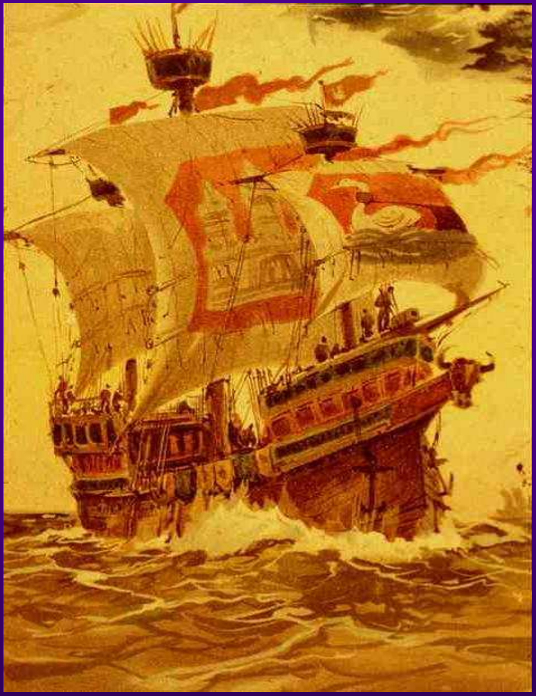
SUSY Searches: *Lessons and loopholes from LEP*



Aleph Delphi L3 Opal

SUSY02

DESY Hamburg

Rob McPherson

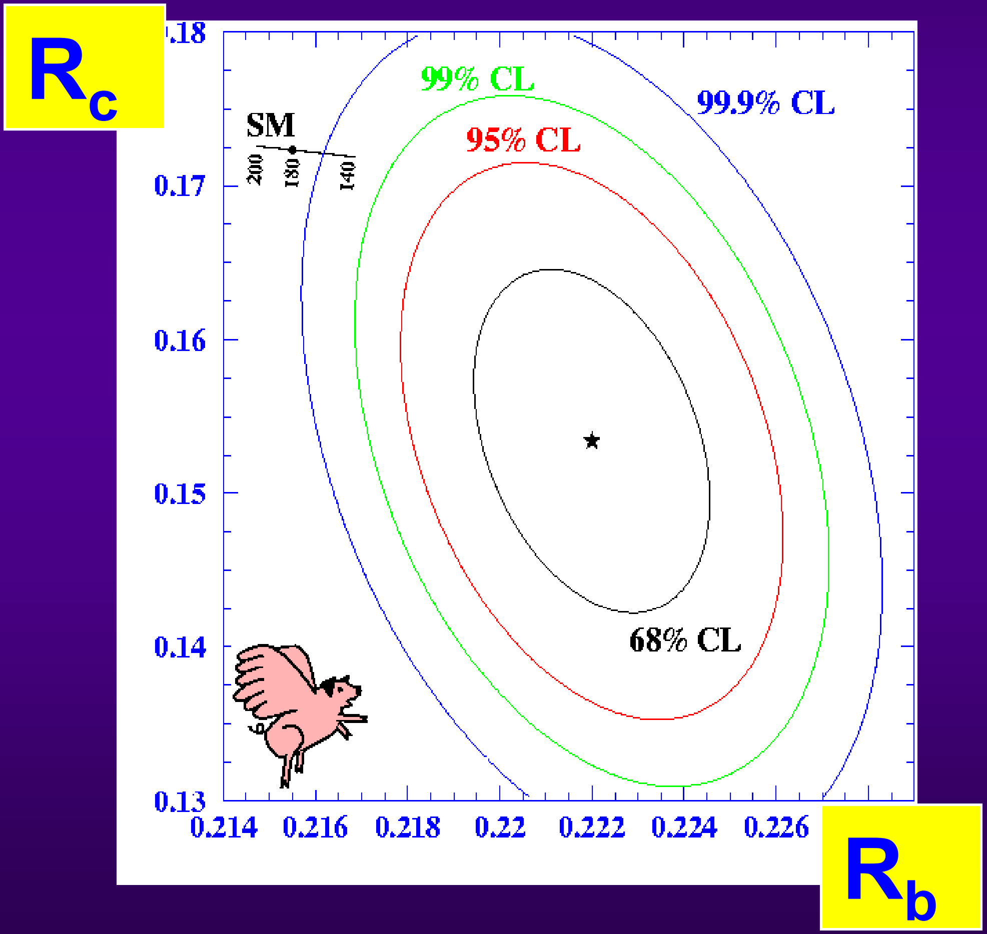
University of Victoria

Institute of Particle Physics

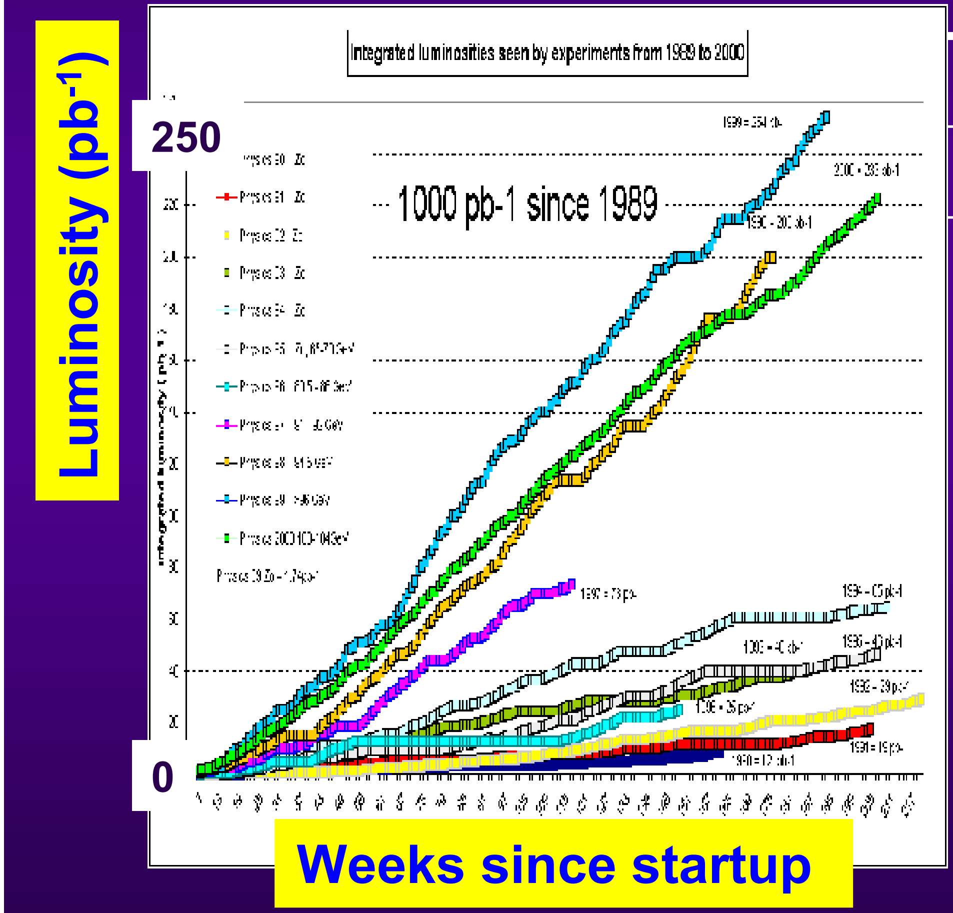
Expect SUSY@LEP2?

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

Brussels/Beijing 1995:



LEP Data Sets



Stage	E_{CM} (GeV)	Year	Lumi/Expt (pb^{-1})
LEP 1	$\approx M_Z$	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: $\approx$ 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	$\tilde{h},\tilde{H}$	$\} \tilde{\chi}^0_{1\text{-}4}$			
		$\tilde{Z}$		Z^0		
	$H^\pm$	$\tilde{H}^\pm$	$\} \tilde{\chi}^\pm_{1,2}$			
		$\tilde{W}^\pm$		$W^\pm$		
		$\tilde{g}$		g		
$\tilde{\ell}_{1,2}$ {	$\tilde{\ell}_{L,R}$	$\ell_{L,R}$				
	$\tilde{\nu}_L$	ν_L				
$\tilde{q}_{1,2}$ {	$\tilde{q}_{L,R}$	$q_{L,R}$	goldstino		$\tilde{G}$	G
		$\tilde{G}$	←			

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 $\tilde{\ell}$
- Decay chains to NLSP then to $\tilde{G}$
  - Arbitrary suppression
  - Lifetime signatures

Now look for it…

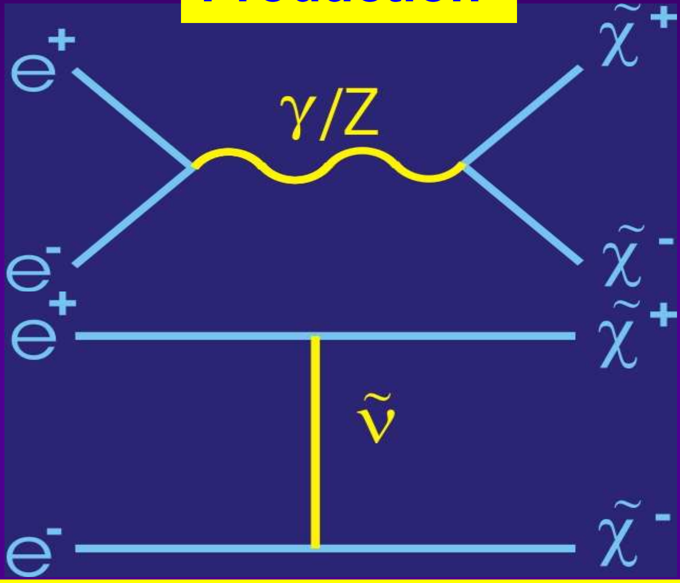
(I) LEP SUSY search strategy

- 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

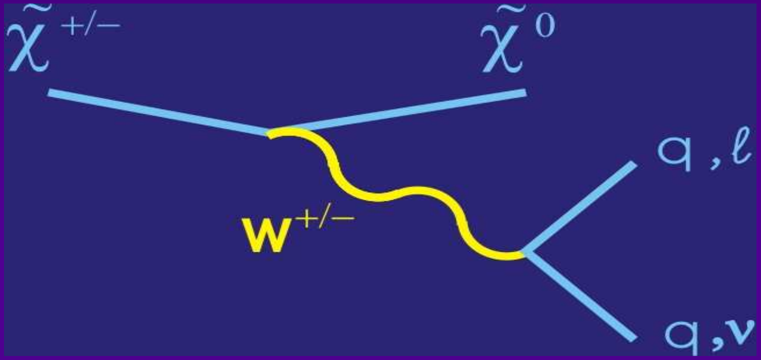
The prototype: $e^+e^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^-$

Standard “gravity mediated” modes

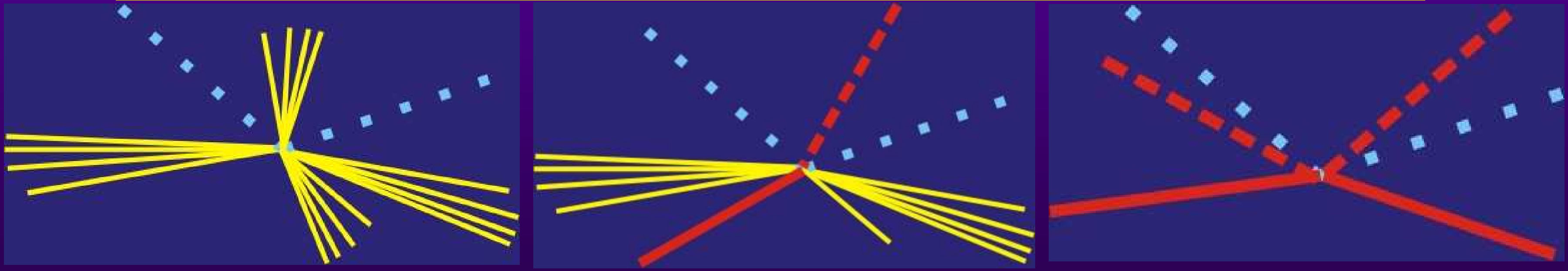
Production


e^+
γ/Z
$\tilde{\chi}^+$
e^-
$\tilde{\chi}^-$
e^+
$\tilde{\chi}^+$
$\tilde{\nu}$
e^-
$\tilde{\chi}^-$

