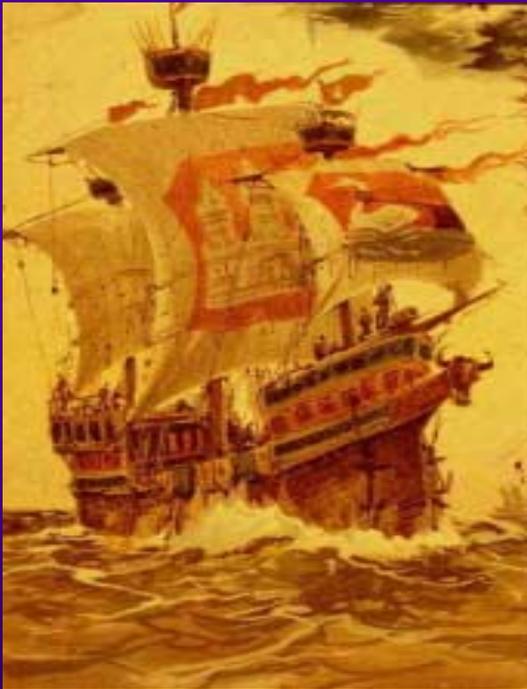


SUSY Searches: *Lessons and loopholes from LEP*



Aleph



Delphi



L3



Opal



SUSY02

DESY Hamburg

Rob McPherson

University of Victoria

Institute of Particle Physics



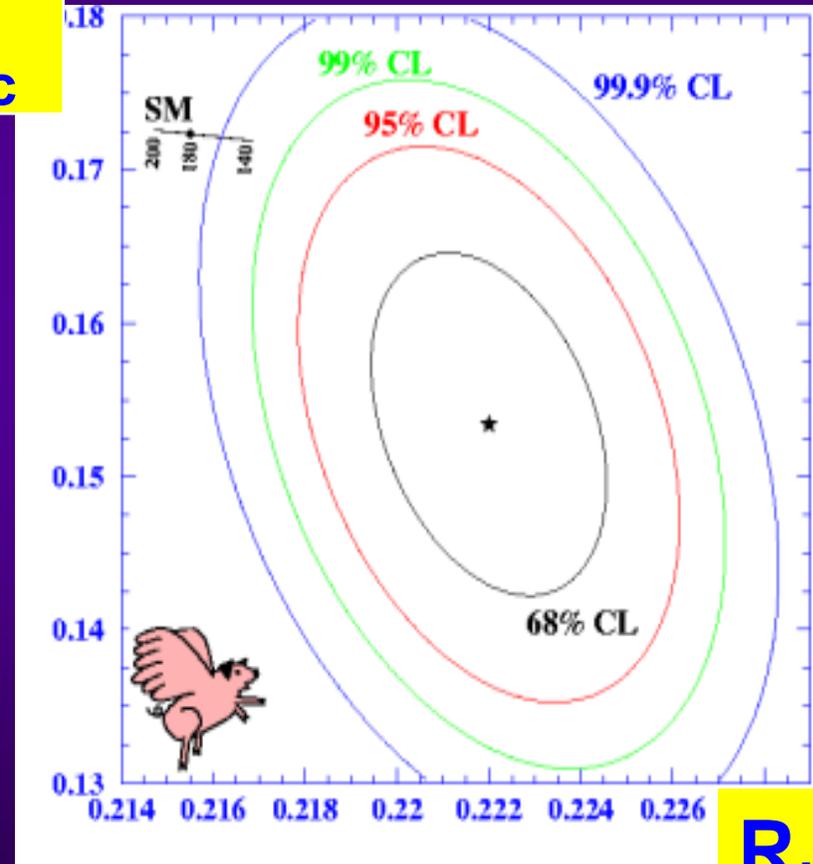
Expect SUSY @LEP2?



- ◆ LEP 1: excluded to $M_{\text{SUSY}} \approx M_Z / 2$
 - ◆ Always loopholes ...
- ◆ R_b high \Rightarrow low M_{SUSY}
- ◆ See $\tilde{\chi}^\pm$ at LEP1.5!

Brussels/Beijing 1995:

R_c



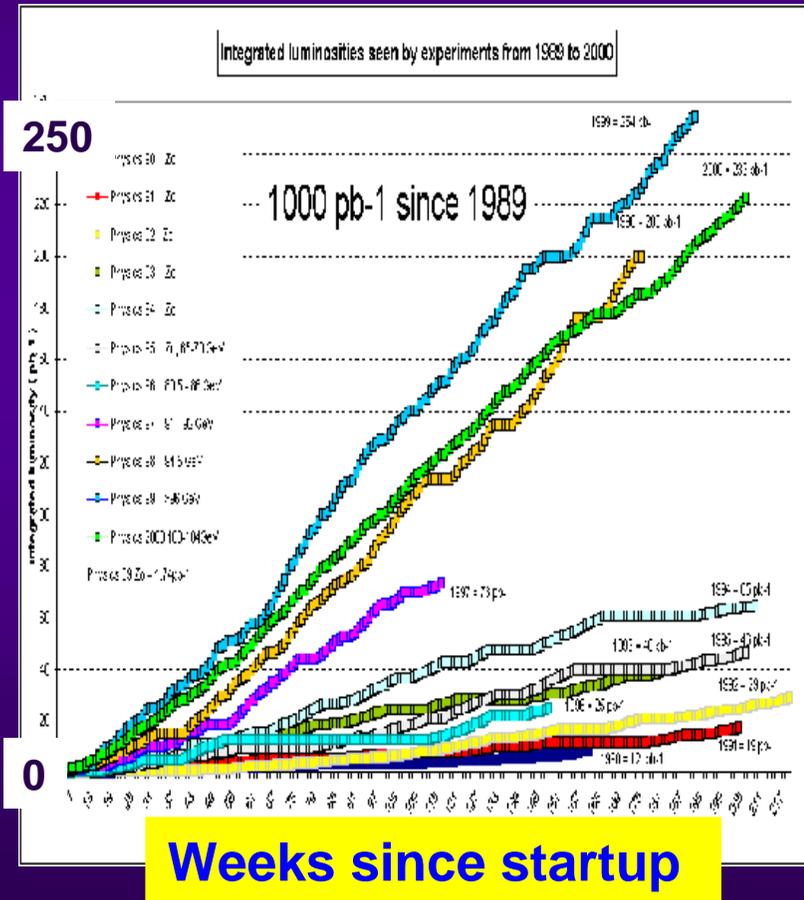
R_b



LEP Data Sets



Luminosity (pb⁻¹)



Stage	E _{CM} (GeV)	Year	Lumi/Expt (pb ⁻¹)
LEP 1	≈ M _Z	89-95	175
LEP1.5	130-140	1995	5
LEP 2	161	1996	10
	172	1996	10
	183	1997	55
	189	1998	180
	192-202	1999	230
	200-209	2000	220

LEP Combined: ≈ 2.6 fb⁻¹



Talk Outline

- ◆ (very) Brief overview
- ◆ Experimental Searches
 - ◆ Charginos in detail
 - ◆ Sleptons in detail
 - ◆ Summary of others
- ◆ SUSY Model-dependent constraints
 - ◆ GMSB – neutralinos, sleptons, GMSB parameters
 - ◆ mSUGRA / CMSSM – squarks, sleptons, LSP
- ◆ Conclusions and perspectives



(s)particles List



	0	1/2	1	3/2	2
		$\tilde{\gamma}$		γ	
h, H, A		\tilde{h}, \tilde{H}	$\left. \begin{array}{l} \tilde{\chi}^0_{1-4} \\ \tilde{Z} \end{array} \right\}$	Z^0	
		\tilde{Z}			
H^\pm		\tilde{H}^\pm	$\left. \begin{array}{l} \tilde{\chi}^\pm_{1,2} \\ \tilde{W}^\pm \end{array} \right\}$	W^\pm	
		\tilde{W}^\pm			
			\tilde{g}	g	
$\tilde{l}_{1,2}$	$\left\{ \begin{array}{l} \tilde{l}_{L,R} \\ \tilde{\nu}_L \end{array} \right.$		$l_{L,R}$		
			$\tilde{\nu}_L$	ν_L	
$\tilde{q}_{1,2}$	$\left\{ \begin{array}{l} \tilde{q}_{L,R} \end{array} \right.$		$q_{L,R}$		
			$\tilde{q}_{L,R}$		
			\tilde{G}	\tilde{G}	G

goldstino





Experimental Features of Different SUSY Models



Gravity Mediation with RPC

- ◆ Stable LSP
 - ◆ CDM candidate: $\tilde{\chi}^0$
- ◆ FCNC problems
 - ◆ Fixed in mSUGRA
- ◆ Decay chains to $\tilde{\chi}^0$
 - ◆ Missing Energy

... with RPV

- ◆ Unstable LSP
 - ◆ No CDM candidate
- ◆ FCNC problem worse
- ◆ Many new signatures

Gauge Mediation with RPC

- ◆ Light \tilde{G} LSP
 - ◆ Probably lose CDM cand.
- ◆ No severe FCNC problem
- ◆ NLSP $\tilde{\chi}^0$ or $\tilde{1}$
- ◆ Decay chains to NLSP then to \tilde{G}
 - ◆ Arbitrary suppression
 - ◆ Lifetime signatures



Now look for it...



(I) LEP SUSY search strategy



- ◆ **With stable, weakly interacting LSP:**
 - ◆ **Search for NLSP pair production**
 - ◆ **Relatively model independent cross-sections**
 - ◆ **Decay into LSP**
 - ◆ **Mass Reach: Beam Energy**
- ◆ **Backgrounds**
 - ◆ **Well understood “initial state” (ISR *etc.*)**
 - ◆ **Well modeled by MC simulation**
 - ◆ **Open triggers, wide coverage of all decay modes**



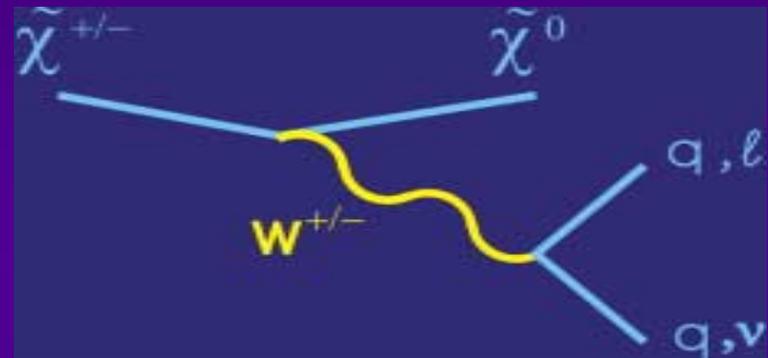
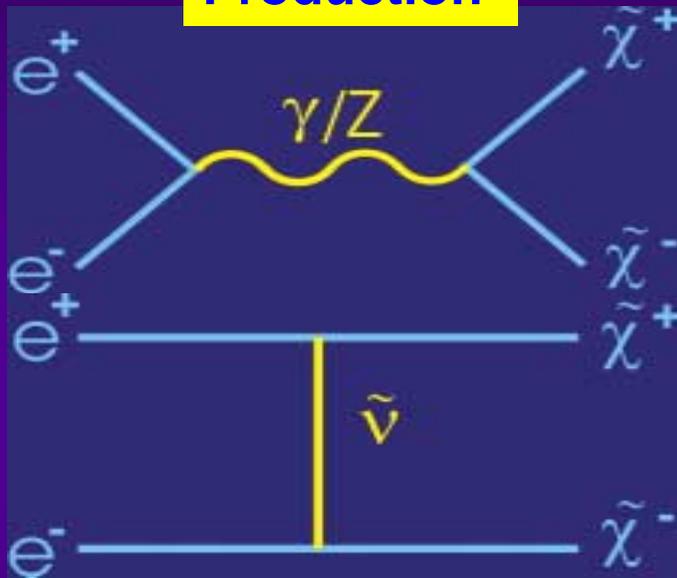
The prototype: $e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-$



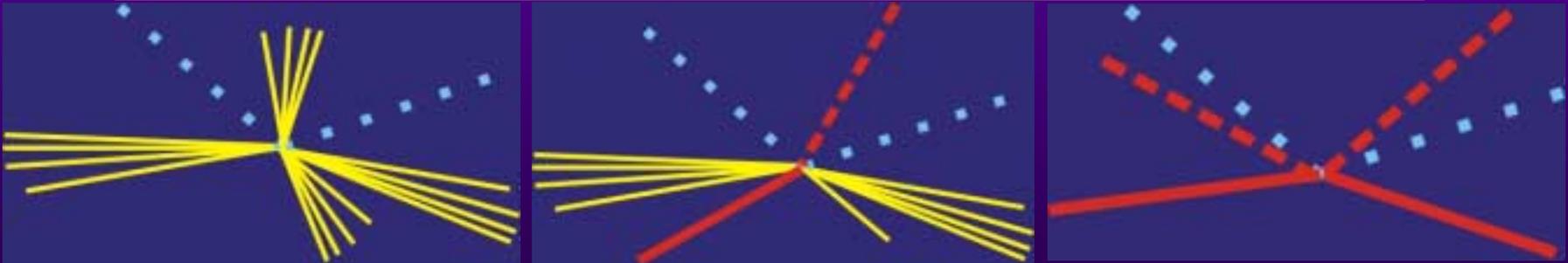
Standard “gravity mediated” modes

Production

Decay

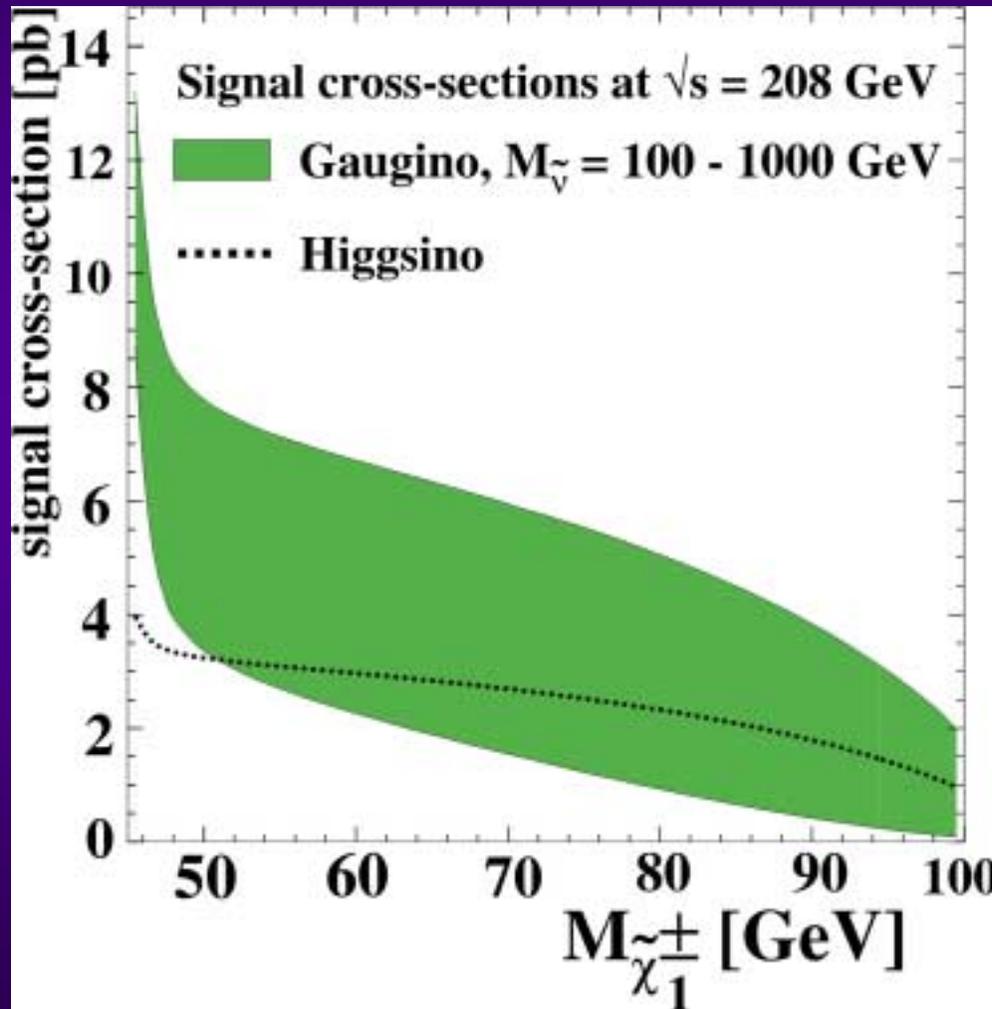


Basic SUSY Searches: Jets/Leptons with Missing Energy





CMSSM Charginos



- ◆ Large cross-section
 - ◆ Usually several pb even near the kinematic limit



Chargino: selection

eg: .OR. of L3 selections for

$E_{cm} = 205 - 208 \text{ GeV}$ ($\approx 200 \text{ pb}^{-1}$)

- ◆ Depends on E_{vis} and missing momentum
 - ◆ $\approx \Delta M = M(\tilde{\chi}^\pm) - M(\tilde{\chi}^0)$
 - ◆ More weakly: $M(\tilde{\chi}^\pm)$
- ◆ But can start with simple cuts
 - ◆ p_{TMiss}
 - ◆ $\cos \theta_{Miss}$
 - ◆ E_{Vis}

ΔM (GeV)	N_{Data}	N_{Exp}
10-30	55	47.0 ± 4.8
40-70	33	36.7 ± 3.6
>80	24	26.1 ± 1.6
All	112	109.7 ± 4.8

- ◆ No Excesses
- ◆ Efficiencies: 10-60% for $\Delta M > 5 \text{ GeV}$
- ◆ Cross-section $> 1 \text{ pb}$ easily excluded

\Rightarrow Are we done yet?



