\alpha)$,
- $\Rightarrow$ exclude $\{m_h, \tan\beta\}$ space by
  - scanning over some CMSSM parm:
    - $0.7 < \tan\beta < 50$
    - $5 < m_A < 2000$ GeV
  - fixing other parameters at ‘reasonable” values:
    - M2 = 1.63 TeV
    - m0 = 1 TeV
    - μ = -100 GeV
    - A = 0 or $\sqrt{6}$ TeV (0 or max mixing)
  - get $m_h > 77$ GeV (OPAL)

MSSM Exclusion



An Annoying Thing (for LEP)



- MSSM tree level: $m_h < m_Z$
  - w/ corrections: $m_h < 130$ GeV
- LEP-2 reach: 114 GeV (this yr!)

Summary of CMSSM Limits (ADLO, Summer, 1999)

- Sleptons (e,m,t): 89/84/71 GeV
- squarks: stop > 87, sbottom > 80 GeV

- $\tilde{c}_1^+$ > 97 GeV
- $\tilde{c}_1^0$ > 34 GeV

- MSSM Higgs bosons (benchmark scan):
  - h > 84.3 GeV
  - A > 84.5 GeV
  - exclude $0.5 < \tan\beta < 3.2$
  - $H^\pm$ > 77.0 GeV