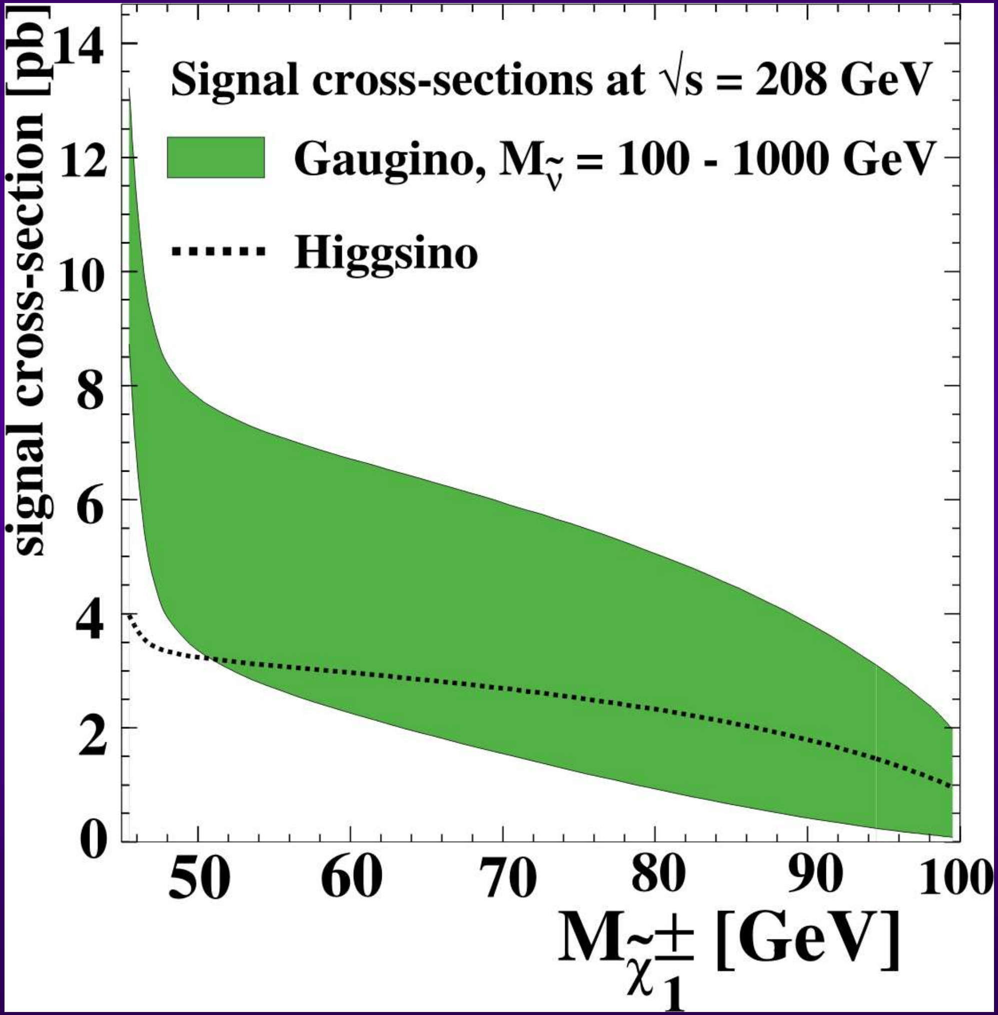
Decay


$\tilde{\chi}^{+/-}$
$\tilde{\chi}^0$
$W^{+/-}$
q, ℓ
q, ν

Basic SUSY Searches: Jets/Leptons with Missing Energy



CMSSM Charginos



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

Chargino: selection

- **Depends on Evis 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}

eg: .OR. of L3 selections for

Ecm = 205 – 208 GeV (≈200 pb^{-1})

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 ΔM > 5 GeV**
- **Cross-section > 1 pb easily excluded**

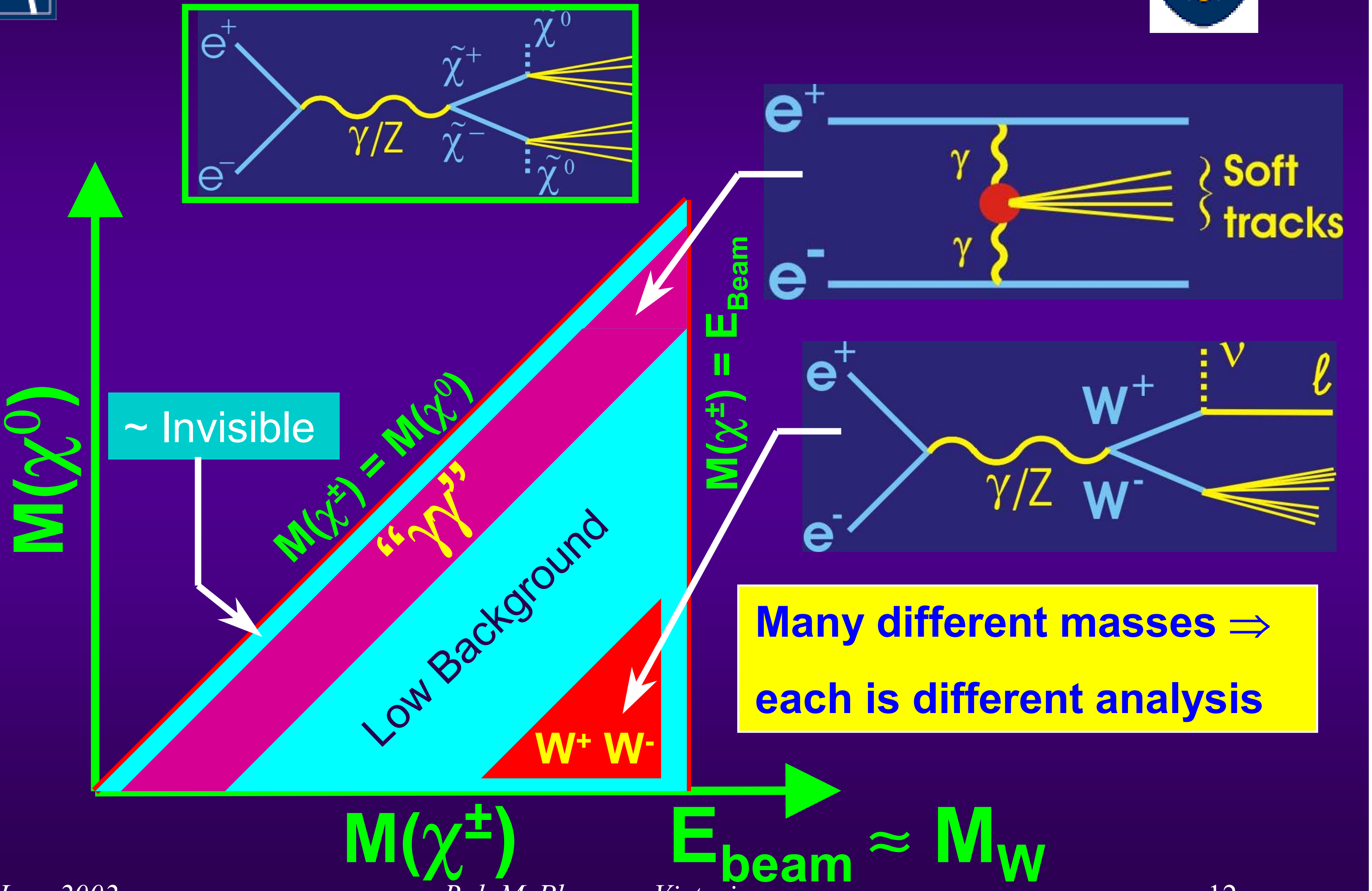
⇒ Are we done yet?

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 ⇒ Target reducible backgrounds



e^+
e^-
γ/Z
$\tilde{\chi}^+$
$\tilde{\chi}^-$
$\tilde{\chi}^0$
$\tilde{\chi}^0$
e^+
e^-
γ
γ
Soft tracks
e^+
e^-
γ/Z
W^+
W^-
ν
ℓ
~ Invisible
$M(\chi^\pm) = M(\chi^0)$
"$\gamma\gamma$"
Low Background
$W^+ W^-$
$M(\chi^\pm) = E_{Beam}$
$M(\chi^0)$
$M(\chi^\pm)$
$E_{beam} \approx M_W$

Many different masses ⇒ each is different analysis

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

- Full M,ΔM dependent likelihood *difficult …*

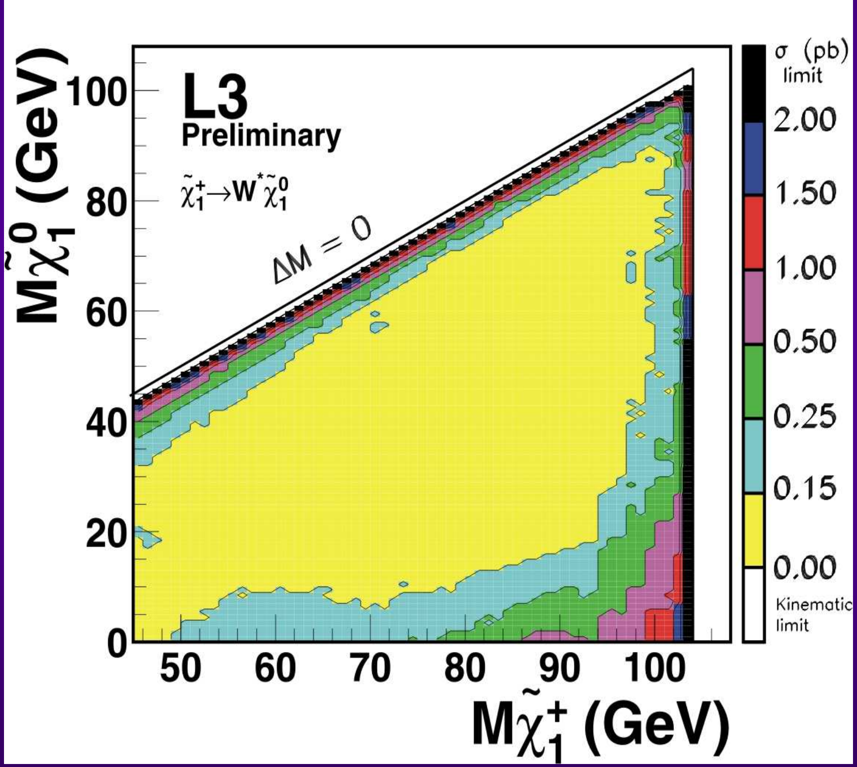
Quantity	Bin	N° Bins
M	5 GeV	20
ΔM	1 GeV	100
E_{CM}	≈ 1 GeV	≈ 10
N_{MC} / Bin		10000
Total MC Events		2 x 10^8

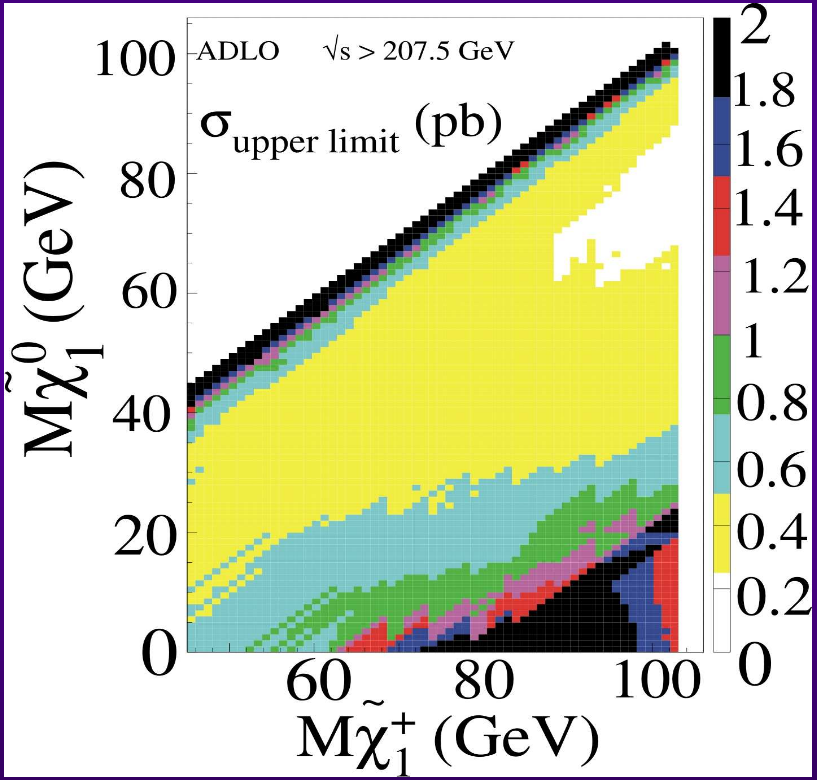
- Few x 10^8 MC events barely possible
- Can revert to simpler
  - ΔM regions (L3, Delphi, OPAL)
  - “sliding cuts” (ALEPH)
- For Likelihood, use MCgrid + interpolation
  - Toy MC calibrated with full MC (DELPHI)
  - Likelihood histogram interpolation (OPAL)