Could we have missed $\tilde{\chi}^+ \tilde{\chi}^-$



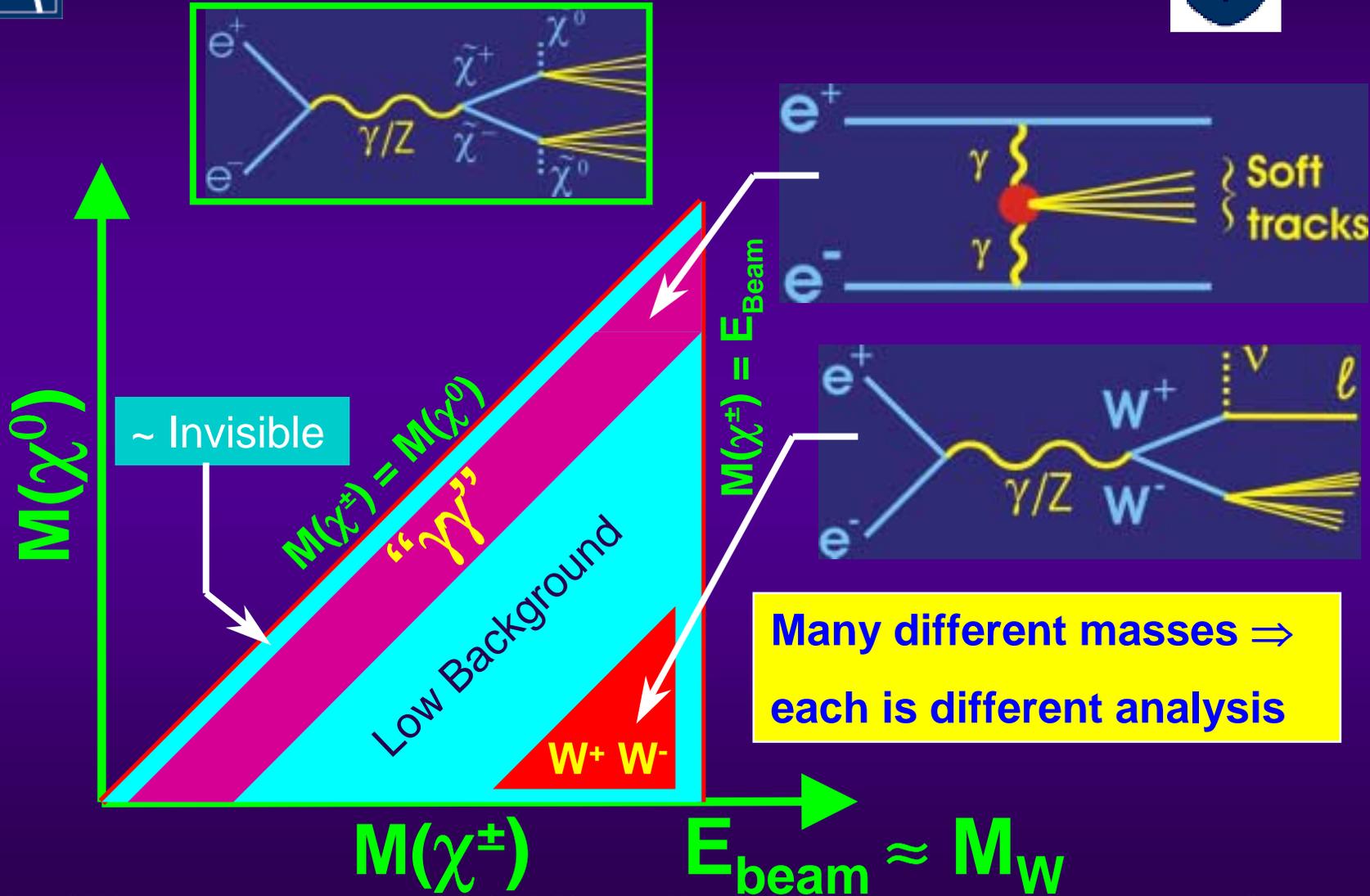
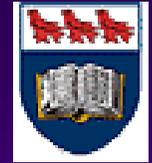
??

Possible *LOOPHOLES*

- ◆ **Smaller cross-sections?**
 - ◆ Design (much?) more sensitive selections
 - ◆ M , ΔM dependent cuts, likelihoods ...
- ◆ **Very small ΔM ? (< few GeV)**
 - ◆ “deep higgsino”: $\mu \ll M_2$
 - ◆ Gaugino but without GUT unification
 - ◆ AMSB ...
 - ◆ **Harder to detect, may have lifetime**
- ◆ **Or maybe other decay modes missed**
 - ◆ **RPV (especially no missing energy)**
 - ◆ **GMSB (extra photons or leptons)**



$\tilde{\chi}^+ \tilde{\chi}^-$: Refined selections \Rightarrow Target reducible backgrounds





$\tilde{\chi}^+ \tilde{\chi}^-$: Likelihoods *etc.*

- ◆ Full $M, \Delta M$ dependent likelihood *difficult ...*

Quantity	Bin	N° Bins
M	5 GeV	20
ΔM	1 GeV	100
E_{CM}	≈ 1 GeV	≈ 10
N_{MC} / Bin		10000
Total MC Events		2×10^8

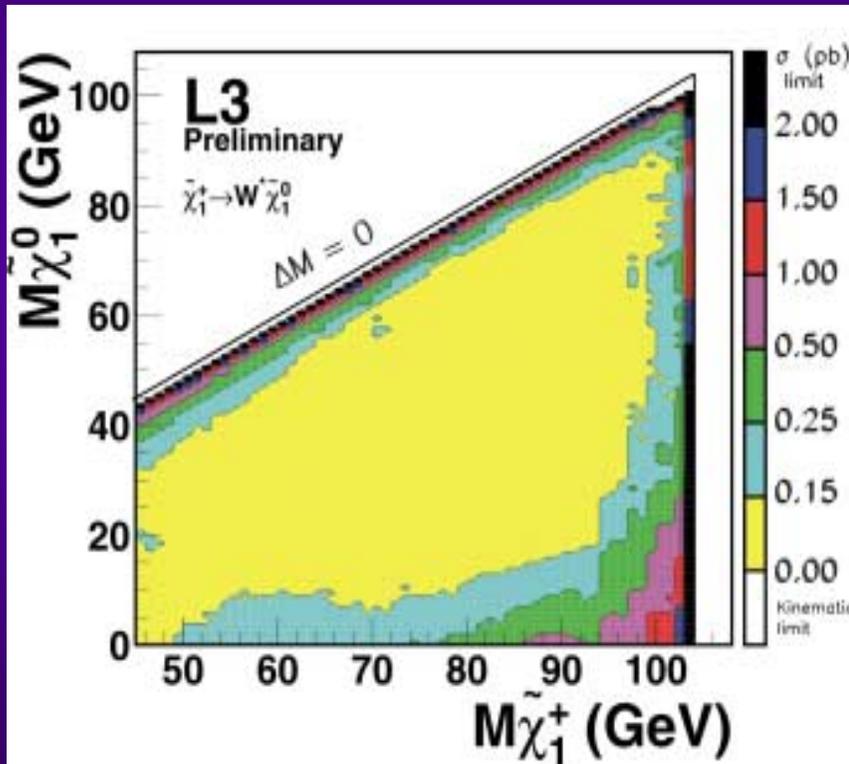
- ◆ Few $\times 10^8$ MC events barely possible
- ◆ Can revert to simpler
 - ◆ ΔM regions (L3, Delphi, OPAL)
 - ◆ “sliding cuts” (ALEPH)
- ◆ For Likelihood, use MCgrid + interpolation
 - ◆ Toy MC calibrated with full MC (DELPHI)
 - ◆ Likelihood histogram interpolation (OPAL)



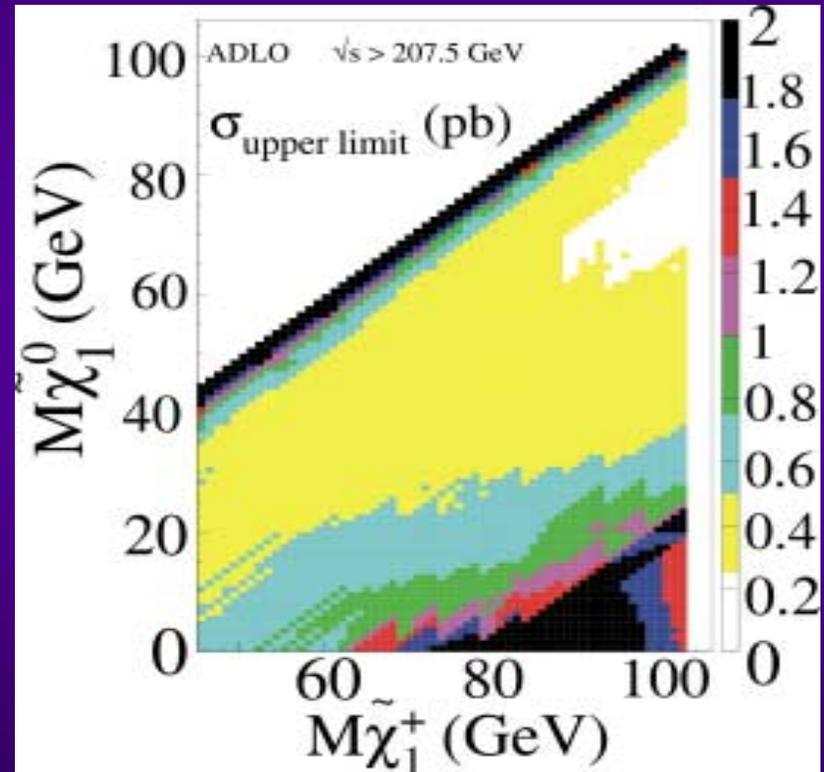
$\tilde{\chi}^+ \tilde{\chi}^-$: Search Results



- ◆ L3, Full LEP II data sets:
- ◆ ADLO 35.2 pb⁻¹
- ◆ Ecm > 207.5 GeV



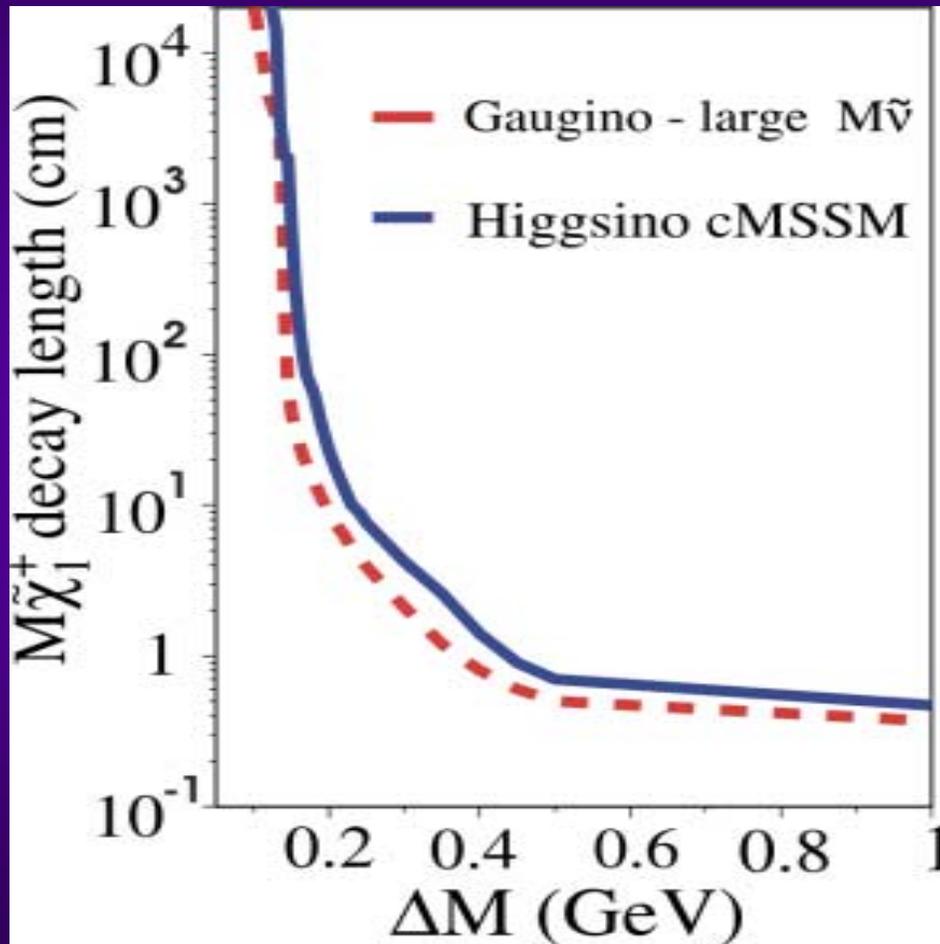
$\sigma < 0.1 \text{ pb}$



$\sigma < 1 \text{ pb @ } 208 \text{ GeV}$



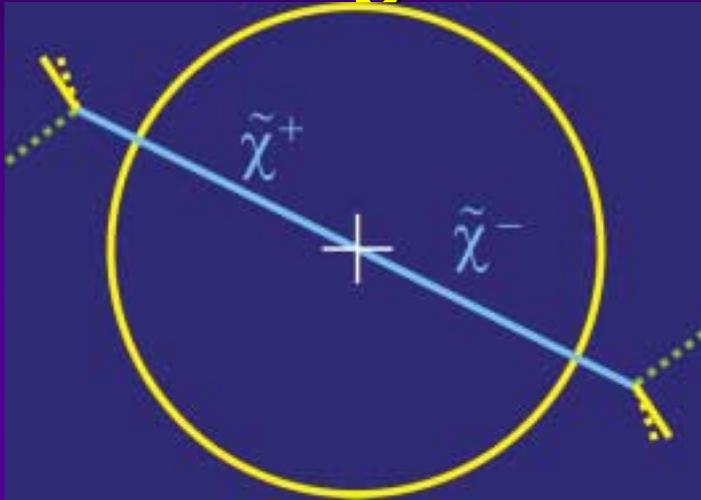
$\tilde{\chi}^+ \tilde{\chi}^-$: Lifetime for small ΔM



- ◆ $\Delta M < M_\pi$:
 - ◆ \approx **Stable**
- ◆ $\Delta M > 500$ MeV:
 - ◆ **Lifetime small**



$\tilde{\chi}^+ \tilde{\chi}^-$: very small $\Delta M < M_\pi$: Long Lived Charged Particles

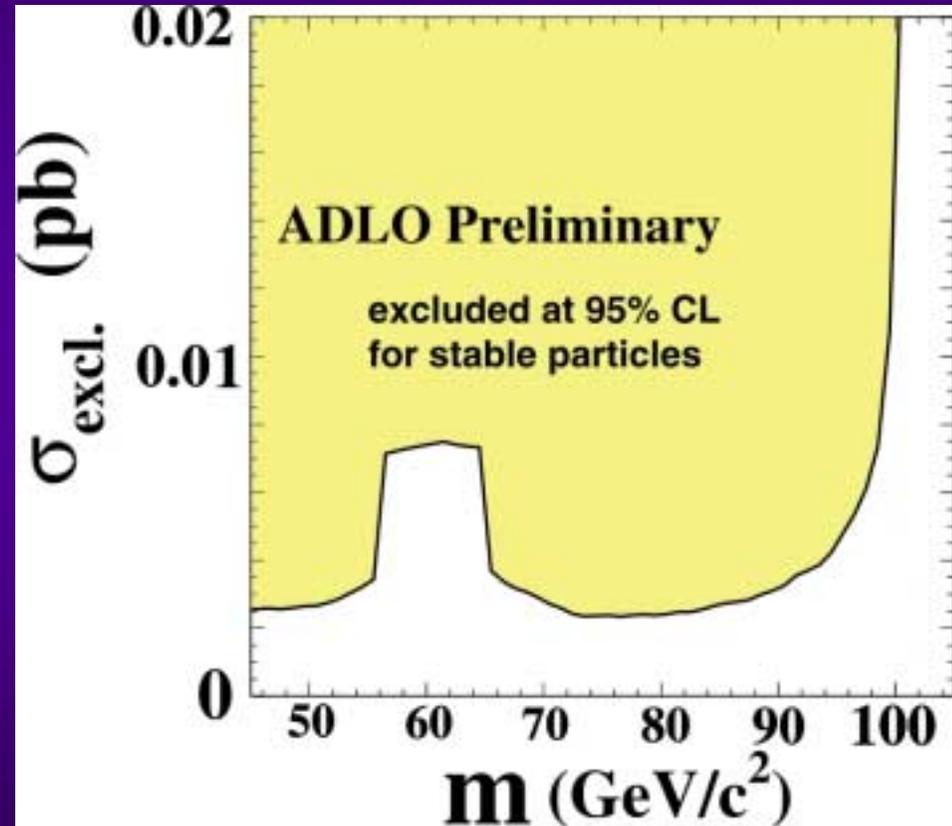


Heavy “Stable” Charged Particles

- Kinematics (p,E)
- dE/dX
- DELPHI: RICH

Almost background free

No Evidence

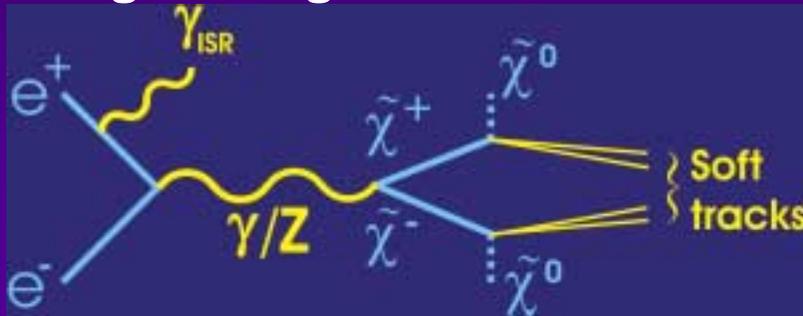




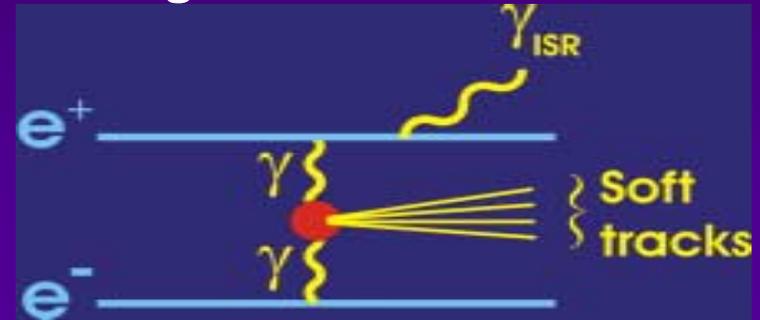
$\tilde{\chi}^{\pm}: M_{\pi} < \Delta M < 5 \text{ GeV} \Rightarrow \text{ISR}$



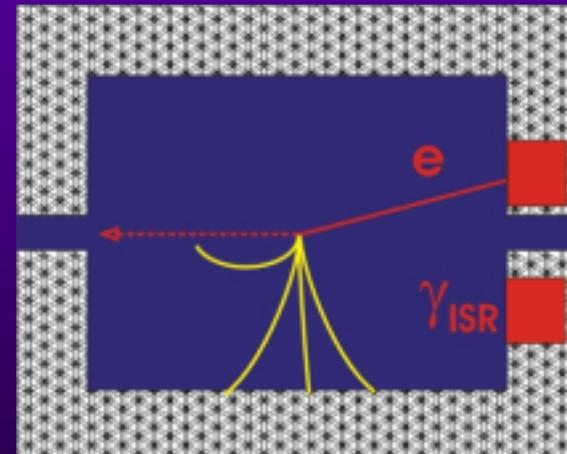
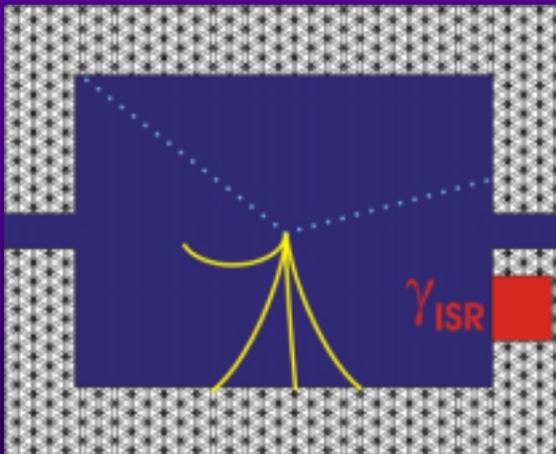
Signal: Big $\sigma \sim$ Observable



Background: Enormous σ !



Analysis: tag γ with soft tracks, veto e



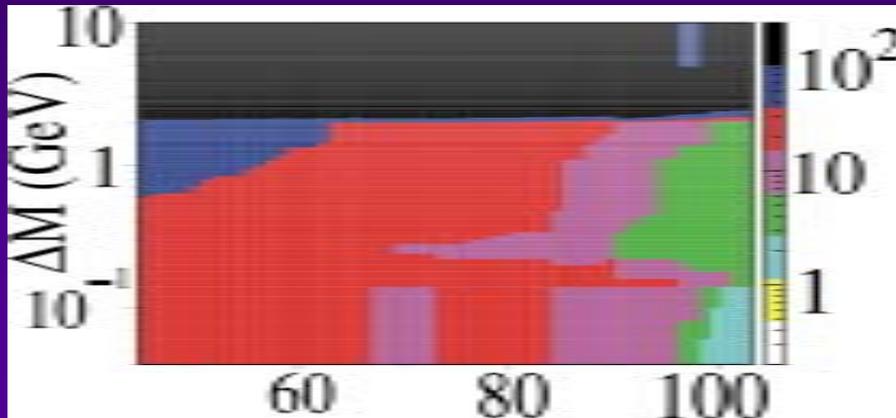


Small ΔM : Higgsino Results

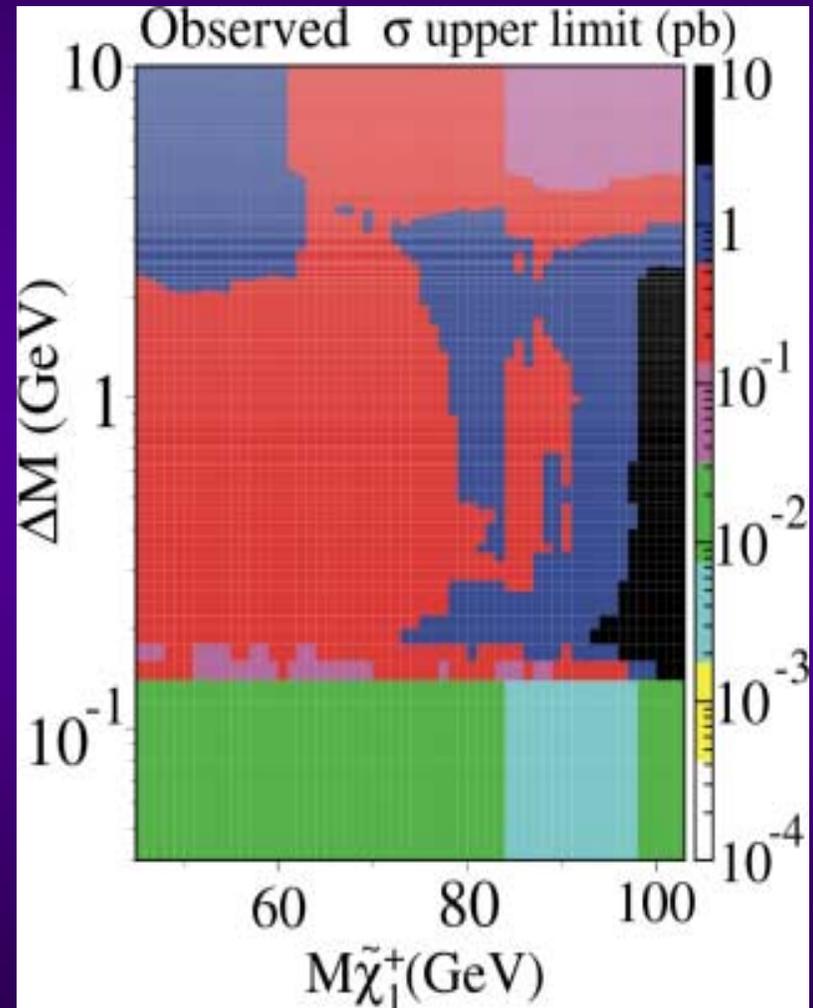
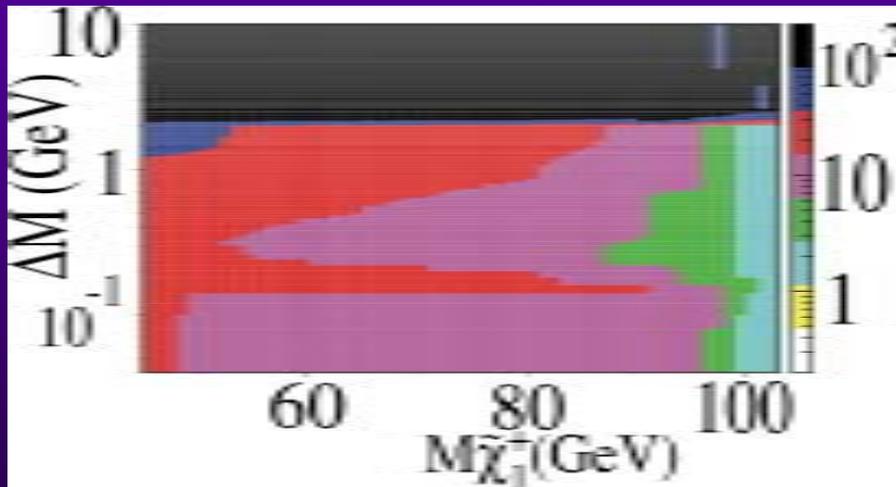
ADLO Preliminary



ADLO Events Observed:



ADLO Events Expected:

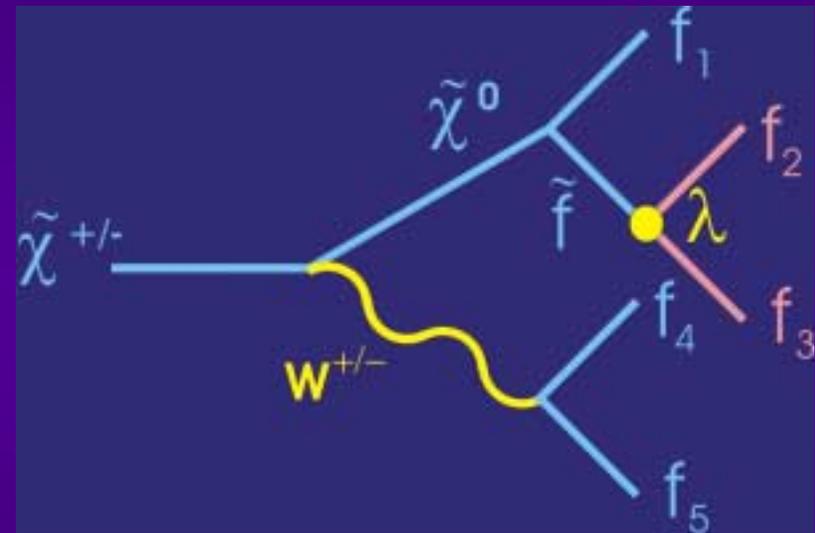
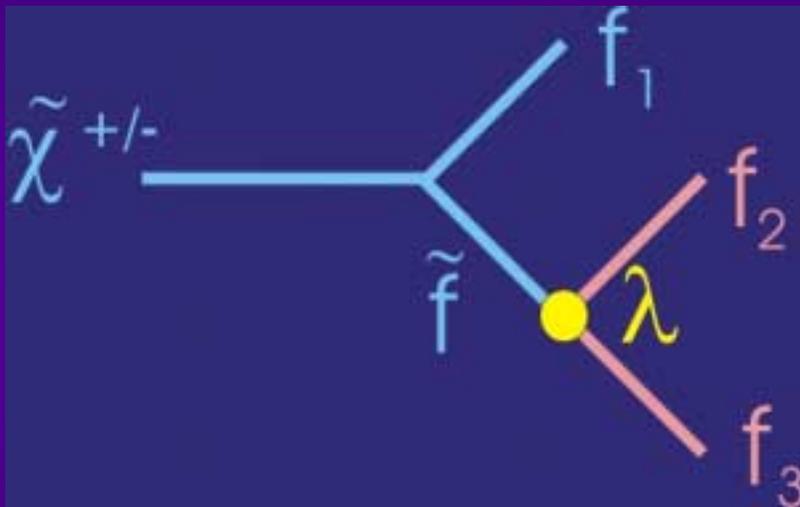




$\tilde{\chi}^+ \tilde{\chi}^-$: with RPV?

DIRECT RPV

INDIRECT RPV



6 fermion final states

10 (!) fermion final states

\Rightarrow Low background, but many analyses needed!



RPV $\tilde{\chi}^+ \tilde{\chi}^-$: LLE results



General, open selections:

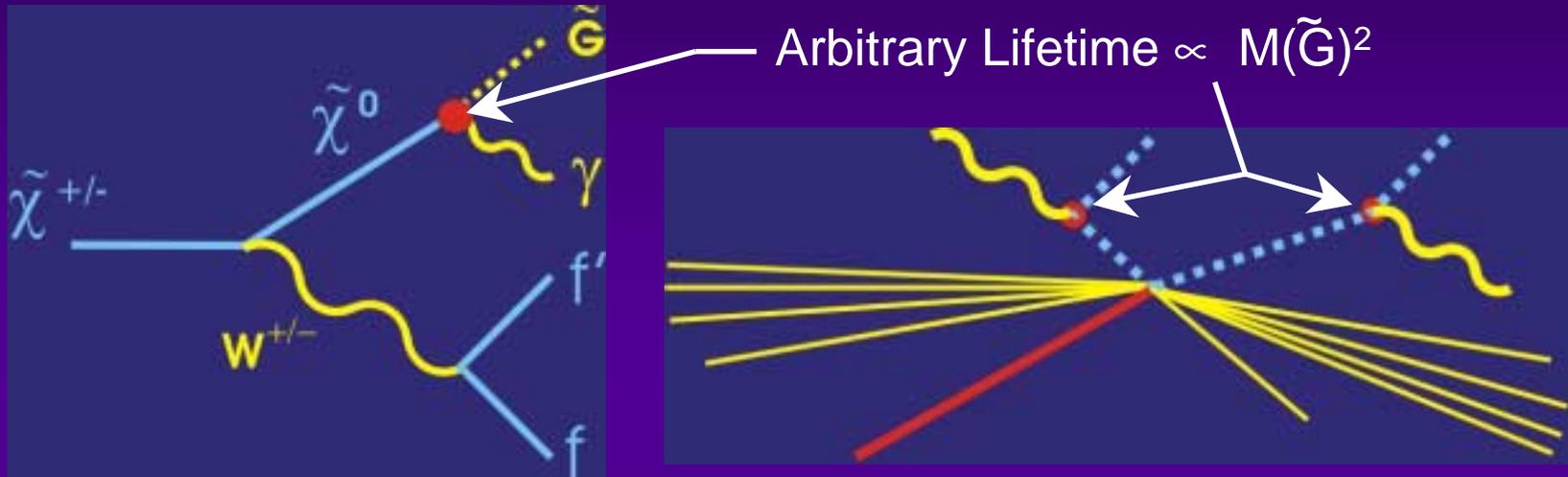
eg: λ_{133} (“LLE”) L3 192—208 GeV:

Process	Channel	Data	Bkg
direct	≥ 4 l+jets + E_{miss}	40	37
Indirect	2 or 4 l + E_{miss}	10	10.1

- ◆ Efficiency:
 - ◆ 20 — 40%
- ◆ Max cross-section:
 - ◆ 0.05 — 0.2 pb 95% C.L.