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

- **L3, Full LEPII data sets:**

- **ADLO 35.2 pb^{-1}**
- **Ecm > 207.5 GeV**

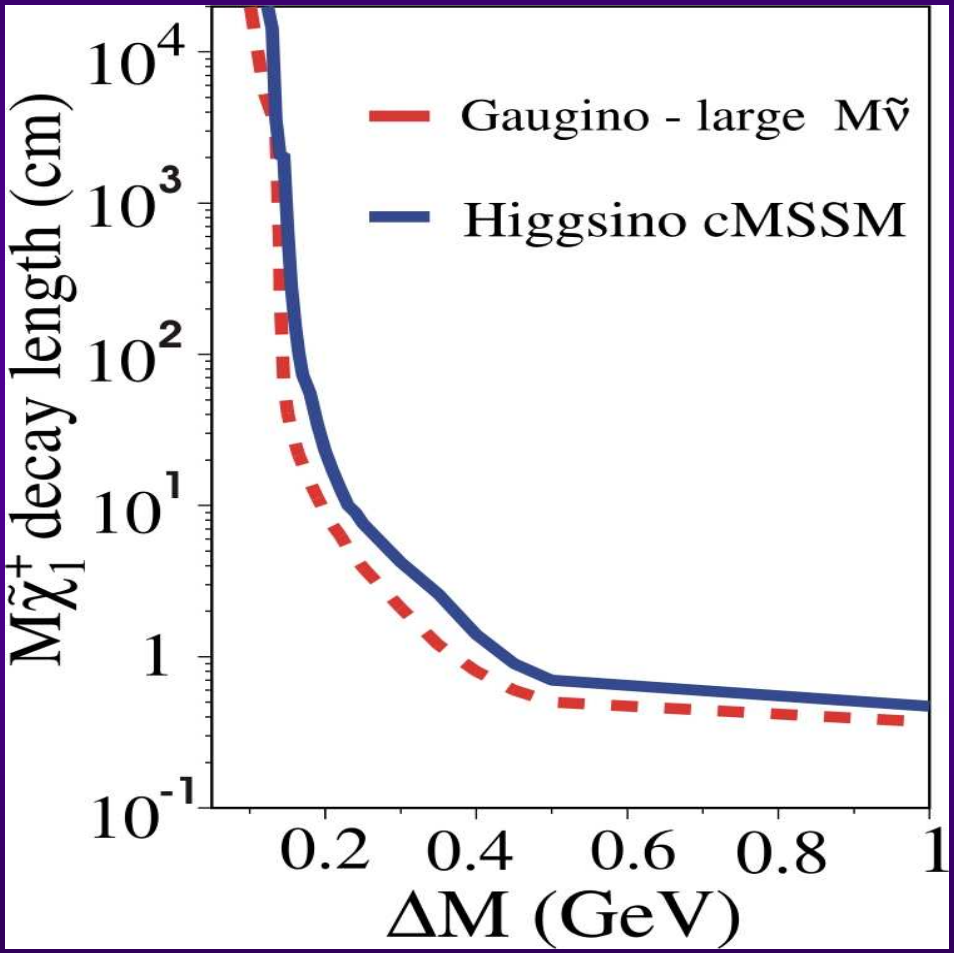




σ < 0.1 pb

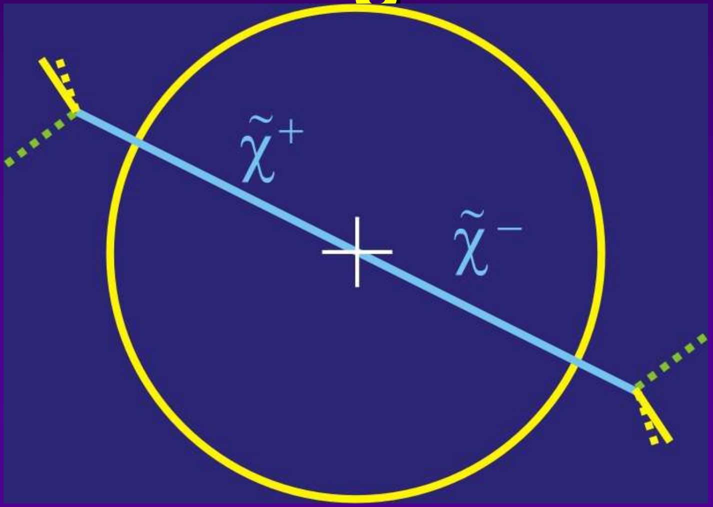
σ < 1 pb @ 208 GeV

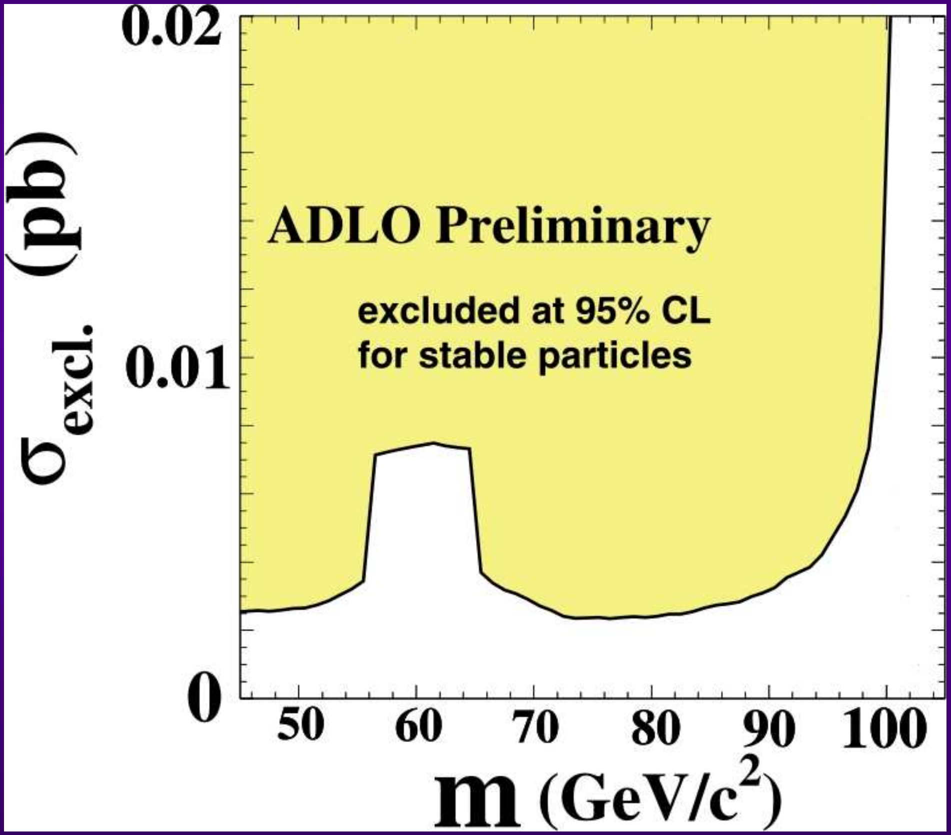
$\tilde{\chi}^+\tilde{\chi}^-$: Lifetime for small ΔM



- $\Delta M < M_\pi$:
  - ≈ **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

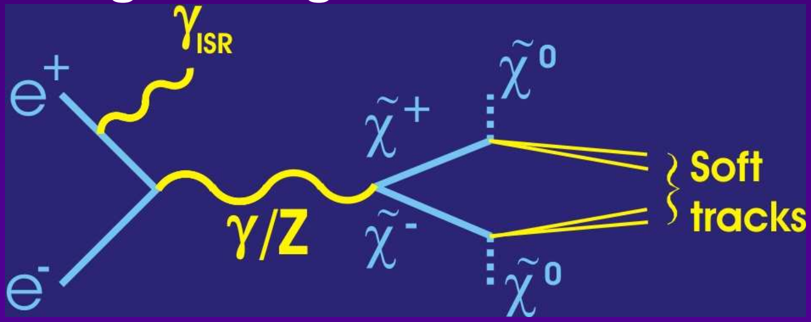
- -- Kinematics (p,E)
- -- dE/dX
- -- DELPHI: RICH

Almost background free

No Evidence

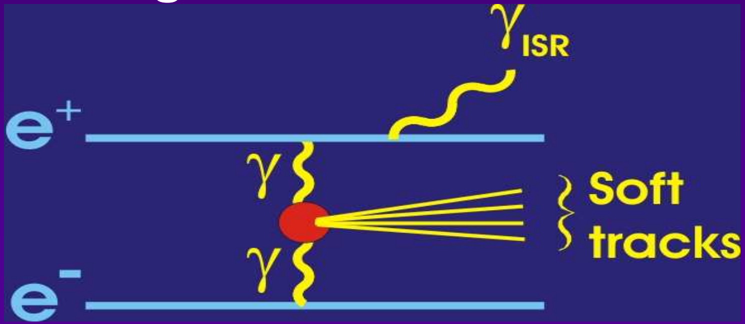
$\tilde{\chi}^{\pm}$: $M_{\pi} < \Delta M < 5$ GeV $\Rightarrow$ ISR

Signal: Big σ ~ Observable



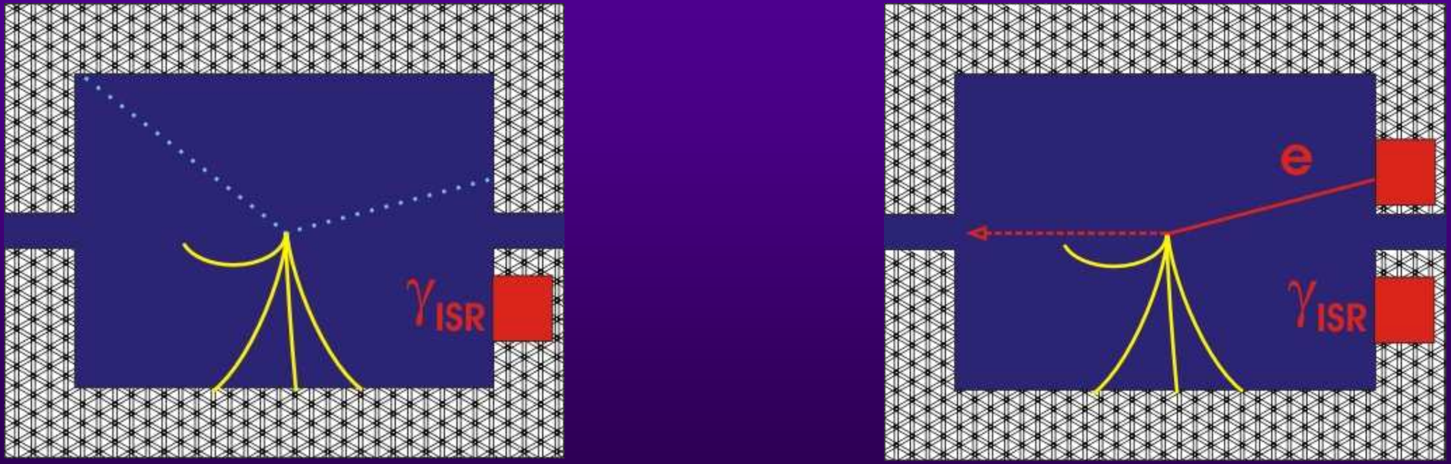
γ_{ISR}
e^+
e^-
γ/Z
$\tilde{\chi}^+$
$\tilde{\chi}^-$
$\tilde{\chi}^0$
$\tilde{\chi}^0$
Soft tracks

Background: Enormous σ !



γ_{ISR}
e^+
e^-
γ
γ
Soft tracks

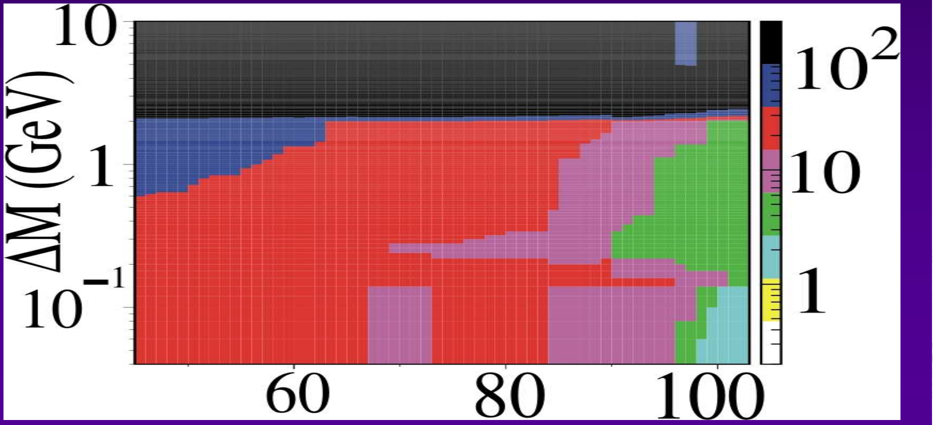
Analysis: **tag γ** with soft tracks, **veto e**



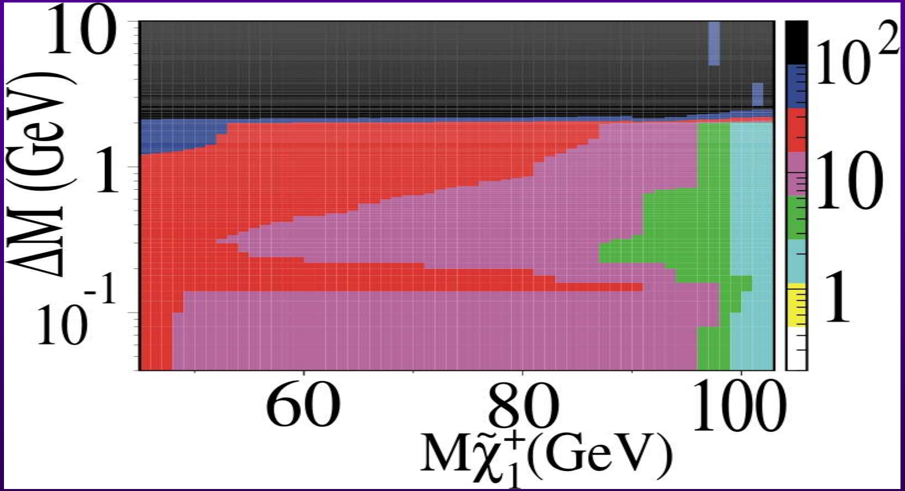
γ_{ISR}
e
γ_{ISR}

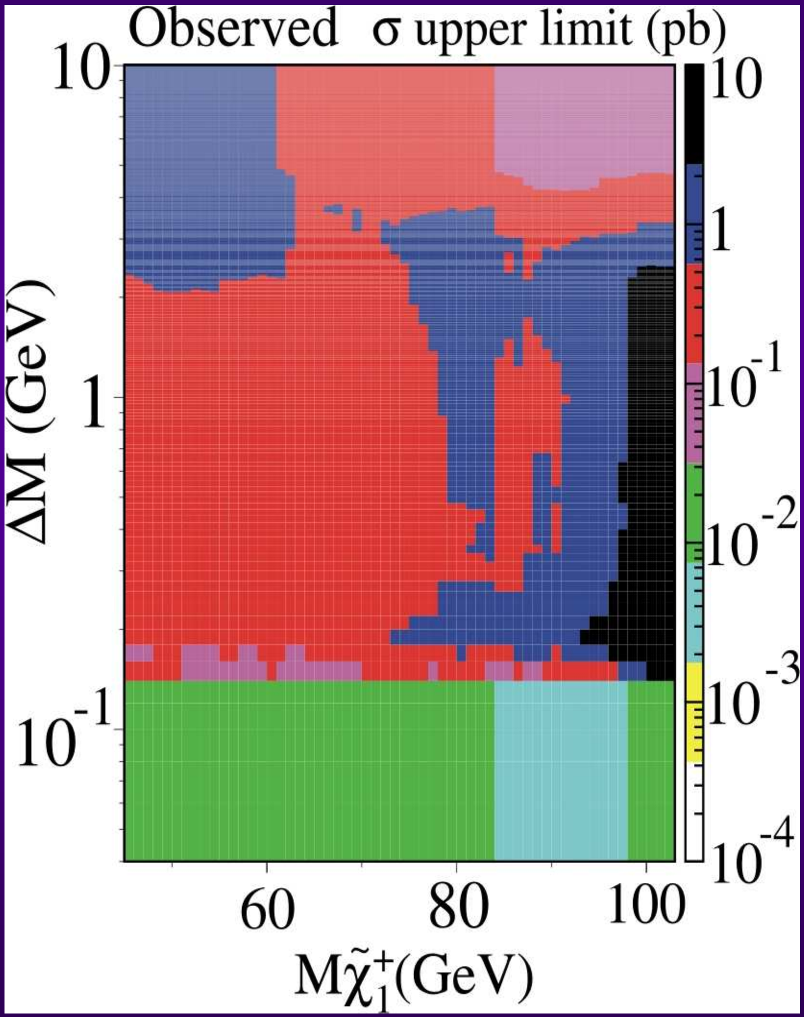
Small ΔM: Higgsino Results ADLO Preliminary