$\tilde{\chi}^+ \tilde{\chi}^-$: with GMSB $\tilde{\chi}^0$ NLSP

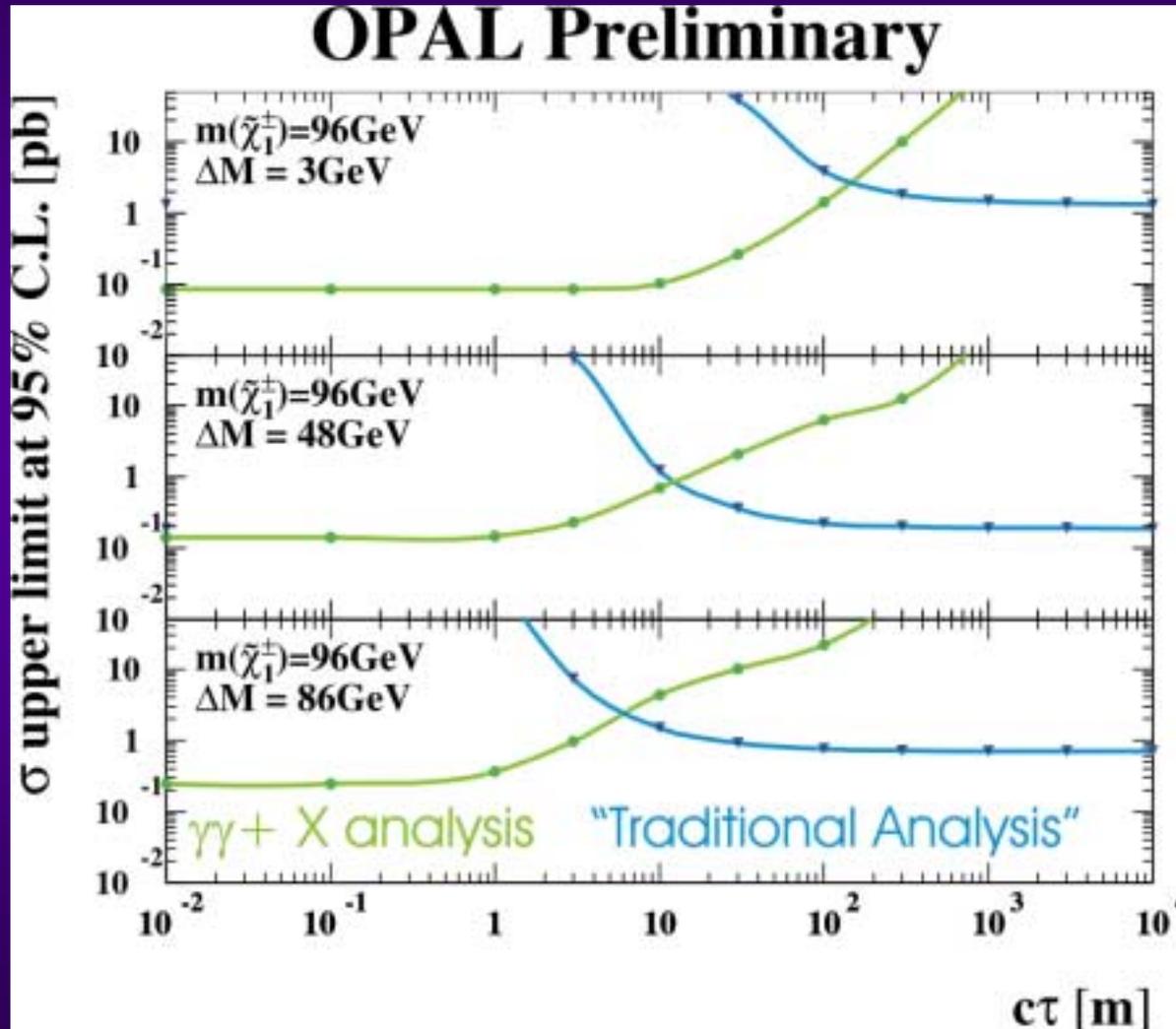


- 1) Long $\tilde{\chi}^0$ lifetimes: “Traditional” search
- 2) Short $\tilde{\chi}^0$ lifetimes: $\tilde{\chi}^+ \tilde{\chi}^-$ with γ 's
- 3) All lifetimes: (1) .OR. (2)

\Rightarrow Overlap tricky to get right !



$\tilde{\chi}^+ \tilde{\chi}^-$: GMSB $\tilde{\chi}^0$ NLSP Results

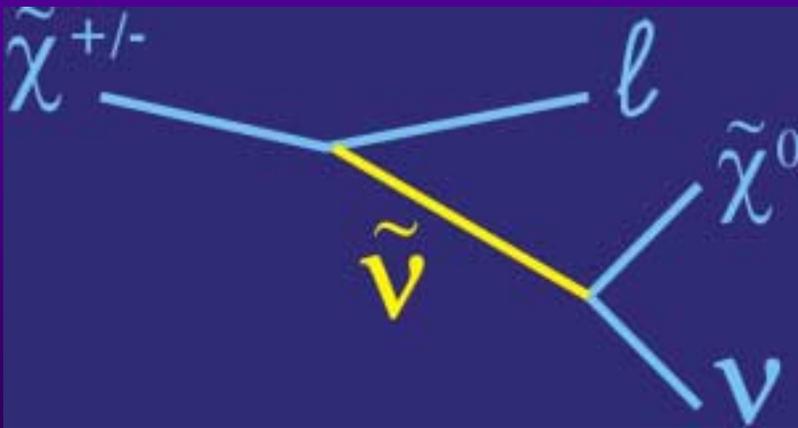
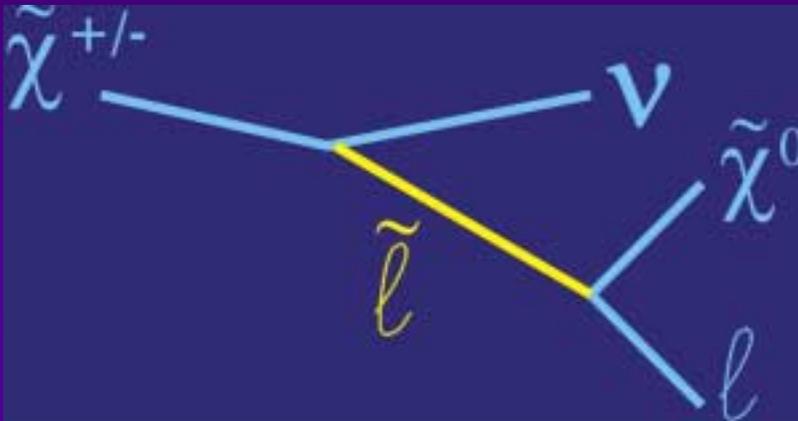




$\tilde{\chi}^+ \tilde{\chi}^-$ basic loophole:



Light sleptons \approx invisible $\tilde{\chi}^\pm$ decays

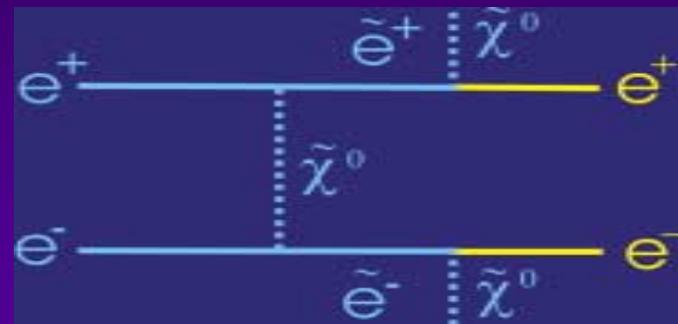
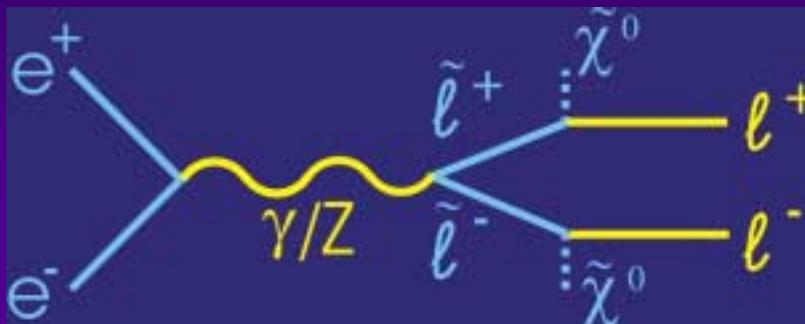


- ◆ Reduced cross-section
- ◆ 2 body leptonic decays
- ◆ Can be \approx invisible
 - ◆ $M(\tilde{l}) = M(\tilde{\chi}_1^0)$
 - ◆ $M(\tilde{\nu}) = M(\tilde{\chi}^\pm)$
- ◆ Can try tricks but ...
- ◆ **Slepton** search imperative



$$e^+e^- \rightarrow \tilde{l}^+ \tilde{l}^-$$

Standard “gravity mediated” modes

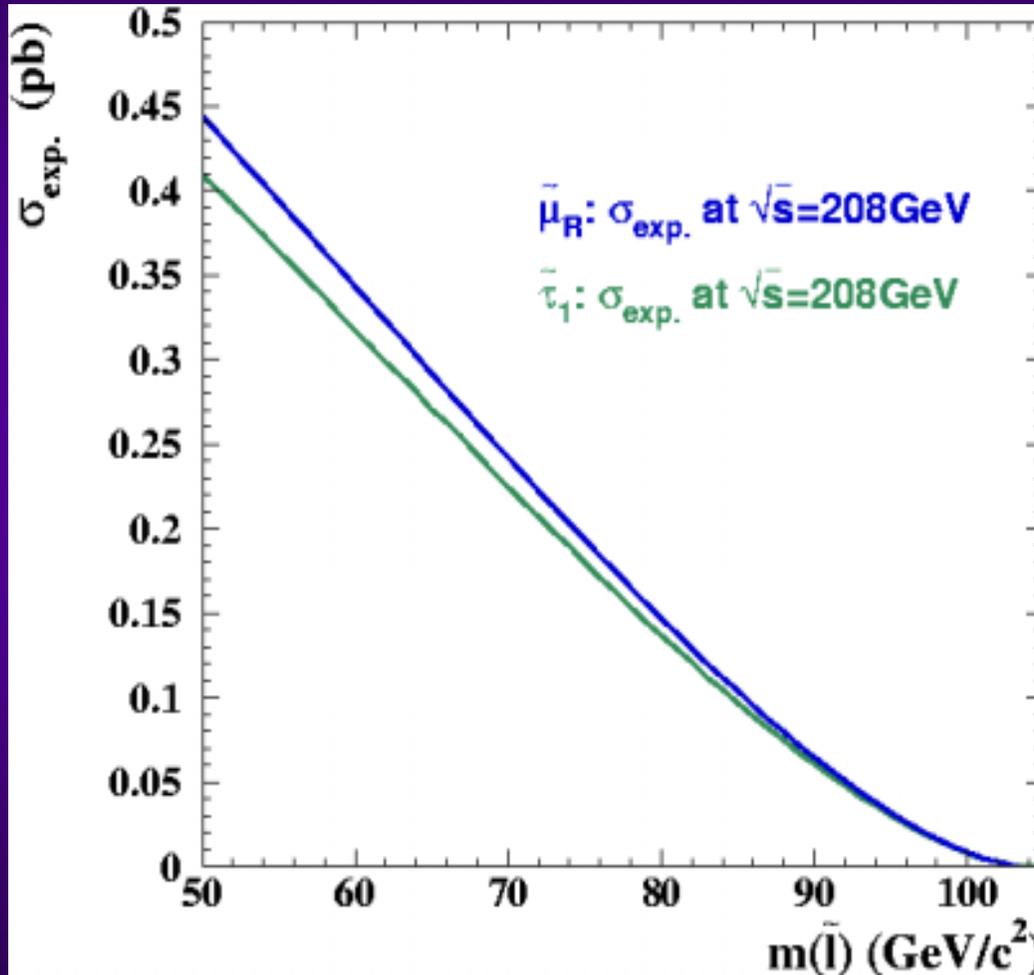


- ◆ “Acoplanar Leptons”
 - ◆ $l^+ l^- + E_{\text{miss}}$
- ◆ Similar to Charginos with leptonic decays
 - ◆ \Rightarrow **Can recycle ...**
- ◆ s-channel cross-sections rather model independent

- ◆ **Selectrons:**
 - ◆ **Also t-channel**
 - ◆ More forward peaked
 - ◆ Usually higher cross-section
 - ◆ **Can also be smaller**



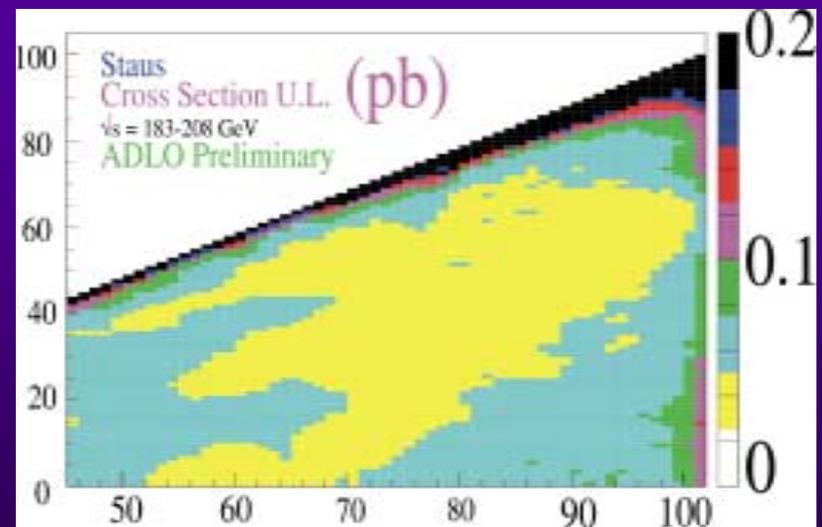
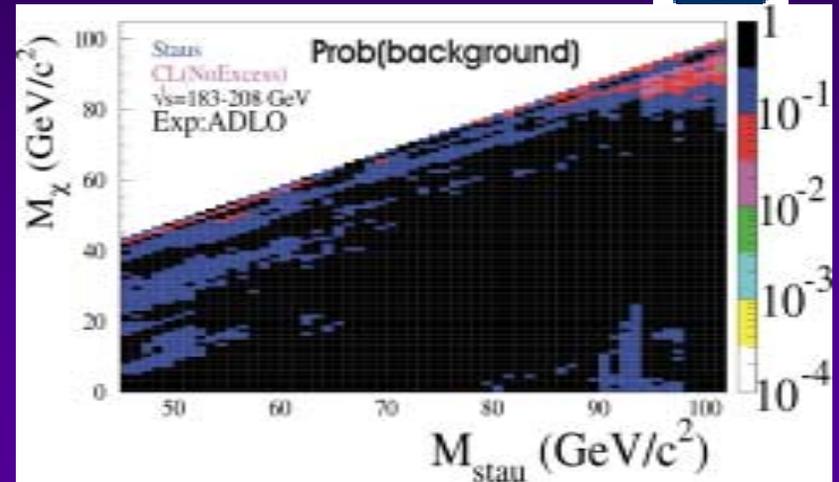
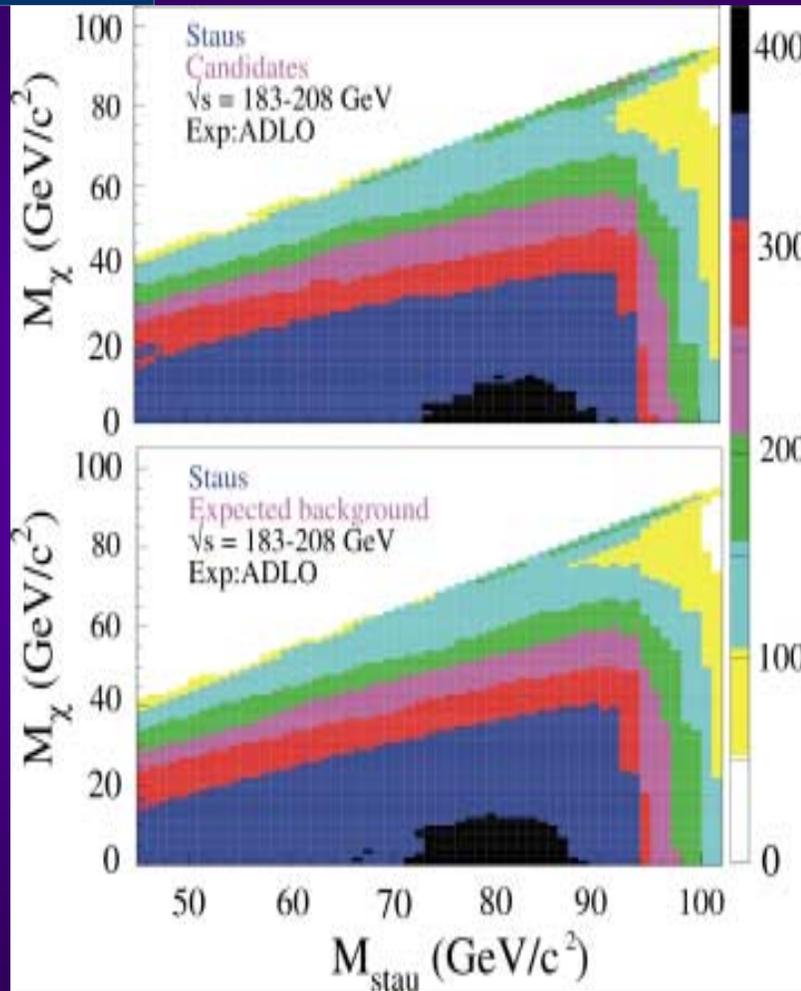
$e^+e^- \rightarrow \tilde{l}^+ \tilde{l}^-$: cross-sections