ADLO Events Observed:



ADLO Events Expected:

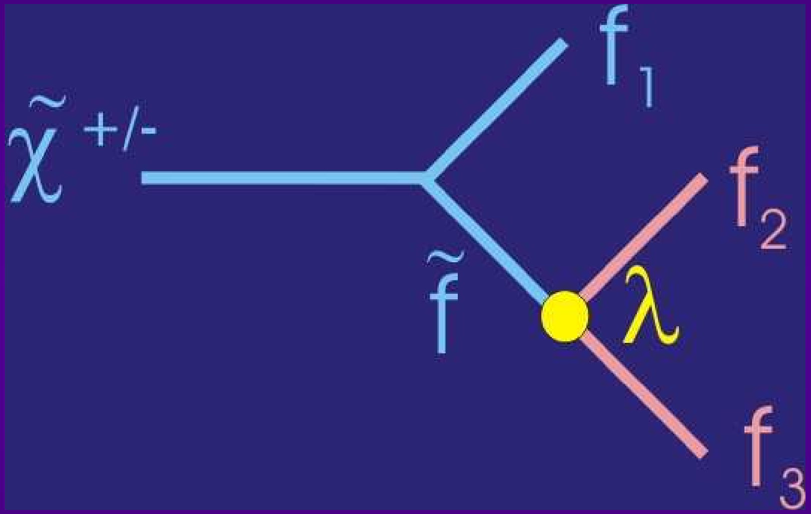




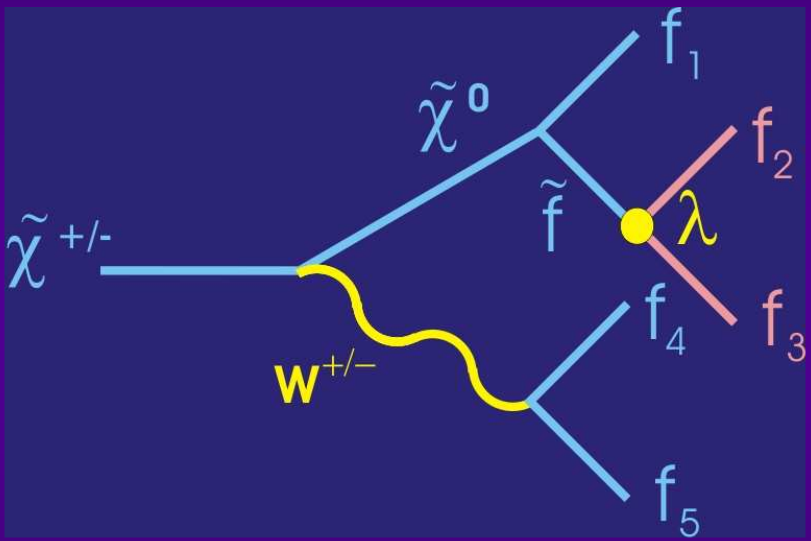
$\tilde{\chi}^+ \tilde{\chi}^-$: with RPV?

DIRECT RPV

INDIRECT RPV



$\tilde{\chi}^{+/-}$
f_1
f_2
$\tilde{f}$
λ
f_3



$\tilde{\chi}^{+/-}$
$\tilde{\chi}^0$
f_1
f_2
$\tilde{f}$
λ
f_3
f_4
$W^{+/-}$
f_5

6 fermion final states

10 (!) fermion final states

⇒ Low background, but many analyses needed!

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

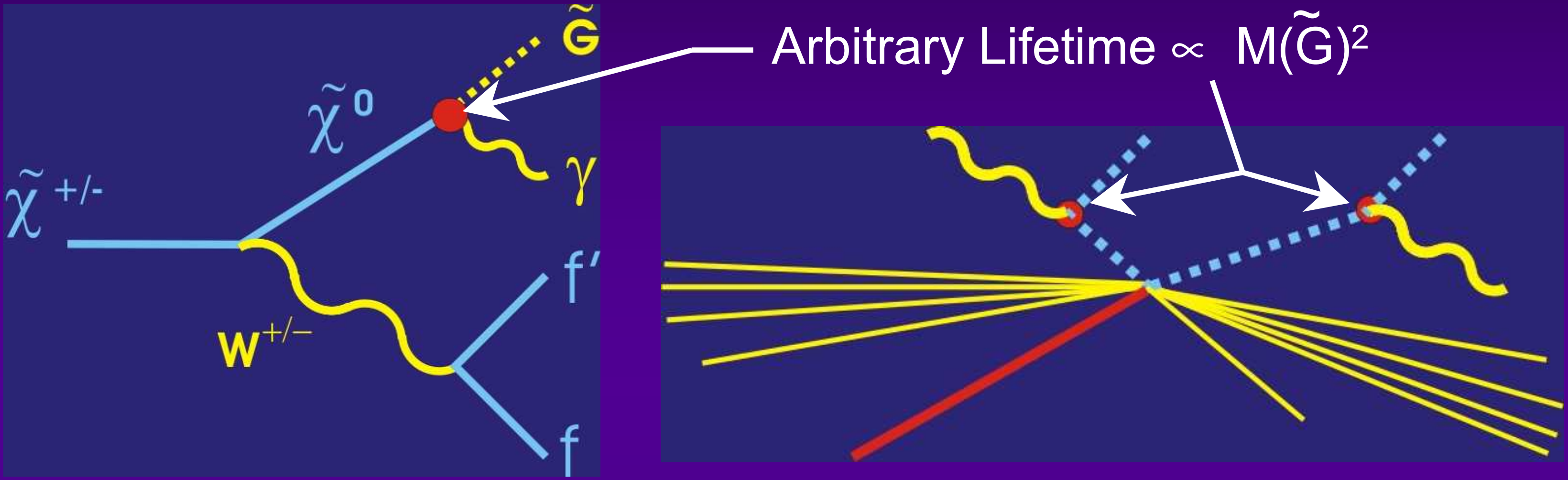
General, open selections:

eg: λ_{133} **("LLE") L3 192—208 GeV:**

Process	Channel	Data	Bkg
direct	$\geq 4\ \ell$+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

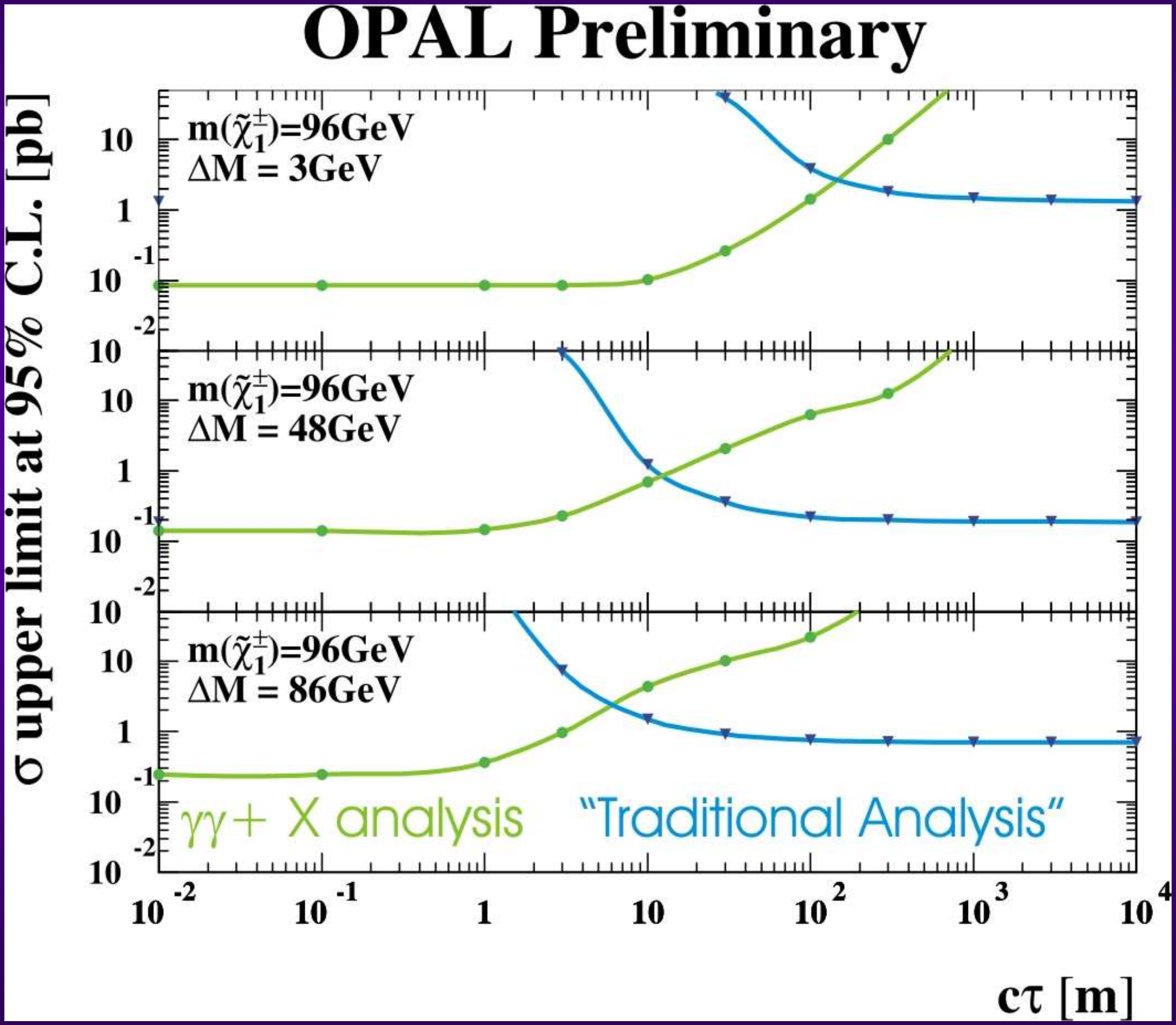

$\tilde{G}$
$\tilde{\chi}^0$
γ
$\tilde{\chi}^{+/-}$
f′
$W^{+/-}$
f

Arbitrary Lifetime ∝ $M(\tilde{G})^2$

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)**

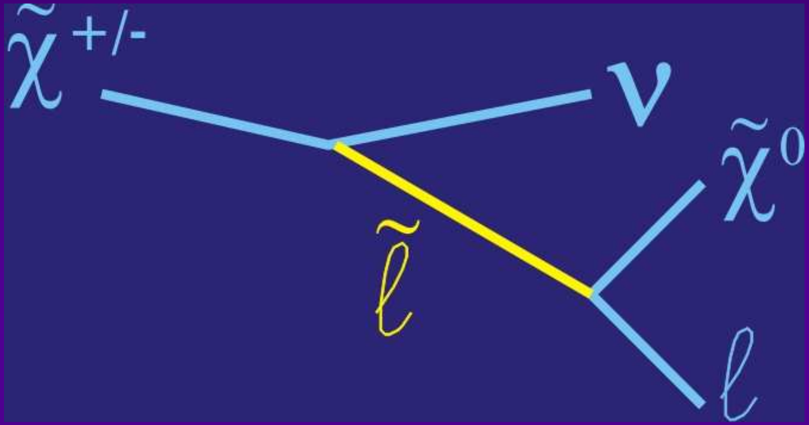
⇒ Overlap tricky to get right !

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

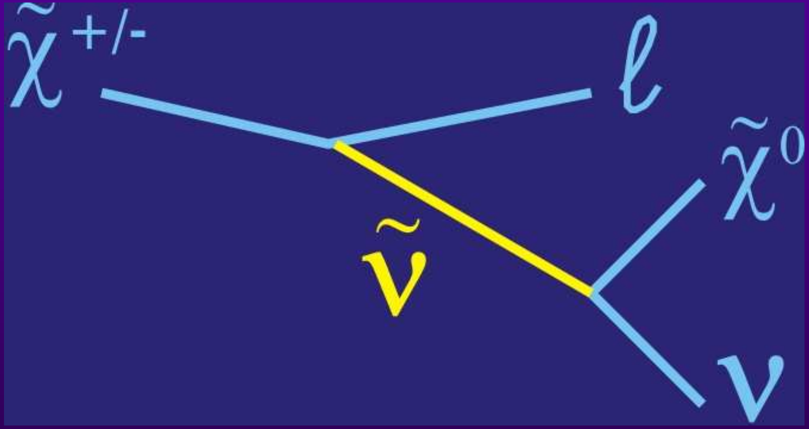


$\tilde{\chi}^+ \tilde{\chi}^-$ basic loophole:

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



$\tilde{\chi}^{+/-}$
ν
$\tilde{\chi}^0$
$\tilde{\ell}$
ℓ

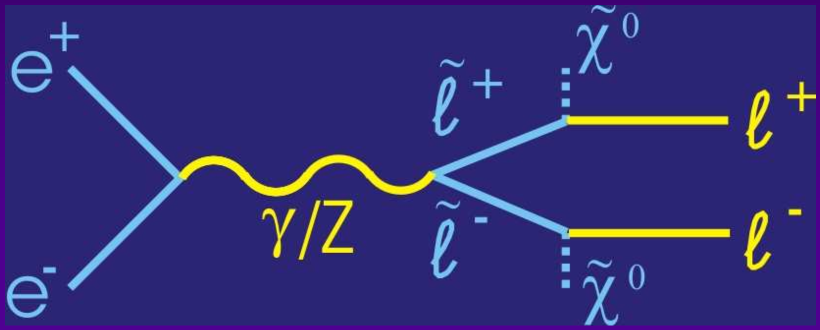


$\tilde{\chi}^{+/-}$
ℓ
$\tilde{\chi}^0$
$\tilde{\nu}$
ν

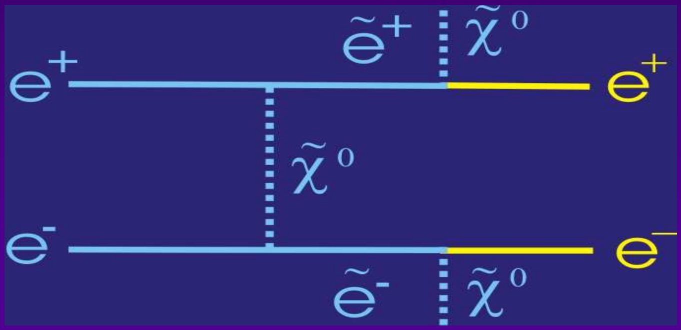
- Reduced cross-section
- 2 body leptonic decays
- Can be ≈ invisible
  - $M(\tilde{\ell}) = M(\tilde{\chi}^0_1)$
  - $M(\tilde{\nu}) = M(\tilde{\chi}^\pm)$
- Can try tricks but …
- Slepton search imperative

$e^+e^- \to \tilde{\ell}^+\,\tilde{\ell}^-$

Standard “gravity mediated” modes

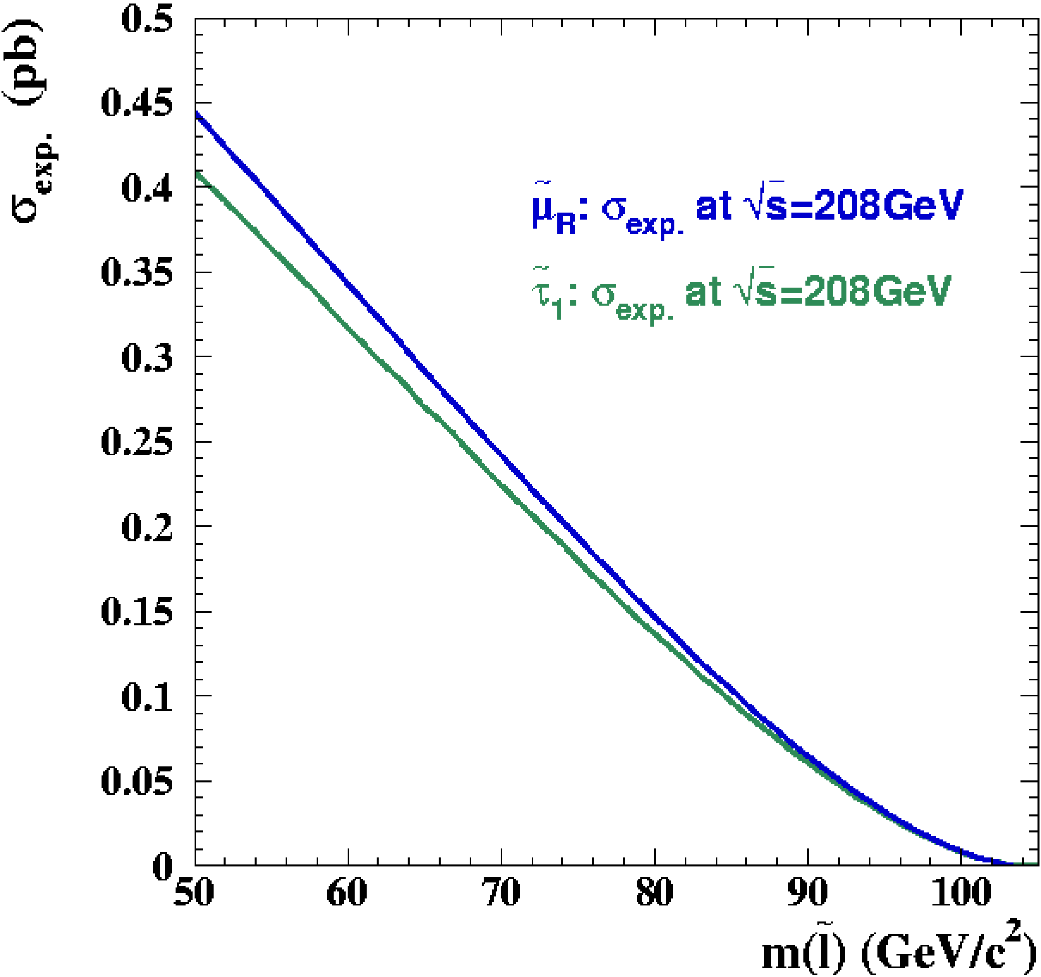

e^+
e^-
γ/Z
$\tilde{\ell}^+$
$\tilde{\ell}^-$
$\tilde{\chi}^0$
$\tilde{\chi}^0$
ℓ^+
ℓ^-

- “Acoplanar Leptons”
  - $\ell^+\,\ell^- + E_{miss}$
- Similar to Charginos with leptonic decays
  - ⇒ Can recycle …
- s-channel cross-sections rather model independent


e^+
e^-
$\tilde{e}^+$
$\tilde{\chi}^0$
$\tilde{\chi}^0$
$\tilde{e}^-$
$\tilde{\chi}^0$
e^+
e^-

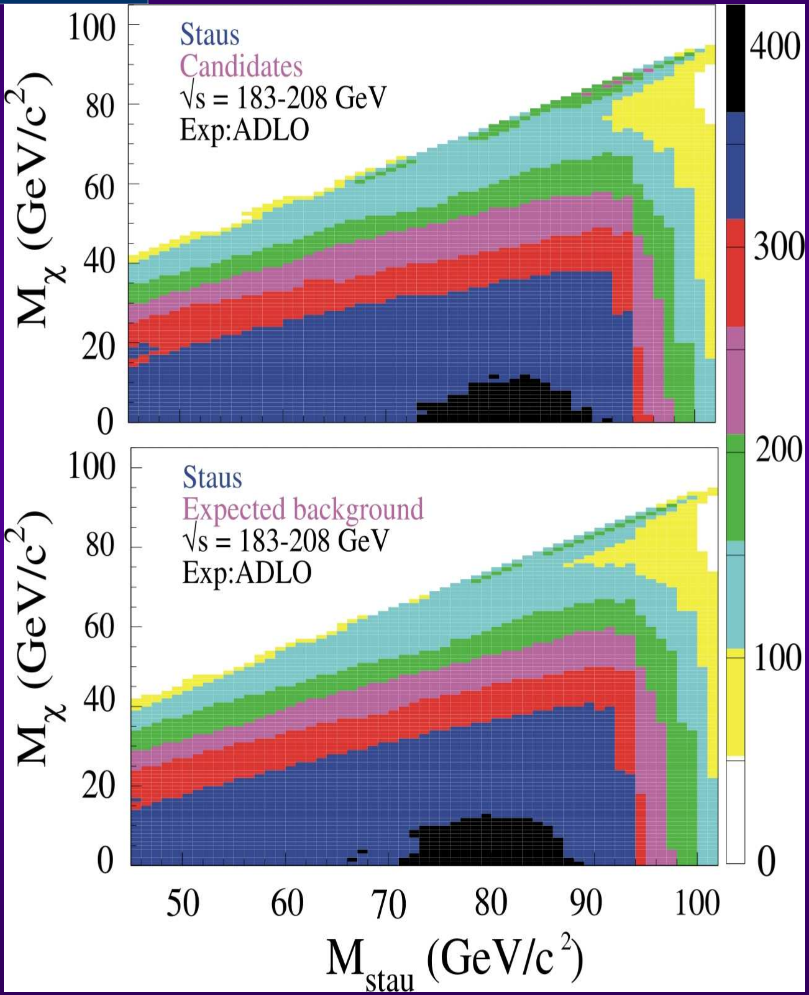
- Selectrons:
  - Also t-channel
- More forward peaked
- Usually higher cross-section
  - Can also be smaller

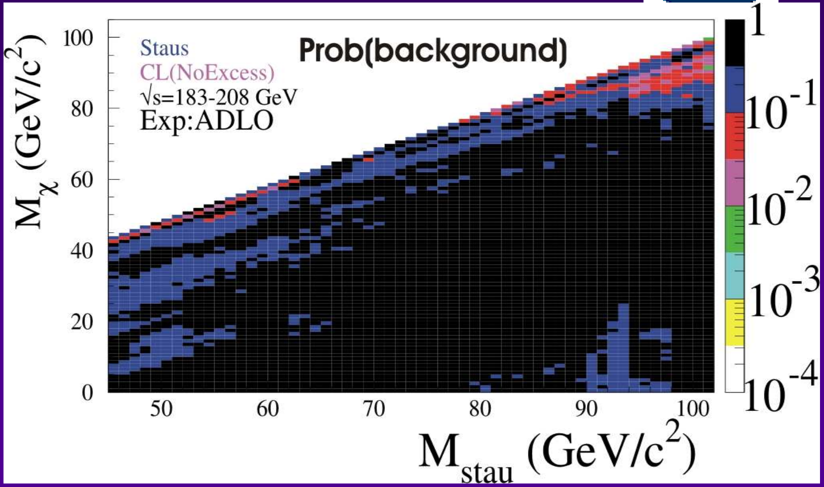
$e^+e^- \rightarrow \tilde{\ell}^+\tilde{\ell}^-$: cross-sections

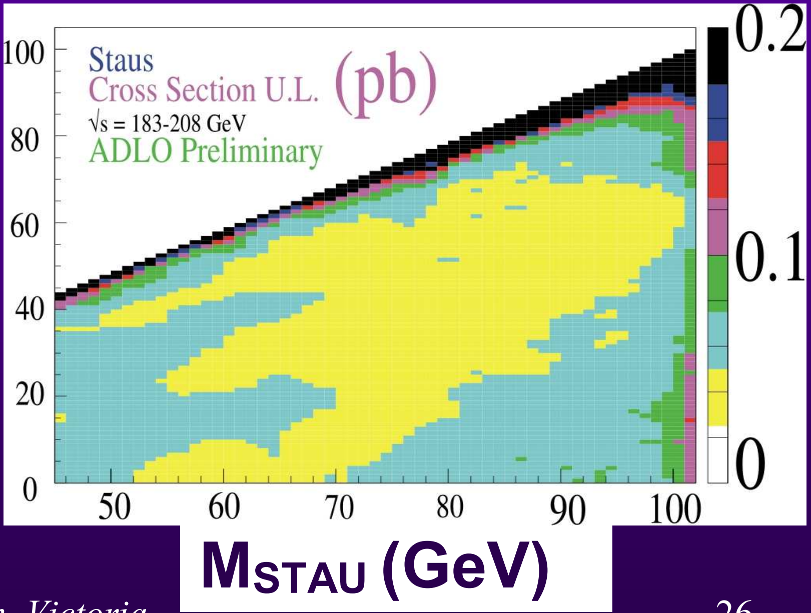


- Smuons:
  - Almost model-independent
- Staus:
  - Mixing can decouple from Z
- Selectrons:
  - t-channel makes cross-section very model-dependent

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

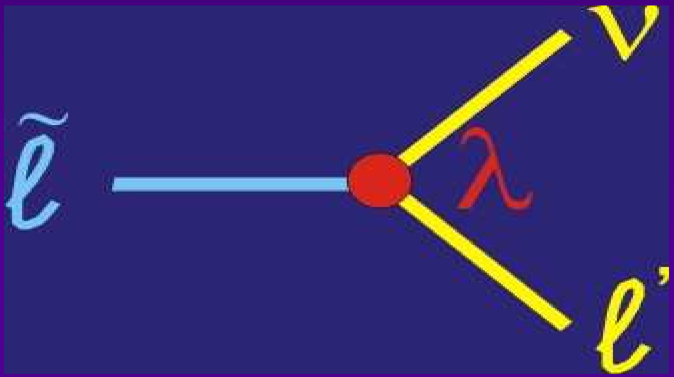




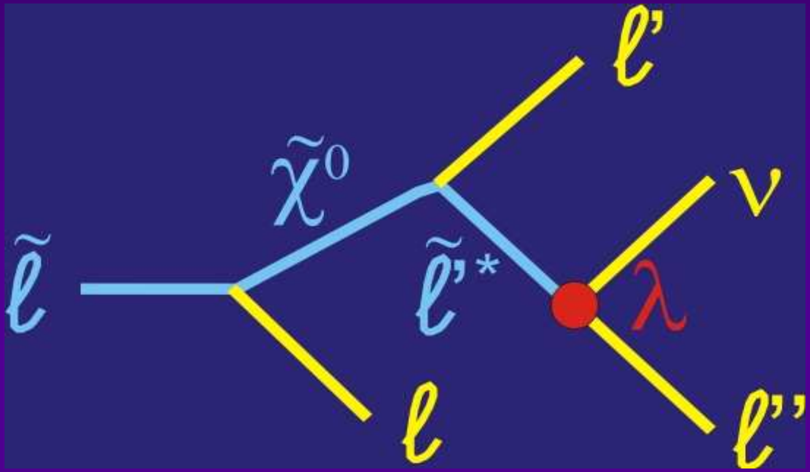


$e^+e^- \rightarrow \tilde{\ell}^+ \tilde{\ell}^-$: with RPV

DIRECT RPV


$\tilde{\ell}$
λ
ν
ℓ'