- ◆ **Smuons:**
 - ◆ Almost model-independent
- ◆ **Staus:**
 - ◆ Mixing can decouple from Z
- ◆ **Selectrons:**
 - ◆ t-channel makes cross-section very model-dependent



eg: $e^+e^- \rightarrow \tilde{\tau}^+ \tilde{\tau}^-$: results



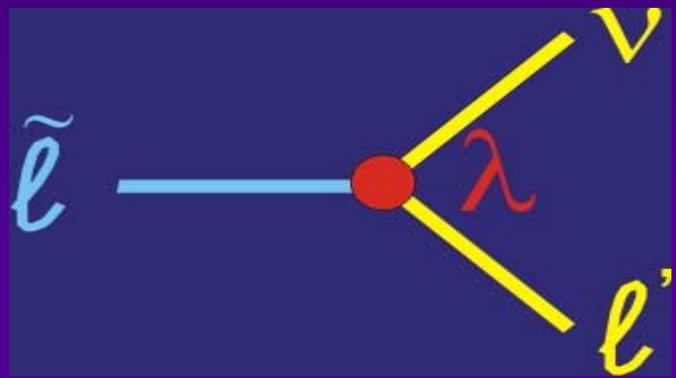
M_{STAU} (GeV)



$e^+e^- \rightarrow \tilde{l}^+ \tilde{l}^-$: with RPV

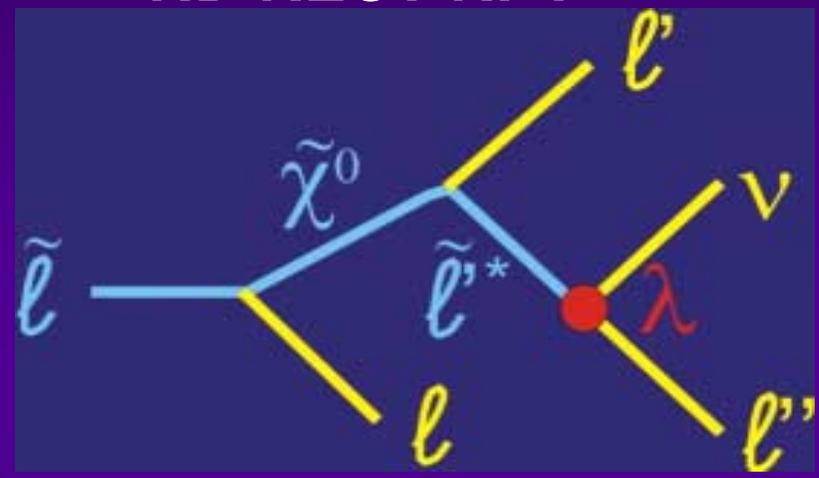


DIRECT RPV



- ◆ $l^+ l^- + E_{\text{miss}}$
- ◆ Recycle other channels ...

INDIRECT RPV



- ◆ $6 l + E_{\text{miss}}$
- ◆ Very low background

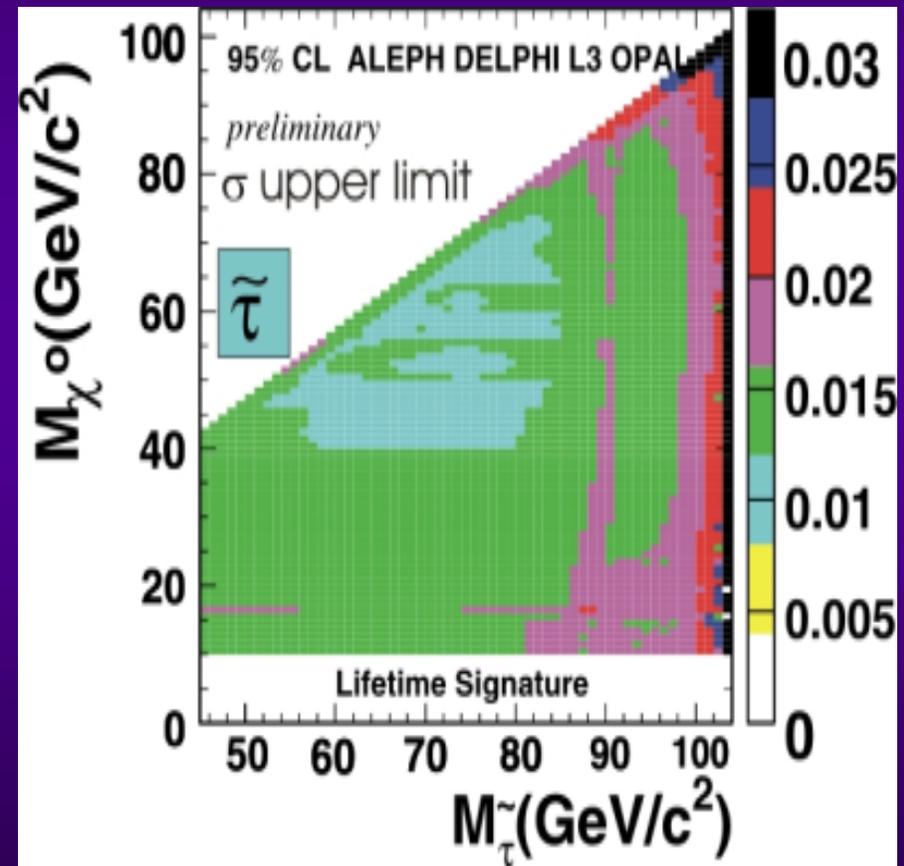
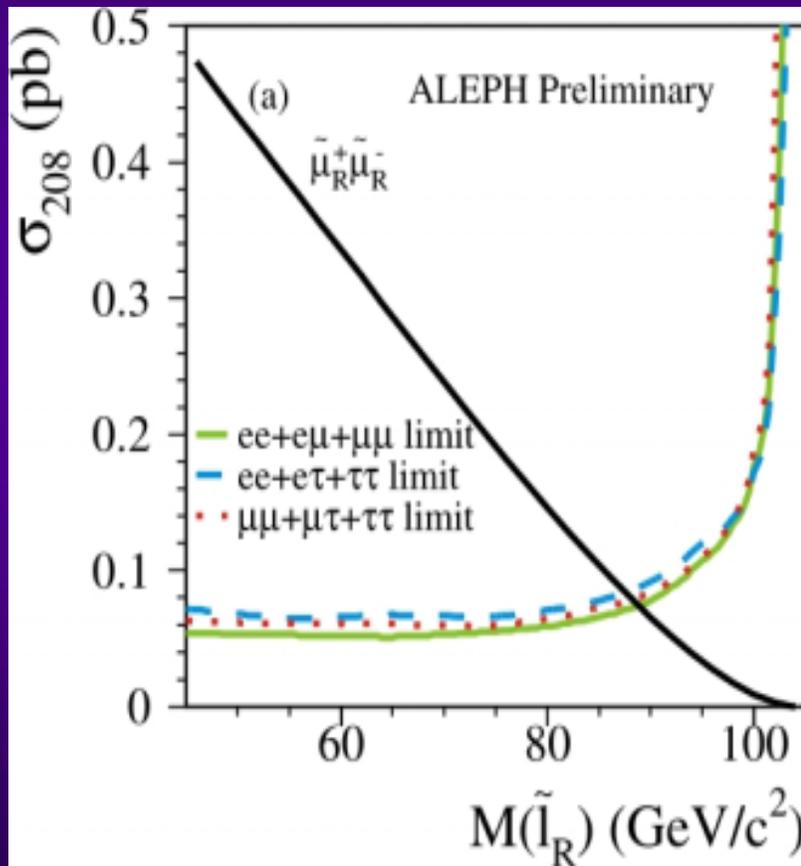


$\tilde{l}^+ \tilde{l}^-$ with RPV: Results



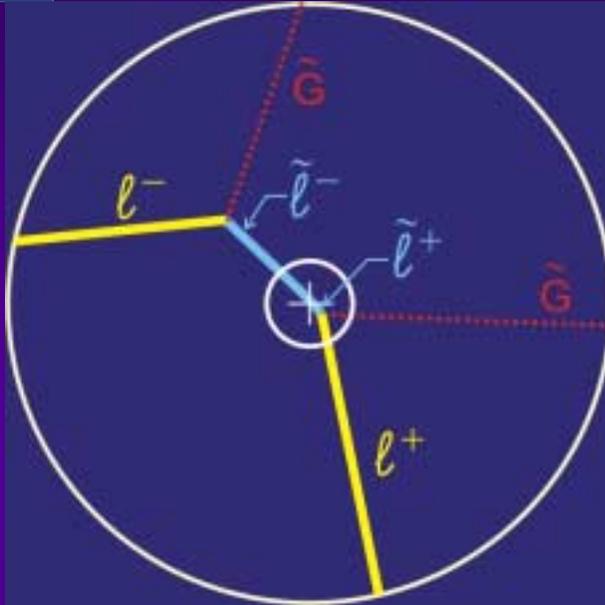
Direct Decays (ALEPH)

Indirect Decays (ADLO)





GMSB $\tilde{l}^+ \tilde{l}^-$: Lifetime



- ◆ Many overlapping channels
 - ◆ Kinks, stable: low backgrounds
 - ◆ Kinks, Large IP: unmodeled bkg.
- ◆ Must consider (large) overlaps in analysis

- 1) Very Short Lifetime
⇒ Tracks from origin
- 2) Short Lifetime
⇒ Large Impact Parameter

- 3) Medium Lifetime
⇒ Kinked Tracks
- 4) Long Lifetime
⇒ Heavy Stable Charged

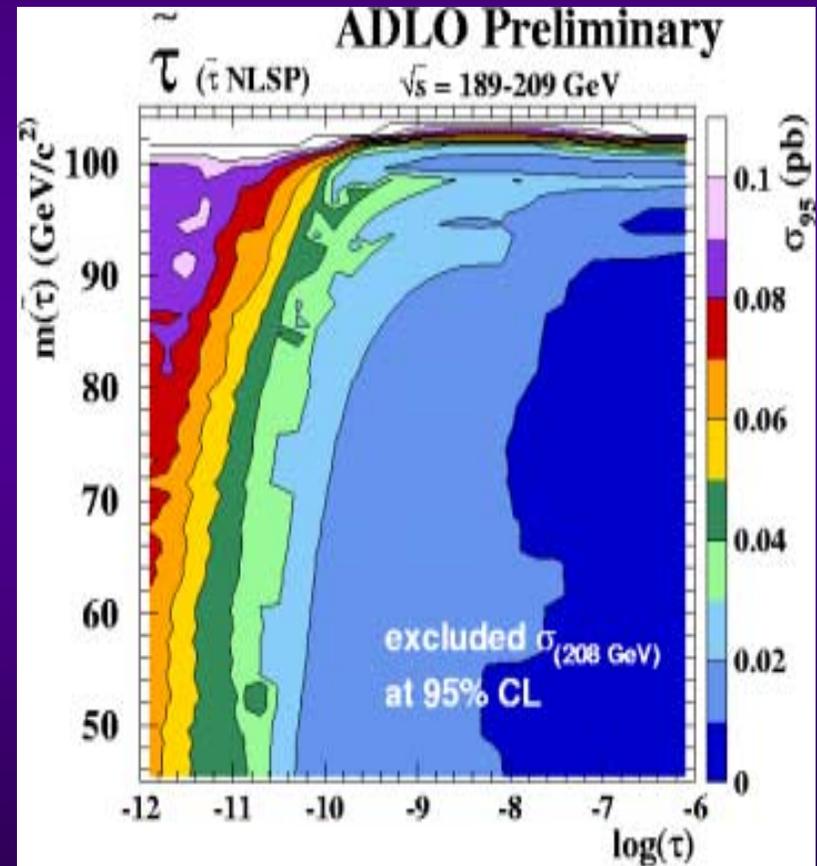
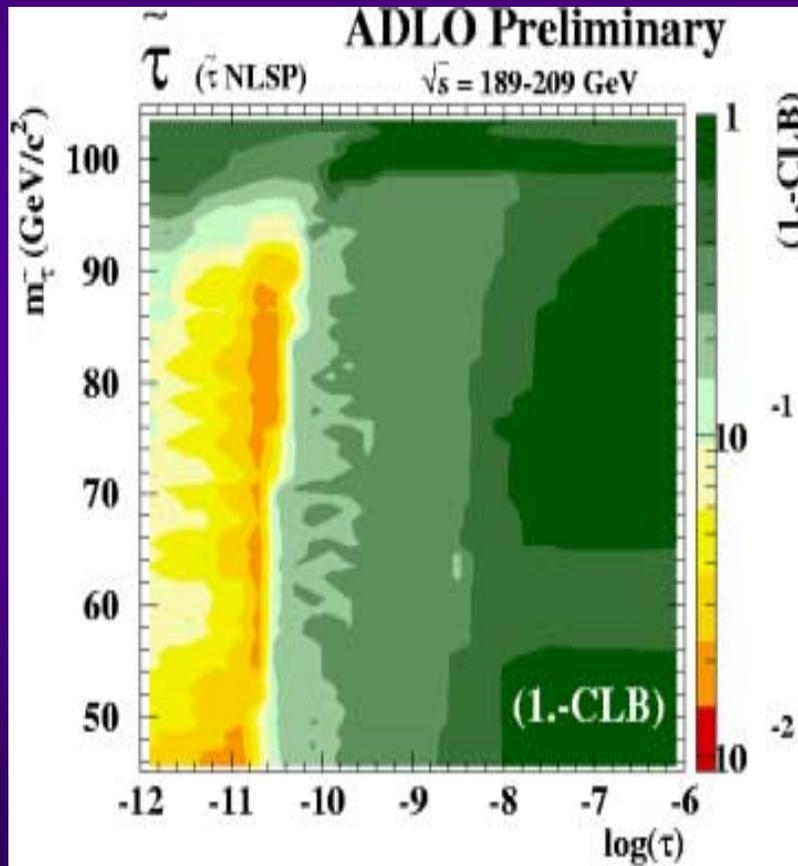


GMSB $\tilde{\tau}^+ \tilde{\tau}^-$: Lifetime



1 – Prob(background)

Excluded Cross-section





LEP SUSY Channels



- ◆ $\tilde{G} \gamma, \tilde{G} \tilde{\chi}^0_1$
 - ◆ Superlight gravitino
- ◆ $\tilde{\chi}^0_1 \tilde{\chi}^0_1$
 - ◆ GMSB, RPV
- ◆ $\tilde{\chi}^+_1 \tilde{\chi}^-_1$
 - ◆ All types of SUSY
- ◆ $\tilde{\chi}^0_1 \tilde{\chi}^0_2, \tilde{\chi}^0_2 \tilde{\chi}^0_2, \tilde{\chi}^+_2 \tilde{\chi}^-_2 \dots$
 - ◆ Cascades can plug exclusion holes
- ◆ Sgoldstinos, AMSB, light gluinos, ...
 - ◆ A bit on the margins ...