INDIRECT RPV

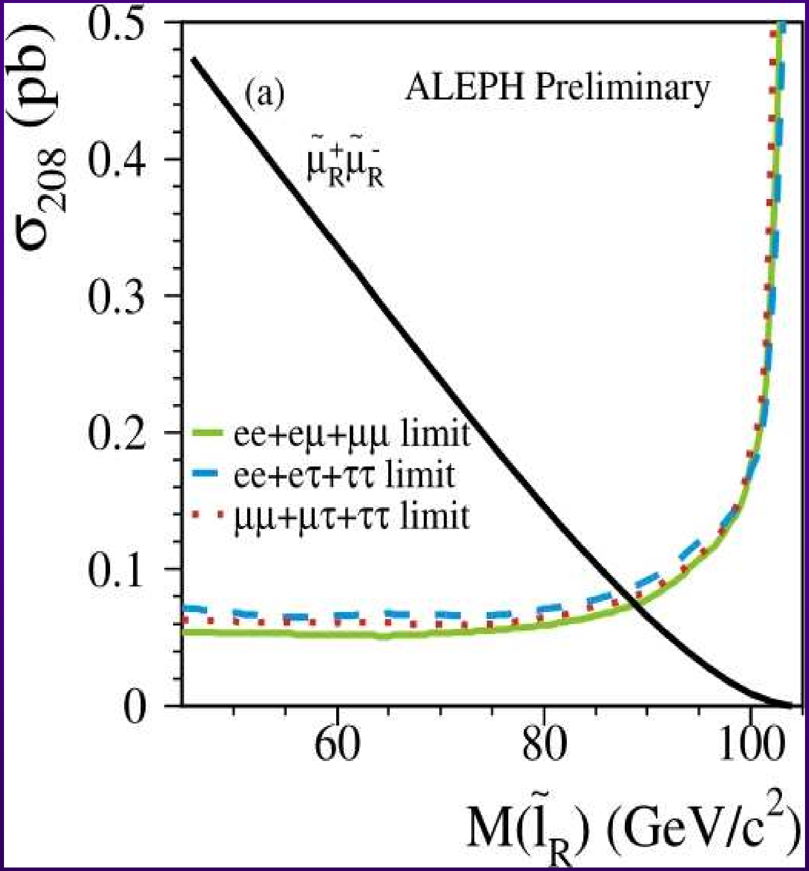

$\tilde{\ell}$
$\tilde{\chi}^0$
ℓ'
$\tilde{\ell}'^*$
λ
ν
ℓ
ℓ''

- $\ell^+ \ell^- + E_{miss}$
- Recycle other channels …

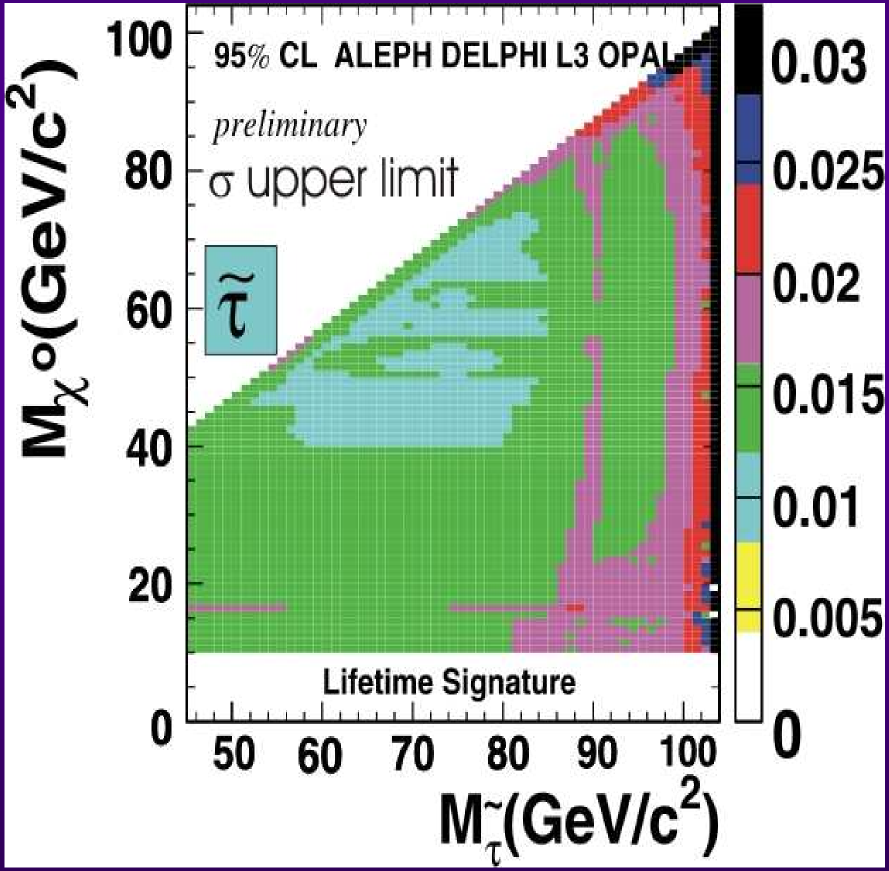
- $6\ \ell\ + E_{miss}$
- Very low background

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

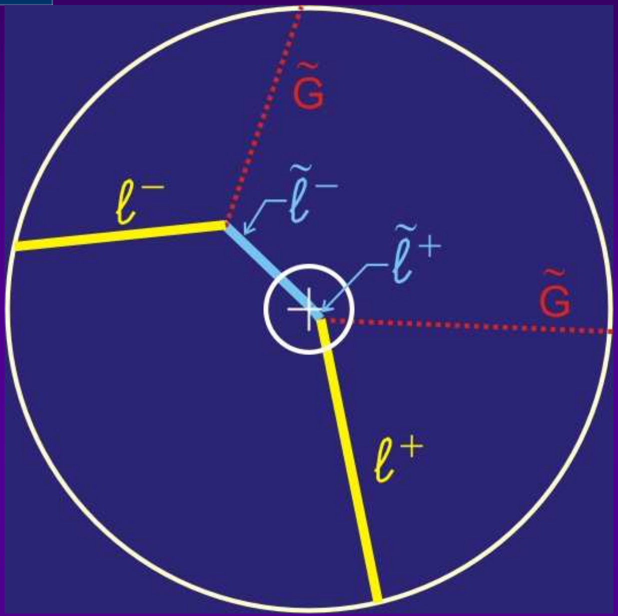
Direct Decays (ALEPH)



Indirect Decays (ADLO)



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

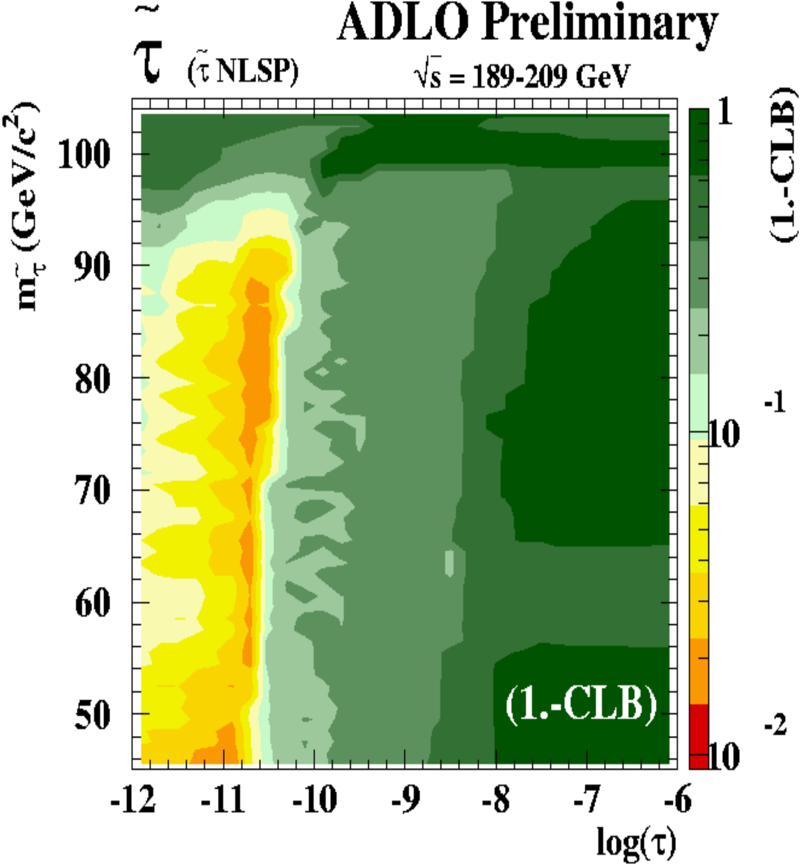

$\tilde{G}$
ℓ^-
$\tilde{\ell}^-$
$\tilde{\ell}^+$
$\tilde{G}$
ℓ^+

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

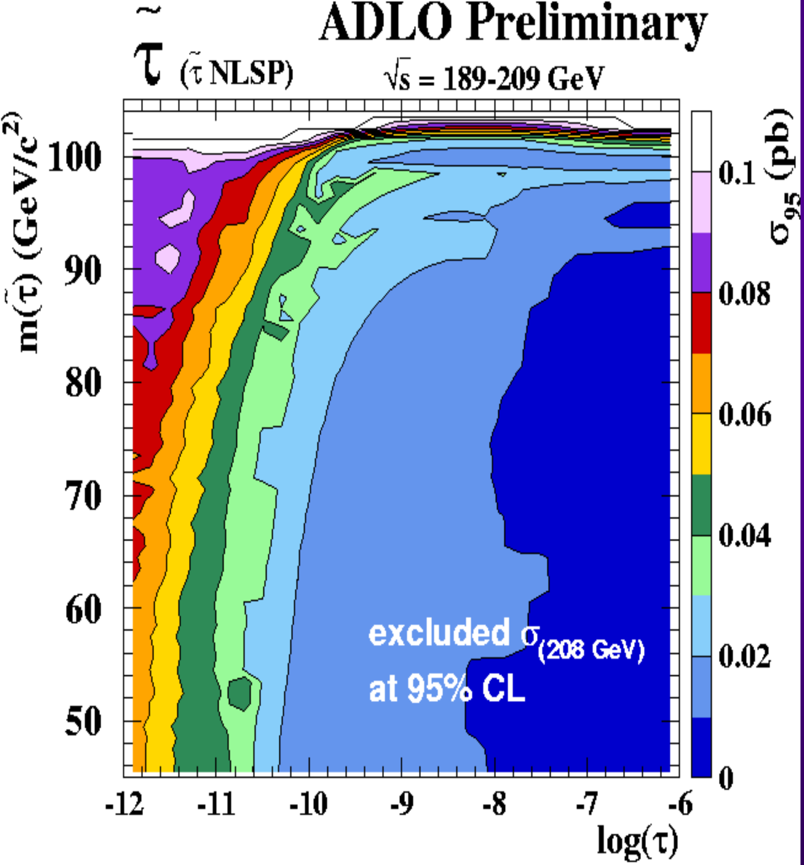
1) Very Short Lifetime
   ⇒ Tracks from origin
2) Short Lifetime
   ⇒ Large Impact Parameter
3) Medium Lifetime
   ⇒ Kinked Tracks
4) Long Lifetime
   ⇒ Heavy Stable Charged

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**
- $\tilde{\chi}^0_1\,\tilde{\chi}^0_2,\ \tilde{\chi}^0_2\,\tilde{\chi}^0_2,\ \tilde{\chi}^+_2\,\tilde{\chi}^-_2$ …
  - **Cascades can plug exclusion holes**
- **Sgoldstinos, AMSB, light gluinos,…**
  - **A bit on the margins …**

- $\tilde{\ell}^+_1\tilde{\ell}^-_1$
  - **All types of SUSY**
- $\tilde{\ell}^+_1\tilde{\ell}^-_2,\ \tilde{\ell}^+_2\tilde{\ell}^-_2$
  - **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**
  - $\tilde{G}$, $\tilde{\chi}^0$, $\tilde{\ell}_R$, $\tilde{\tau}_1$ … ***short***, ***long*** **or** ***all*** **lifetime**
  - Λ, M, N, **tan**β
- ***mSUGRA / CMSSM***
  - $\tilde{q}$, $\tilde{\ell}$, $\tilde{\chi}^{\pm}$
  - M_2 ***vs.*** μ **for different tan**β
  - $\tilde{\chi}^0$ **LSP (CDM candidate)**

Main Frameworks

"General" MSSM

M_1,M_2,M_3	Gaugino masses
$m_{\tilde{f}}$	Sfermion masses
v,tanβ,m_A,μ	Higgs(ino) mass/mixing
A_U, A_D, A_L,	Trilinear sfermion/higgs couplings

} SM + 105
(+45 RPV)
→ FCNC,…

mSUGRA+ (gravity mediation)

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

} "LEP" CMSSM

SM + 4 ½ (or 6) parameters

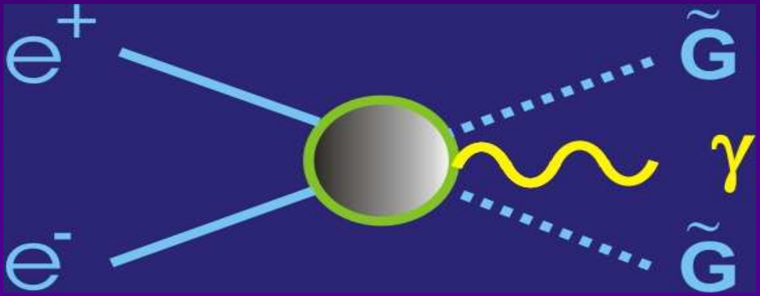
GMSB (gauge mediation)

F	(or $M_{\tilde{G}}$) SUSY Breaking scale
Λ	Sparticle mass scale
M	Messenger mass
N	Number messenger sets
tanβ	v_u/v_d, ratio of higgs vevs
sign(μ)	Sign(Higgs mixing param)

SM + 5 ½ parameters

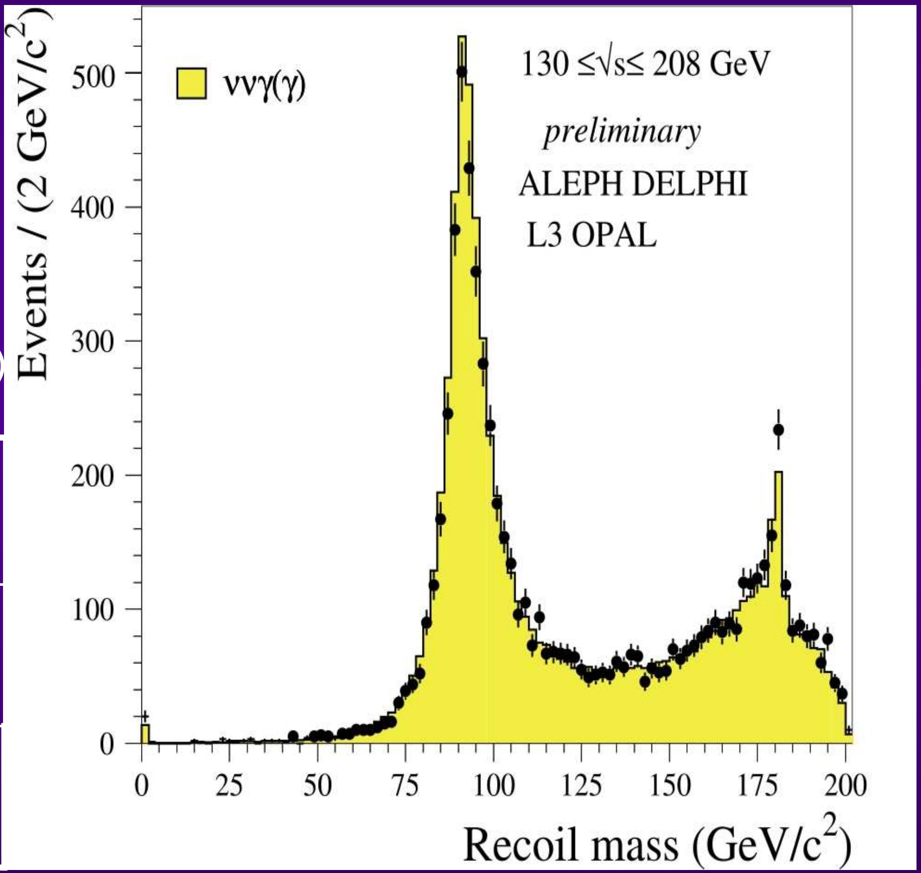
$\tilde{G}$: Absolute mass limit

- **Photon with Emiss**



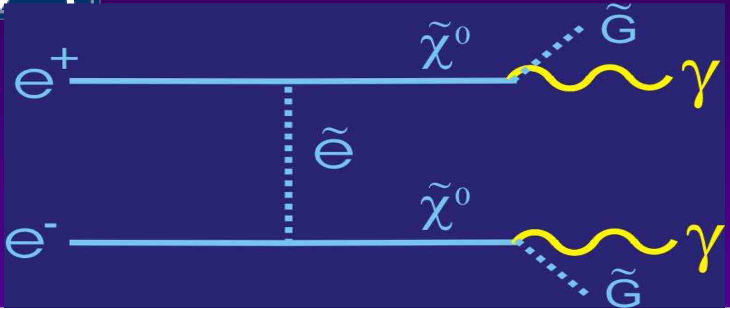
(cross-sections from Brignole, Feruglio, Zwirner)

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



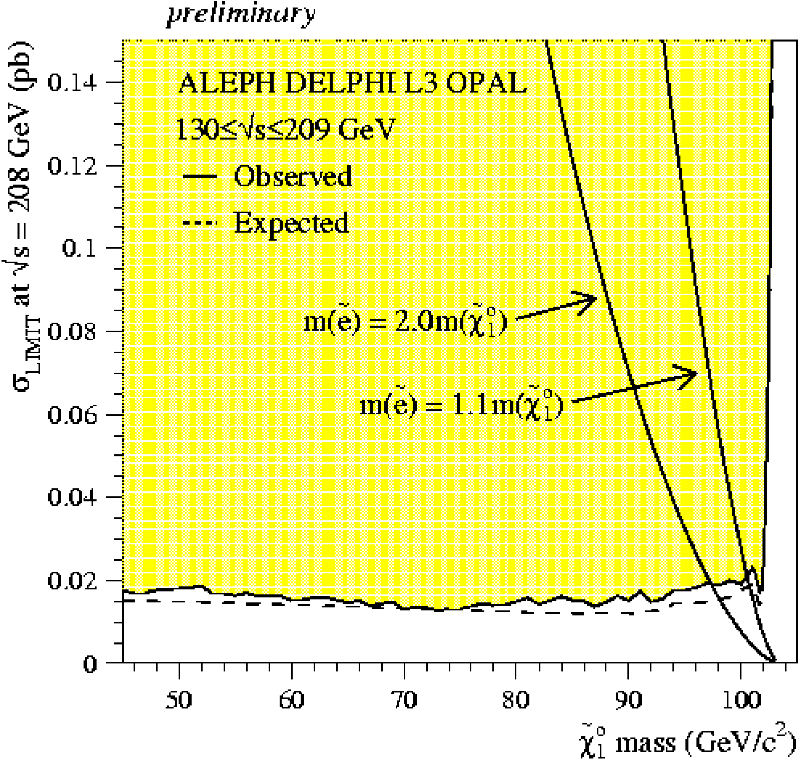
(Tevatron I has similar sensitivity)

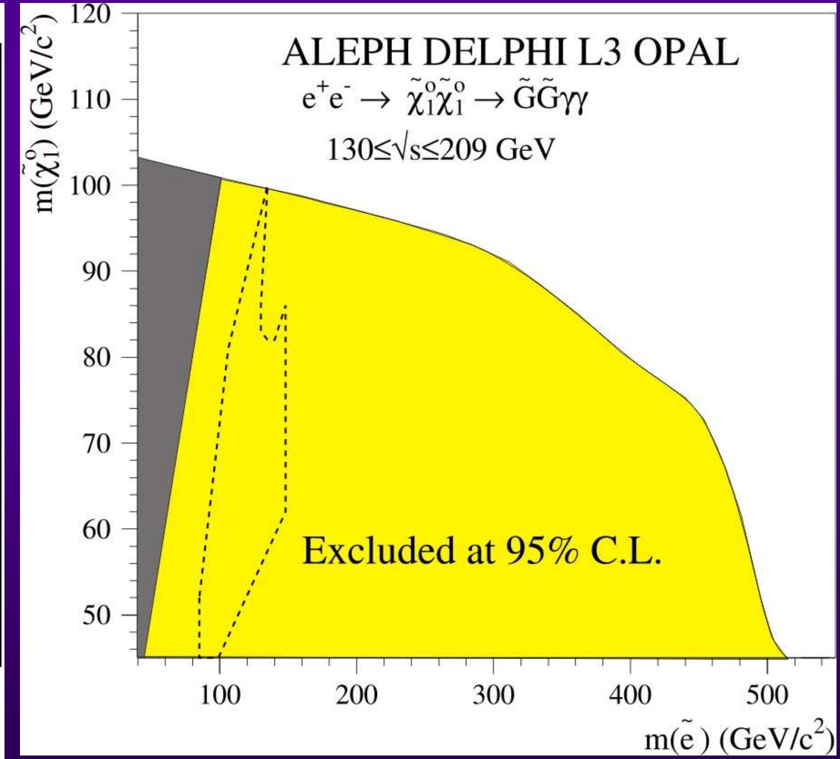
GMSB: $\tilde{\chi}^0$ NLSP $\gamma\gamma$ +Emiss



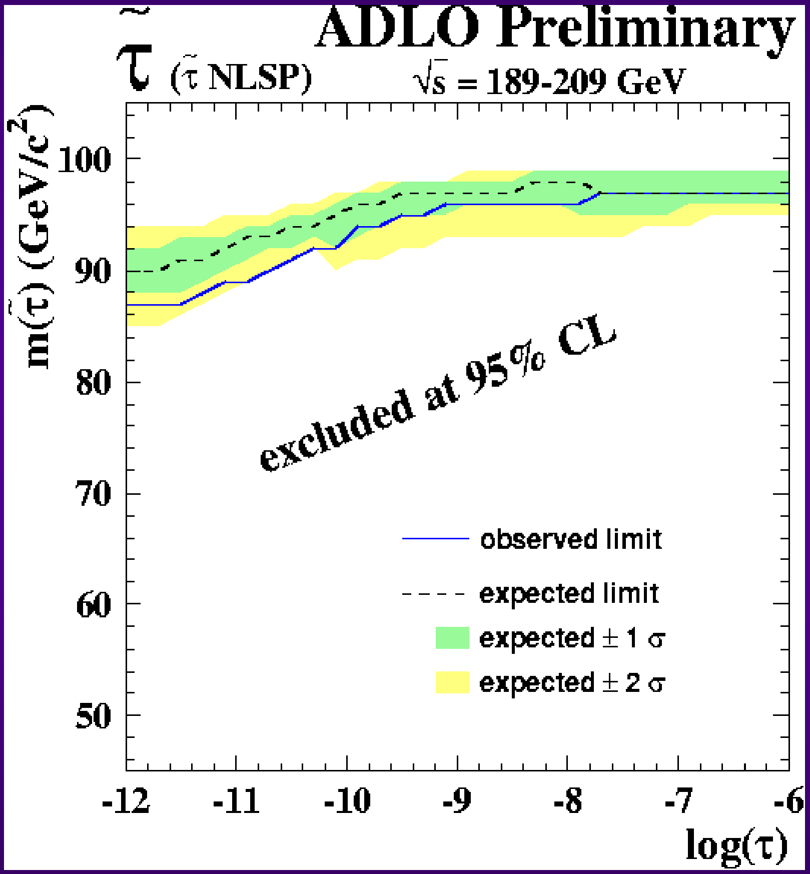
e^+
e^-
$\tilde{e}$
$\tilde{\chi}^0$
$\tilde{\chi}^0$
$\tilde{G}$
$\tilde{G}$
γ
γ

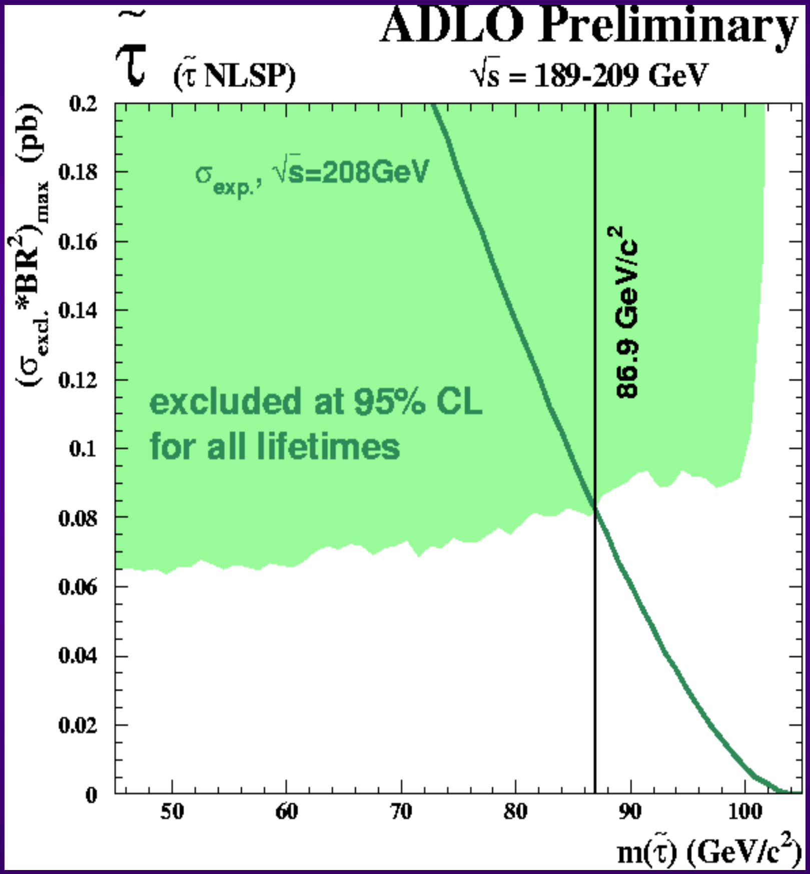
- Dominant for χ^0 NLSP and short lifetimes
- Inspired by CDF $ee\gamma\gamma$ event …





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



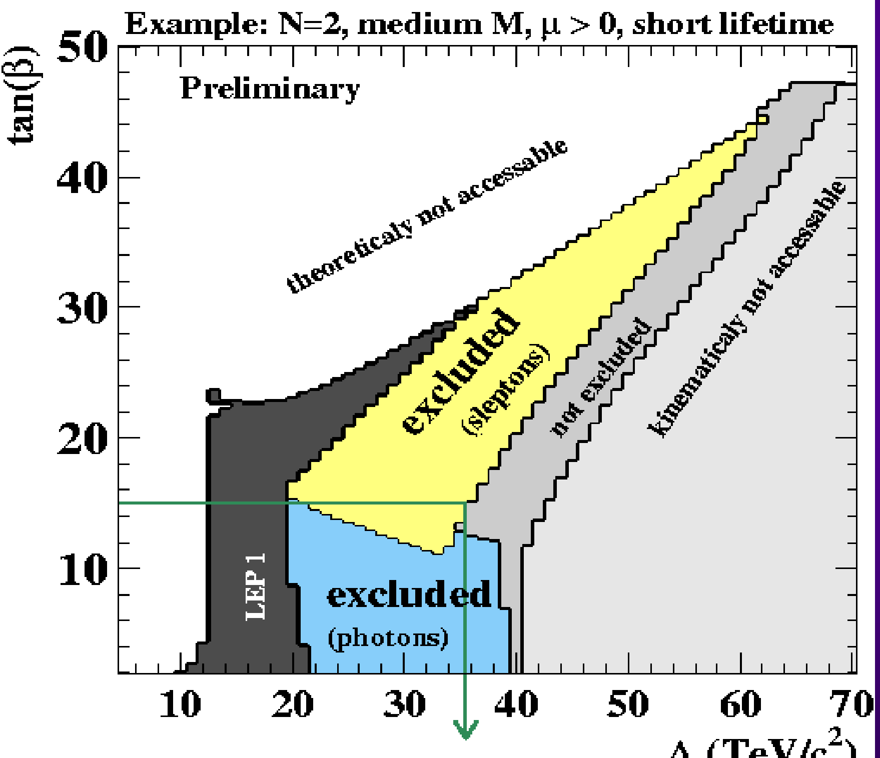


Cross-sections from model scans using Dimopoulos, Thomas, Wells
Nucl.Phys.B488:39-91,1997