- ◆ $\tilde{l}^+_1 \tilde{l}^-_1$
 - ◆ All types of SUSY
- ◆ $\tilde{l}^+_1 \tilde{l}^-_2, \tilde{l}^+_2 \tilde{l}^-_2$
 - ◆ Cascades for exclusion holes
- ◆ $\tilde{t}_1 \tilde{t}_1, \tilde{b}_1 \tilde{b}_1$
 - ◆ Large stop/sbottom mixing
 - ◆ Can probe to small ΔM

No significant excesses

(sigh)



(II) Constraints on SUSY Models



◆ GMSB

- ◆ $\tilde{G}, \tilde{\chi}^0, \tilde{I}_R, \tilde{\tau}_1 \dots$ *short, long* or *all* lifetime
- ◆ $\Lambda, M, N, \tan\beta$

◆ *mSUGRA / CMSSM*

- ◆ $\tilde{q}, \tilde{l}, \tilde{\chi}^\pm$
- ◆ M_2 vs. μ for different $\tan\beta$
- ◆ $\tilde{\chi}^0$ LSP (CDM candidate)



Main Frameworks



“General” MSSM

M_1, M_2, M_3	Gaugino masses	} SM + 105 (+45 RPV) → FCNC, ...
$m_{\tilde{f}}$	Sfermion masses	
$v, \tan\beta, m_A, \mu$	Higgs(ino) mass/mixing	
A_U, A_D, A_L	Trilinear sfermion/higgs couplings	

mSUGRA+ (gravity mediation)

M_2	(or $m_{1/2}$) Get M_1, M_3 from GUT	} “LEP” CMSSM
m_0	Scalar mass at GUT scale	
$\tan\beta$	v_u/v_d , ratio of higgs vevs	
A_0	Common trilinear coupling	
$\text{sign}(\mu)$	Sign(Higgs mixing param)	
μ	Higgs mixing param	
M_A	Higgs mass (use $M_{H\pm}$ CPV)	

SM + 4 ½ (or 6) parameters

GMSB (gauge mediation)

F	(or M_G) SUSY Breaking scale
Λ	Sparticle mass scale
M	Messenger mass
N	Number messenger sets
$\tan\beta$	v_u/v_d , ratio of higgs vevs
$\text{sign}(\mu)$	Sign(Higgs mixing param)

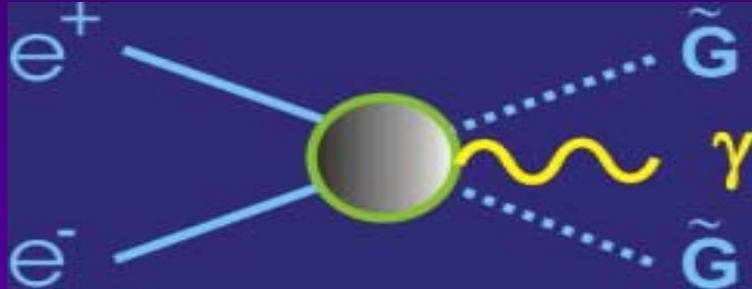
SM + 5 ½ parameters



\tilde{G} : Absolute mass limit



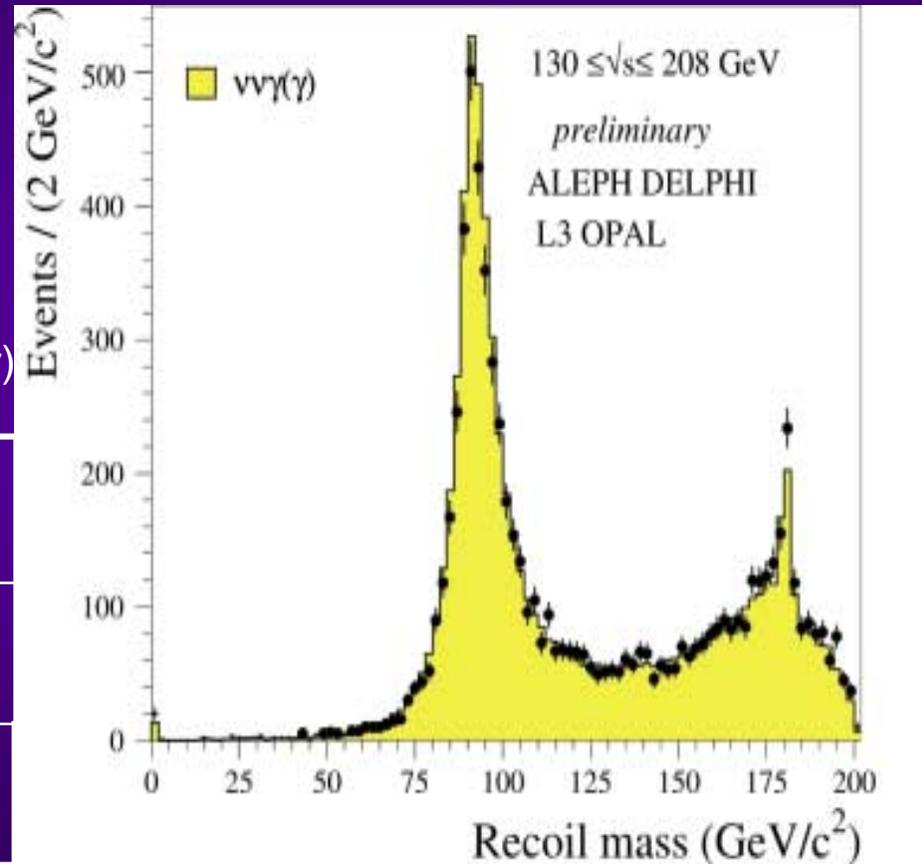
◆ Photon with Emiss



(cross-sections from Brignole, Feruglio, Zwirner)

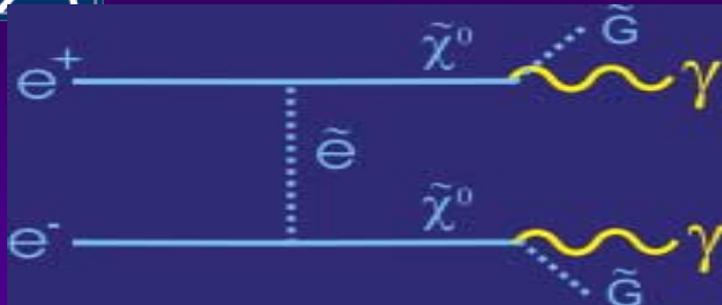
Expt	$M_{\text{grav}} >$ (95%CL)	$\sqrt{F} >$
DELPHI	$1.12 \times 10^{-5} \text{ eV}$	217 GeV
L3 (189)	$8.9 \times 10^{-6} \text{ eV}$	192 GeV

(Tevatron I has similar sensitivity)

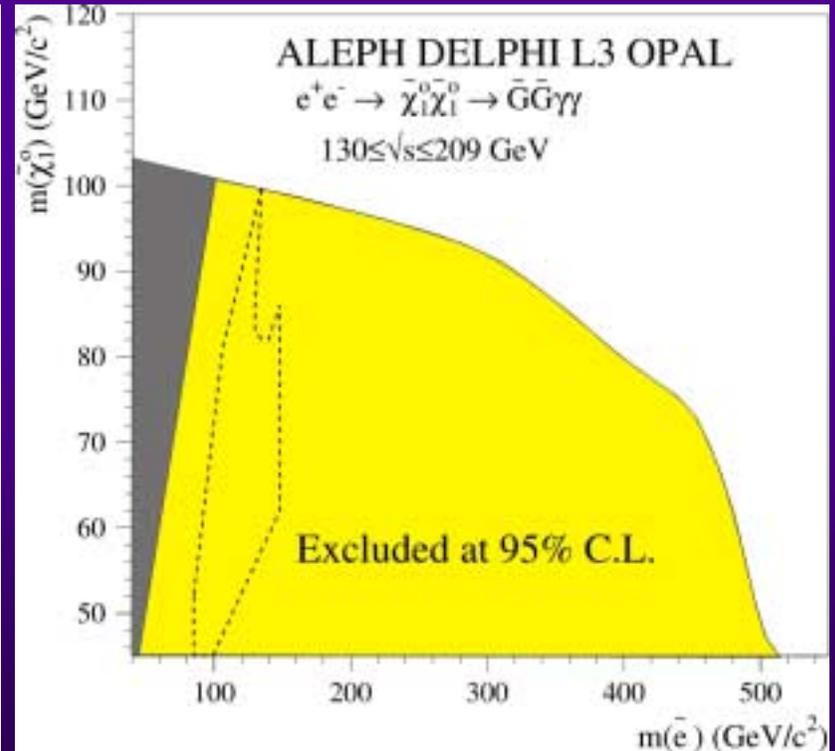
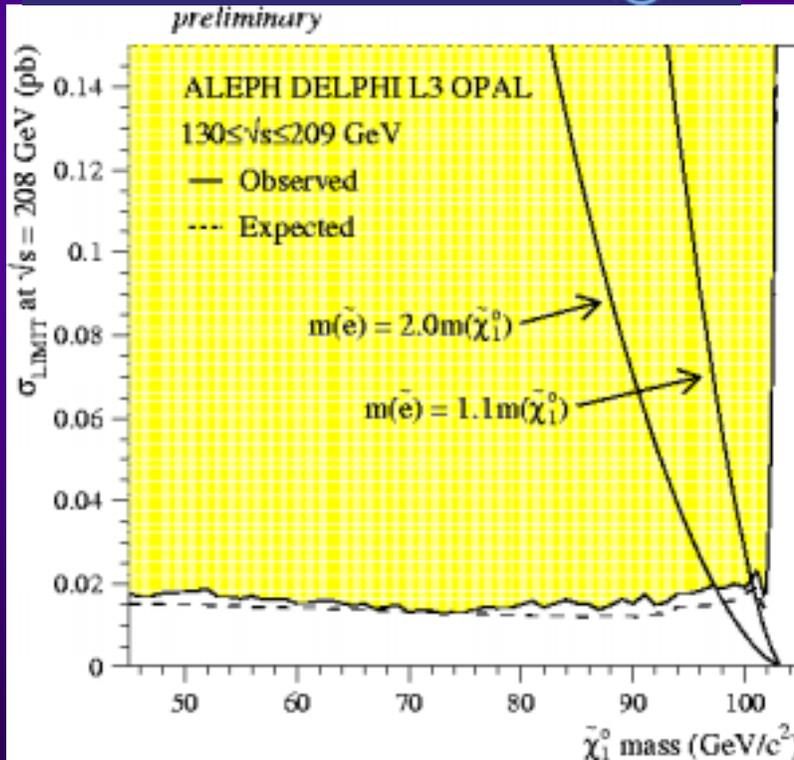




GMSB: $\tilde{\chi}^0$ NLSP $\gamma\gamma$ + Emiss

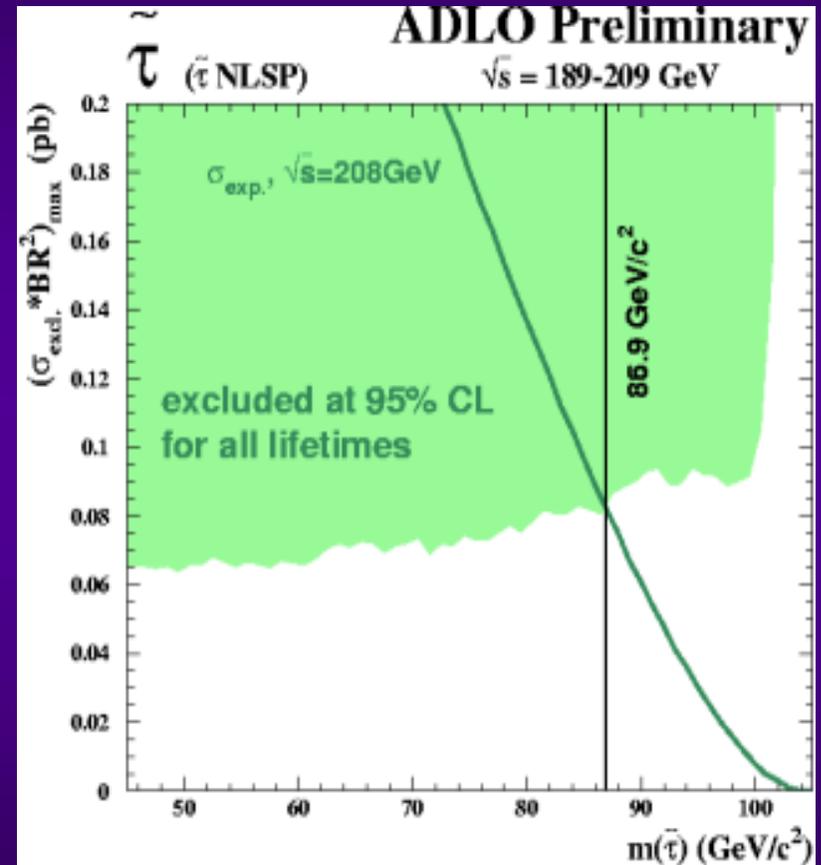
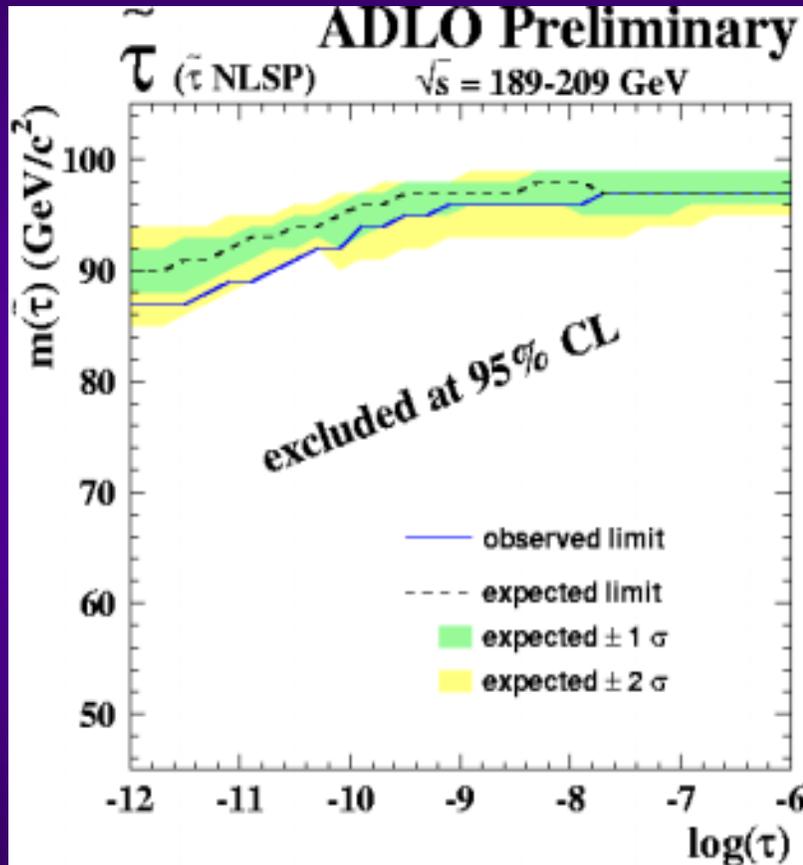


- ◆ Dominant for χ^0 NLSP and short lifetimes
- ◆ Inspired by CDF $e\bar{e}\gamma\gamma$ event ...





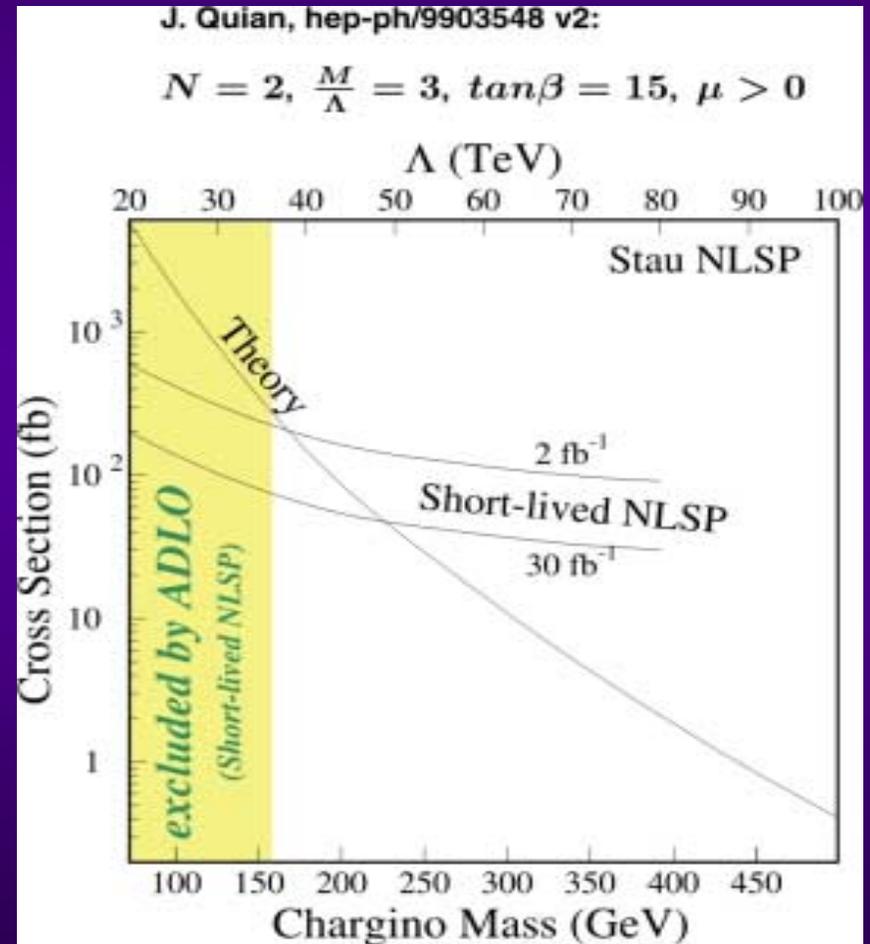
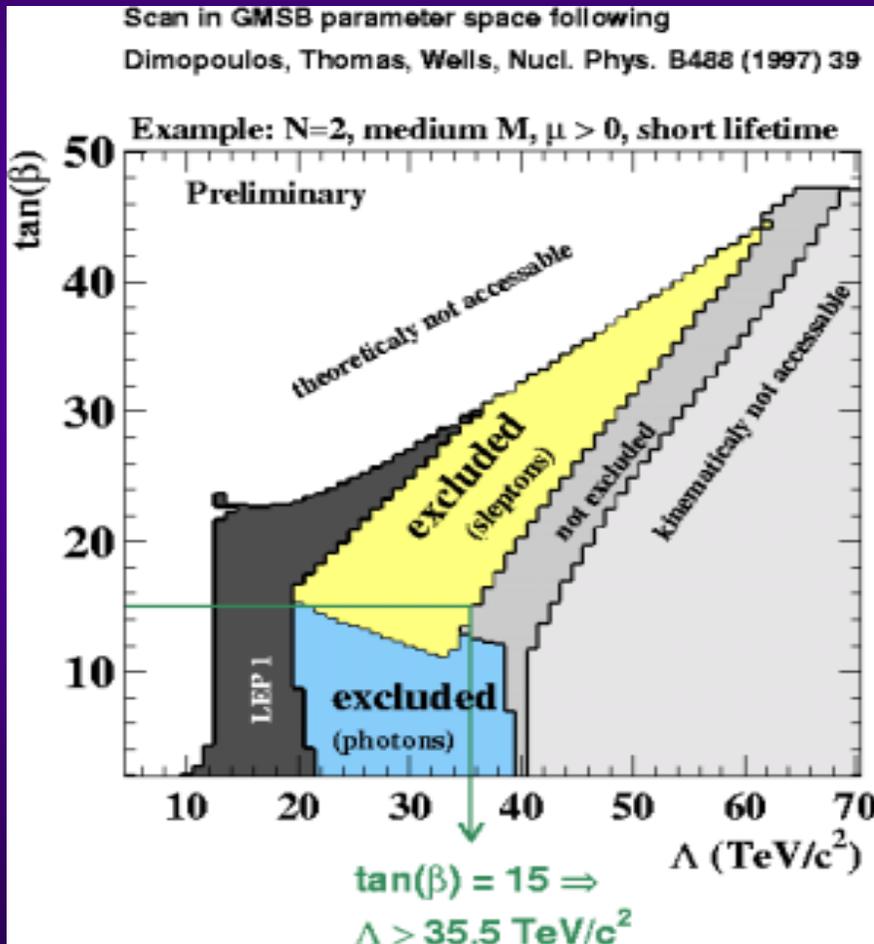
GMSB: $\tilde{\tau}$ NLSP Exclusions



Cross-sections from model scans using Dimopoulos, Thomas, Wells
Nucl.Phys.B488:39-91,1997



GMSB: comparison with Run II benchmark



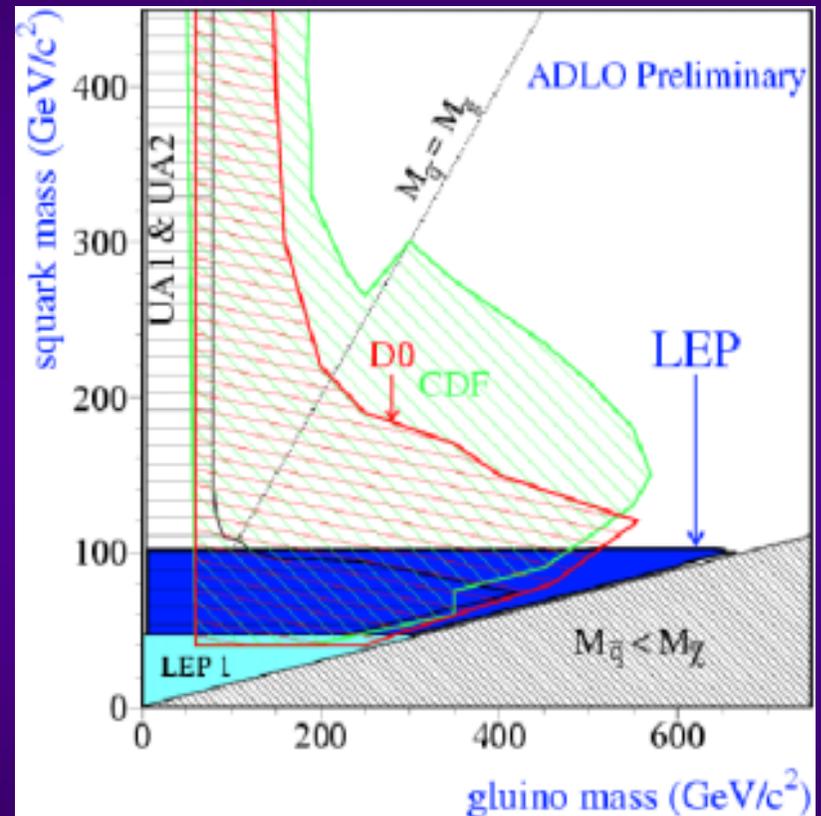
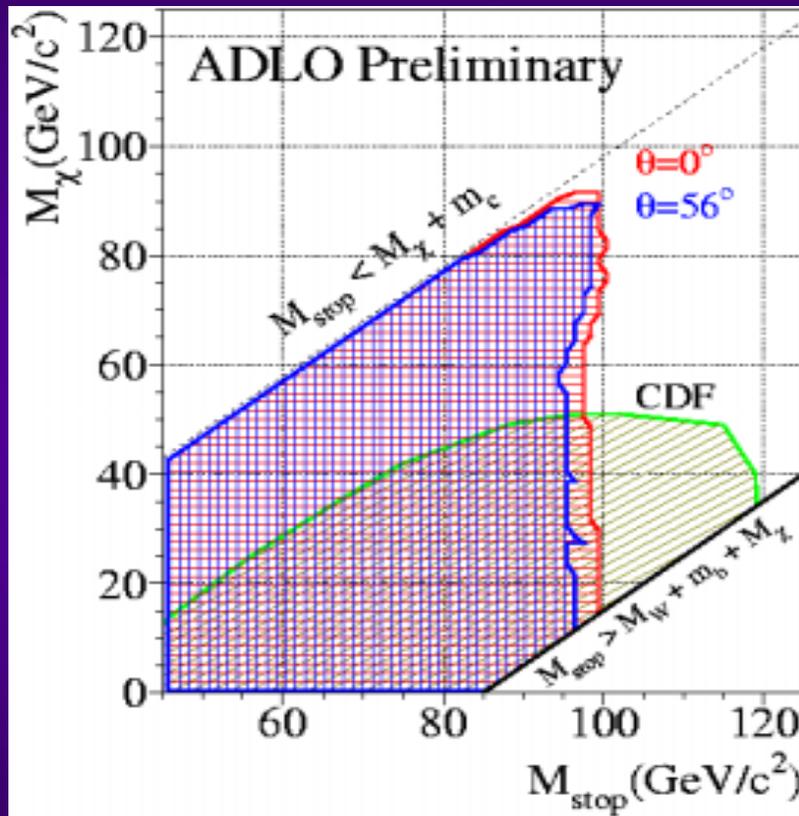


CMSSM: \tilde{q} NLSP



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

General squarks

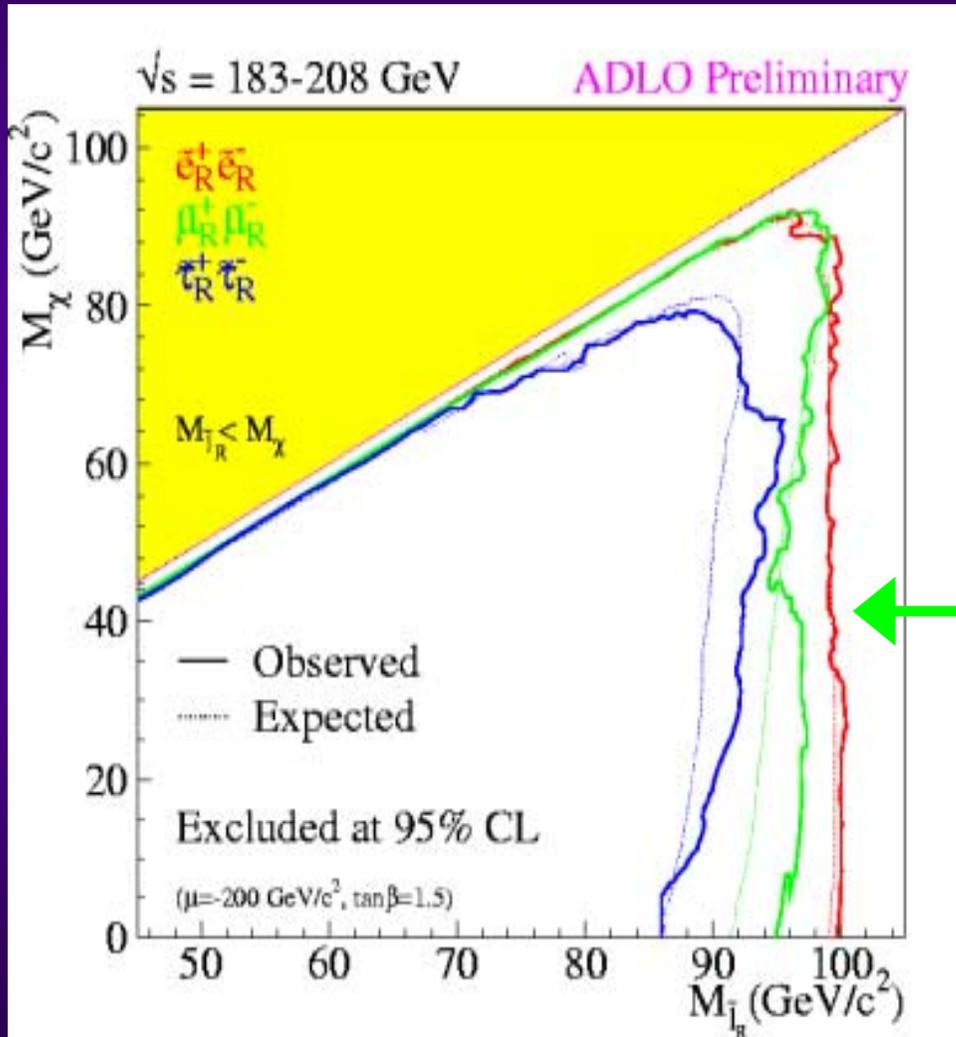


ALEPH:- $\Delta M \approx 0$ excl. $< 63 \text{ GeV}$
 - 4 body decays too

Assumes: - 5 degenerate quarks
 - GUT relations



CMSSM: \tilde{l} NLSP



Mass limits for **40** GeV $\tilde{\chi}^0$
 (ADLO)

Type	Observed (GeV)	Expected (GeV)
\tilde{e}_R	99.4	99.4
$\tilde{\mu}_R$	96.5	94.7
$\tilde{\tau}_R$	91.7	88.8

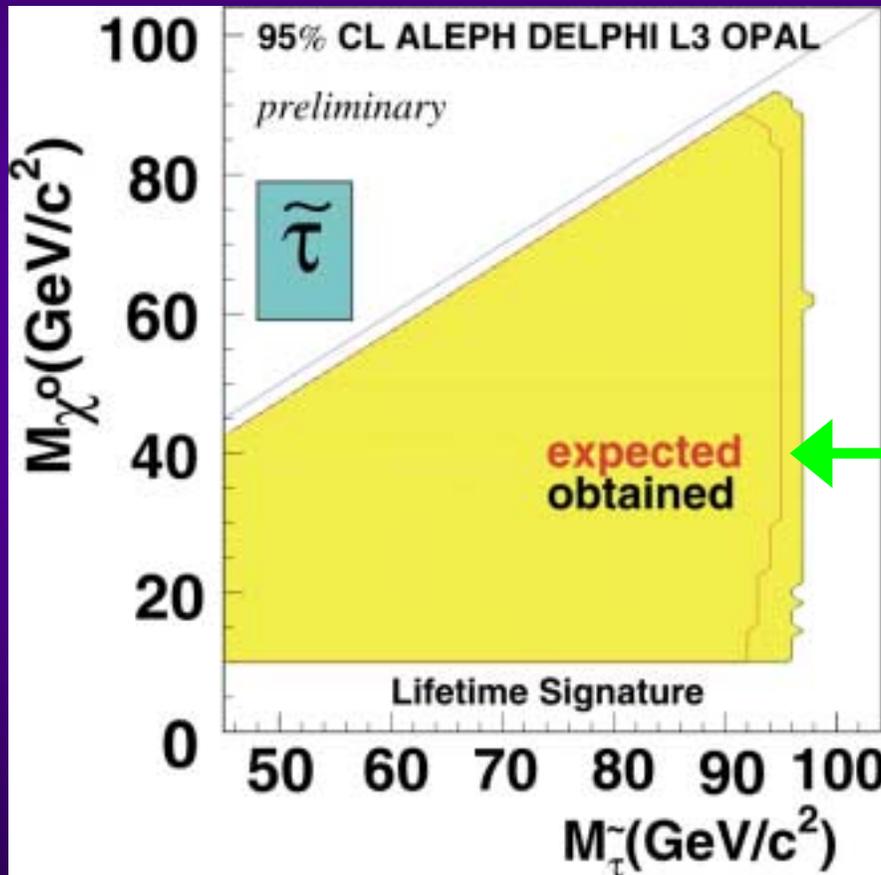


CMSSM: $\tilde{\tau}$ NLSP with RPV



Eg: stau indirect decays, λ (LLE)

Mass limits for 40 GeV $\tilde{\chi}^0$
(ADLO)



Type	Observed (GeV)	Expected (GeV)
\tilde{e}_R	100.3	98.9
$\tilde{\mu}_R$	98.0	95.9
$\tilde{\tau}_R$	96.9	95.0
$\tilde{\nu}_e$	100.1	99.8
$\tilde{\nu}_\mu$	87.1	90.7

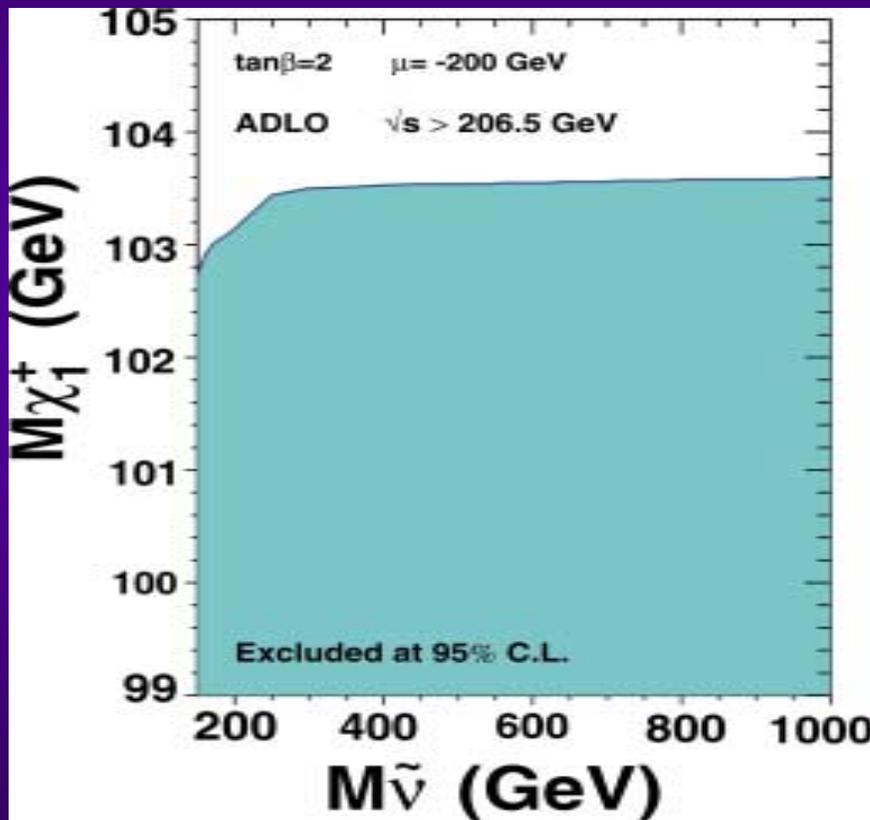


CMSSM: $\tilde{\chi}^\pm$ NLSP

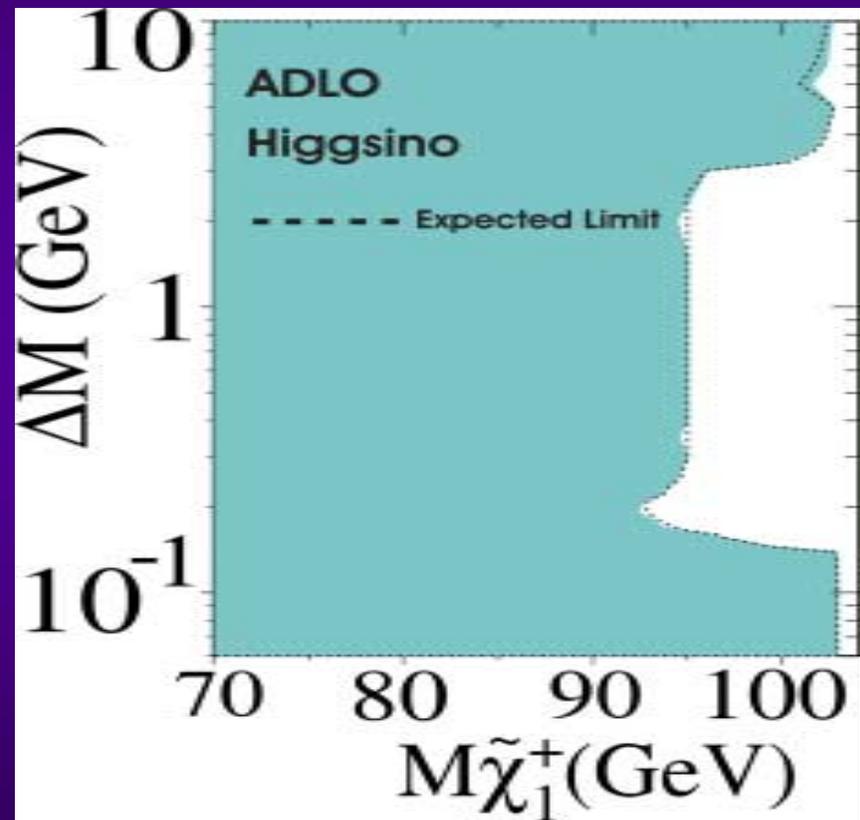


Mass Limit, 100% W^* BR:
(Benchmark: $\tan\beta=2$, $\mu=-200$ GeV)

Even small ΔM
(Deep Higgsino Region)



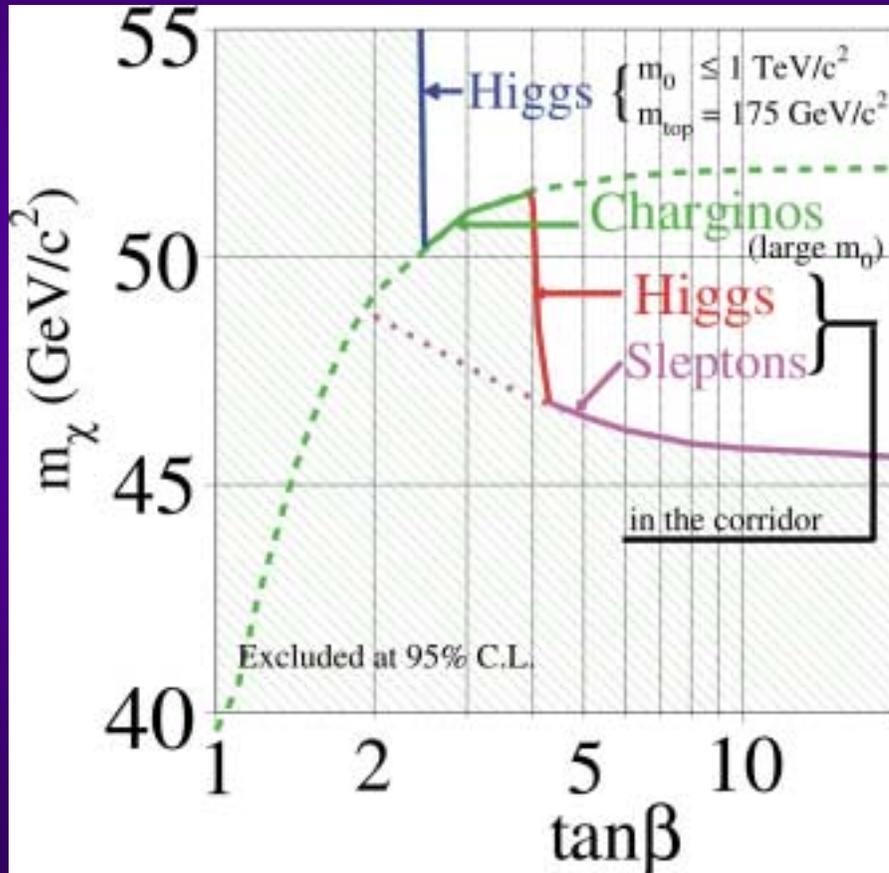
$M > 103$ GeV



$M > 92.4$ GeV



General CMSSM: $\tilde{\chi}^0$ LSP



- ◆ **Chargino dominant**
 - ◆ Except in “corridor” with $M(\tilde{\nu}) \approx M(\tilde{\chi}^\pm)$
- ◆ **Corridor:**
 - ◆ **Sleptons**
- ◆ **Higgs:**
 - ◆ $M_h^{95} \Rightarrow M_{\tilde{t}} \Rightarrow M_2(\tan\beta)$
 - ◆ **Corridor stronger: low m_0**
- ◆ **Result:**
 - ◆ **$M(\tilde{\chi}_1^0) > 45 \text{ GeV}$**
- ◆ **Caveat: no $\tilde{\tau}$ mixing**

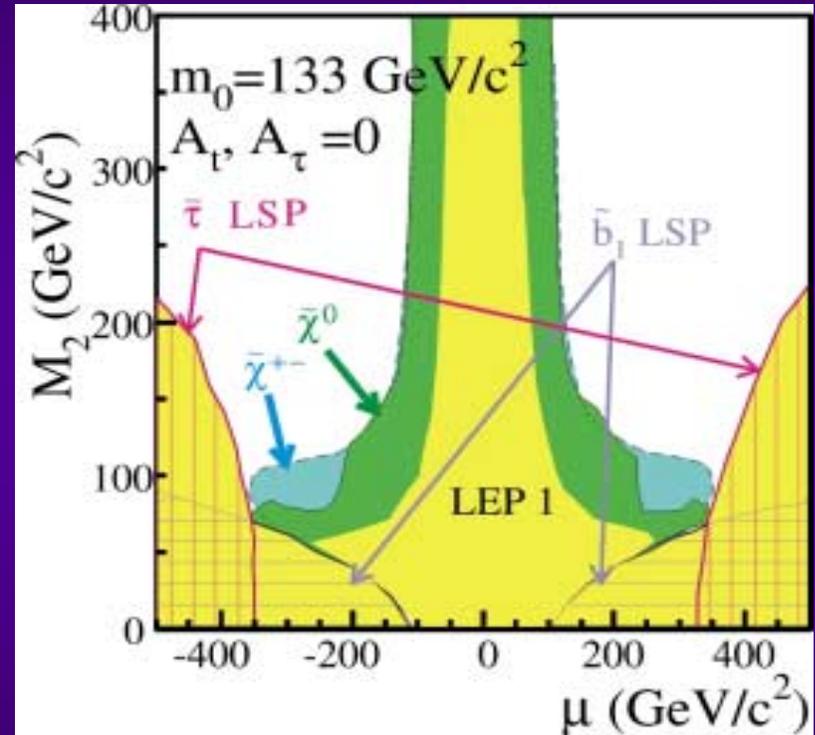
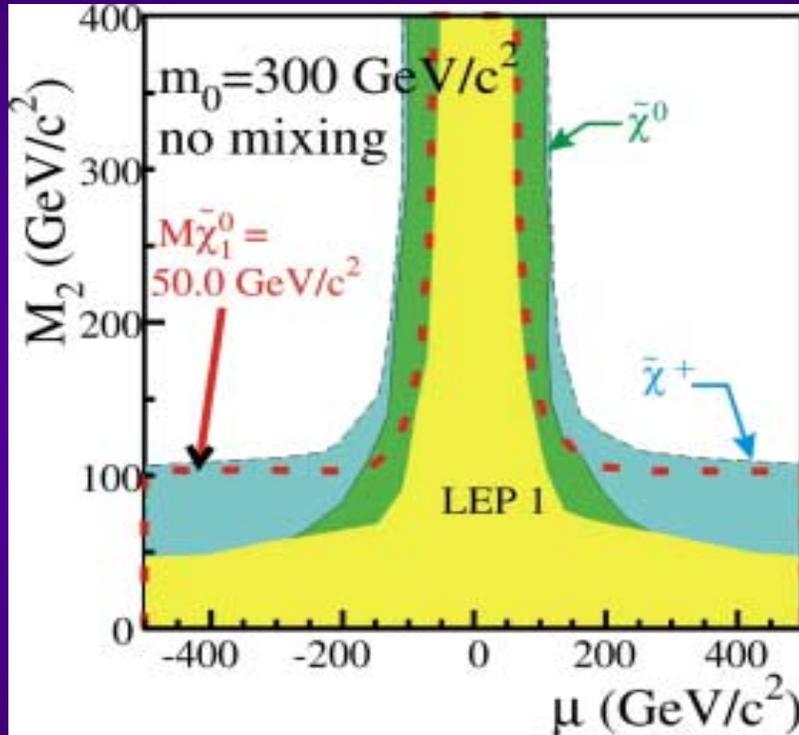


M_2 vs μ : eg with $\tan\beta = 35$, DELPHI



No sfermion mixing

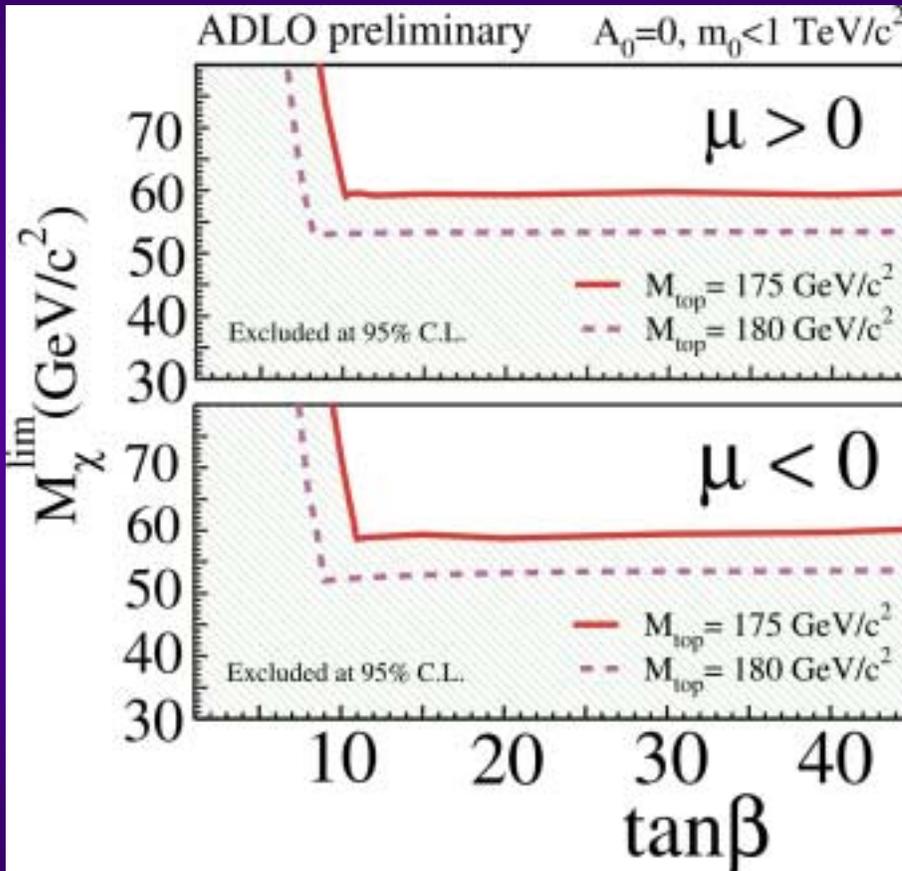
Stau/Sbot Mixing ($A_\tau - \mu \tan\beta$)



- Stau mixing:
- $M(\tilde{\tau}) \approx M(\tilde{\chi}^0)$
 - Invisible stau
 - Invisible chargino



mSUGRA LSP constraint



- ◆ ISAJET mSUGRA scan
 - ◆ $A_0, m_0, m_{1/2}, \tan\beta, \text{sign}(\mu)$
 - ◆ $A_0=0$, but stau mixing allowed
- ◆ Z total/invisible width
- ◆ ADLO hZ constraints
- ◆ No stable stau
- ◆ SUSY search constraints
 - ◆ Charginos
 - ◆ Sleptons
 - ◆ $\tilde{\chi}_2^0 \tilde{\chi}_1^0 \rightarrow \tau (\tilde{\tau}) \tilde{\chi}_1^0 \tilde{\chi}_1^0$
 - ◆ $\tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow \tau \tau (\tilde{\tau} \tilde{\tau}) \tilde{\chi}_1^0 \tilde{\chi}_1^0$

$M_{\text{LSP}} > 59 \text{ GeV} \quad (M_{\text{top}}=175 \text{ GeV})$



More Information

- ◆ Experiments' results from their web pages
 - ◆ <http://alephwww.cern.ch/>
 - ◆ <http://delinfo.cern.ch/Delphi/Welcome.html>
 - ◆ <http://l3www.cern.ch/>
 - ◆ <http://opal.web.cern.ch/Opal/>
- ◆ LEP SUSY Working Group combinations
 - ◆ <http://lepsusy.web.cern.ch/lepsusy/>
- ◆ And see talks at this meeting with many more details:
 - ◆ MSSM: Mikael Berggren, Univ.Paris VI et VII
 - ◆ GMSB: Aran Garcia-Bellido, Royal Holloway, Univ.London
 - ◆ RPV: Silvia Costantini, INFN-Rome



Conclusions

- ◆ The LEP experiments scoured many (all?) corners for SUSY
 - ◆ e^+e^- environment allowed many “exotic susy” modes and holes in parameter spaces to be explored
 - ◆ No serious hints of a signal
- ◆ Years of constructive interaction with the theory community
 - ◆ Standard modes \Rightarrow Null results \Rightarrow New models \Rightarrow New searches
- ◆ $M(\tilde{\chi}^\pm) < E_{\text{beam}} \approx 100 \text{ GeV} \Rightarrow M(\tilde{\chi}^0) < M(\tilde{\chi}^\pm)/2 \approx 50 \text{ GeV}$
 - ◆ Rather robust constraints with very few loopholes left
- ◆ LEP SUSY constraints hard to evade
 - ◆ Must look for NLSP beyond our kinematic limit