GMSB: comparison with Run II benchmark

Scan in GMSB parameter space following

Dimopoulos, Thomas, Wells, Nucl. Phys. B488 (1997) 39

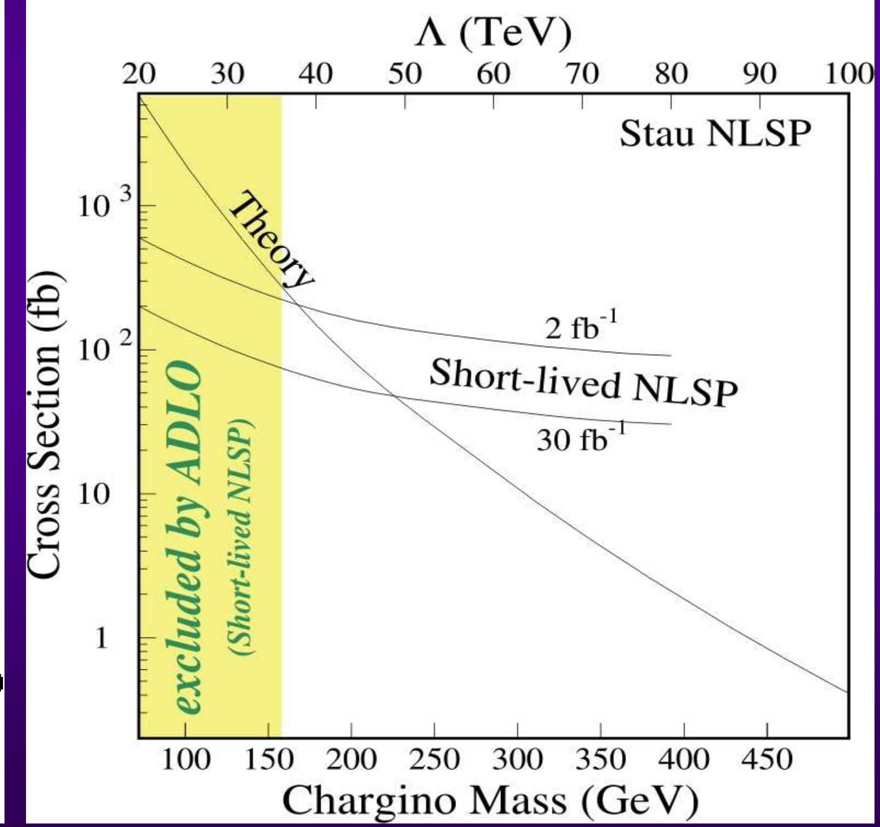


tan(β) = 15 ⇒

Λ > 35.5 TeV/c²

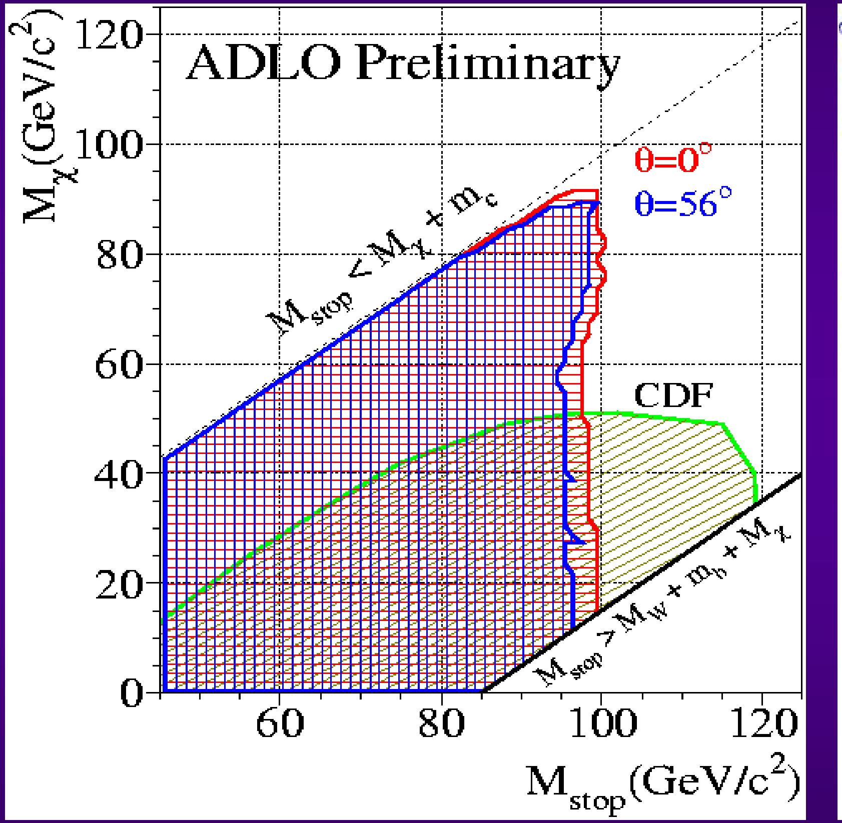
J. Quian, hep-ph/9903548 v2:

$$N = 2,\ \frac{M}{\Lambda} = 3,\ tan\beta = 15,\ \mu > 0$$

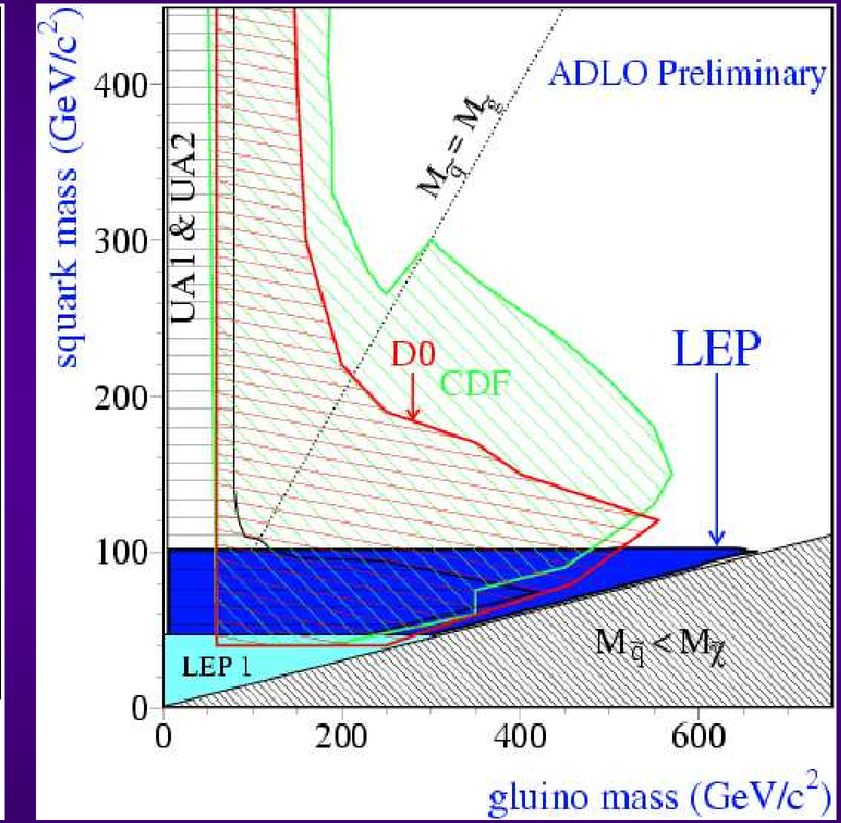


CMSSM: $\tilde{q}$ NLSP

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



General squarks



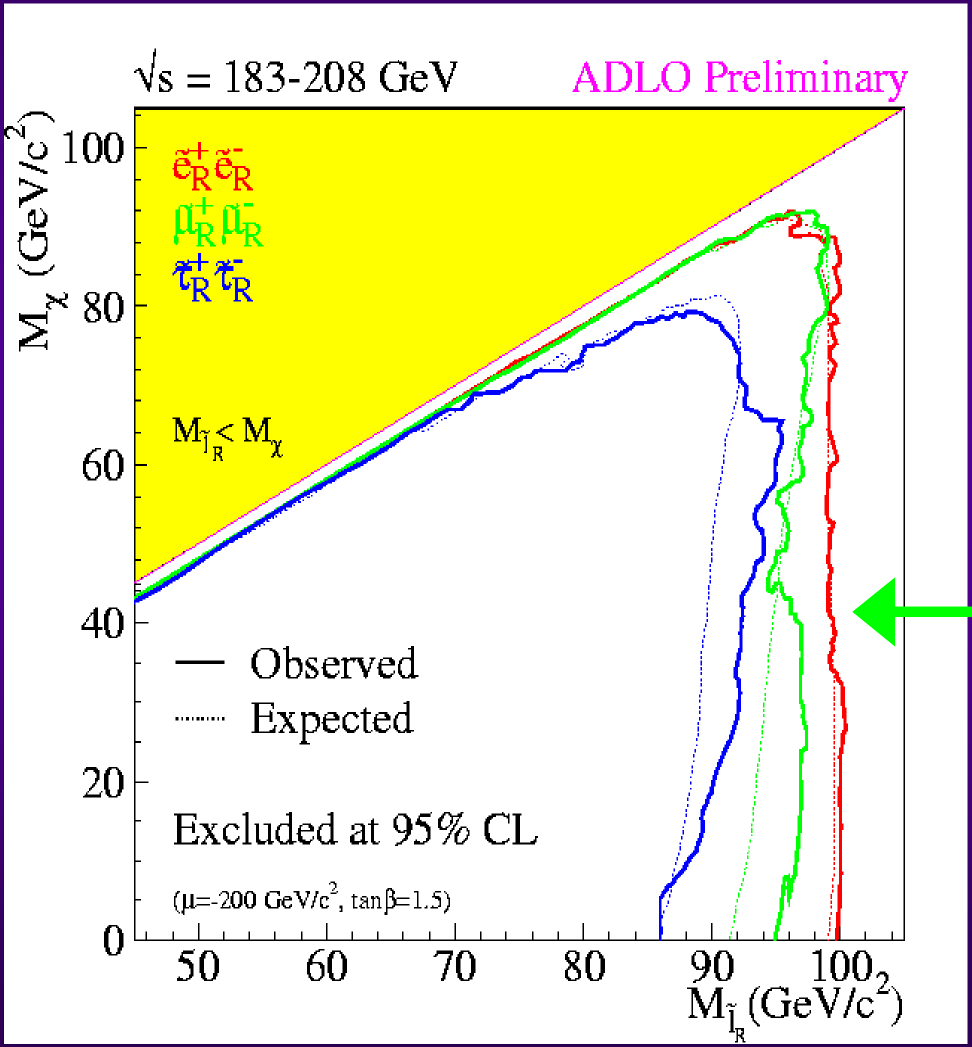
ALEPH: - $\Delta M \approx 0$ **excl. < 63 GeV**

- 4 body decays too

Assumes: - 5 degenerate quarks

- GUT relations

CMSSM: $\tilde{\ell}$ NLSP



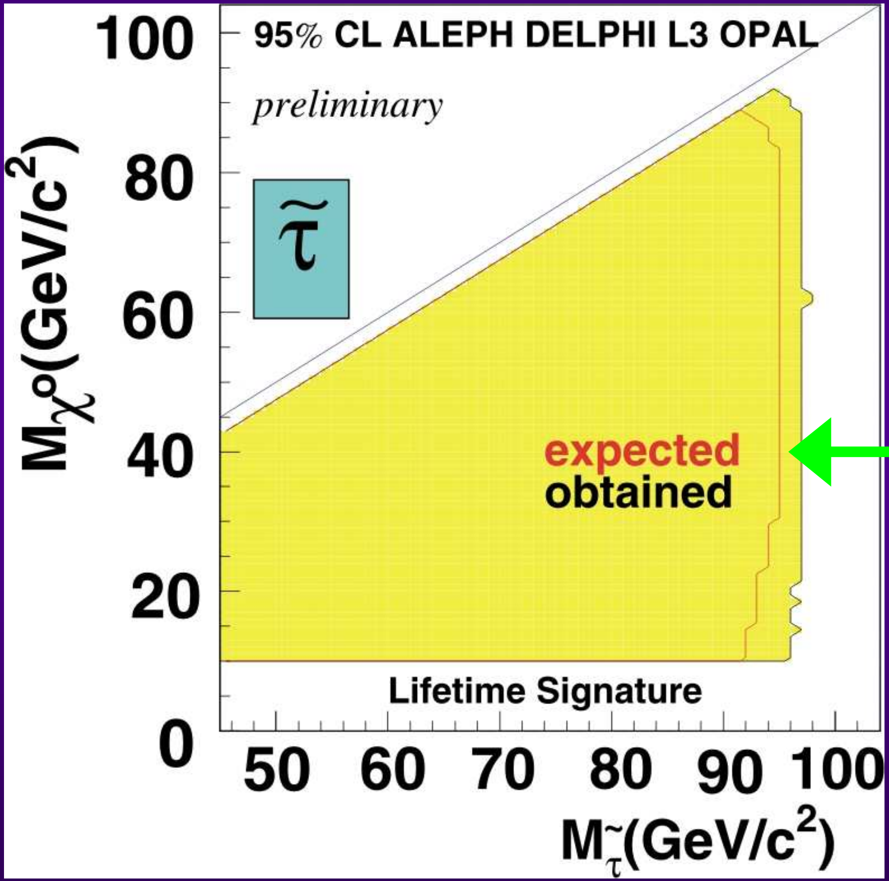
Mass limits for **40** GeV $\tilde{\chi}^0$

(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: $\tilde{\ell}$ NLSP with RPV

Eg: stau indirect decays, λ (LLE)



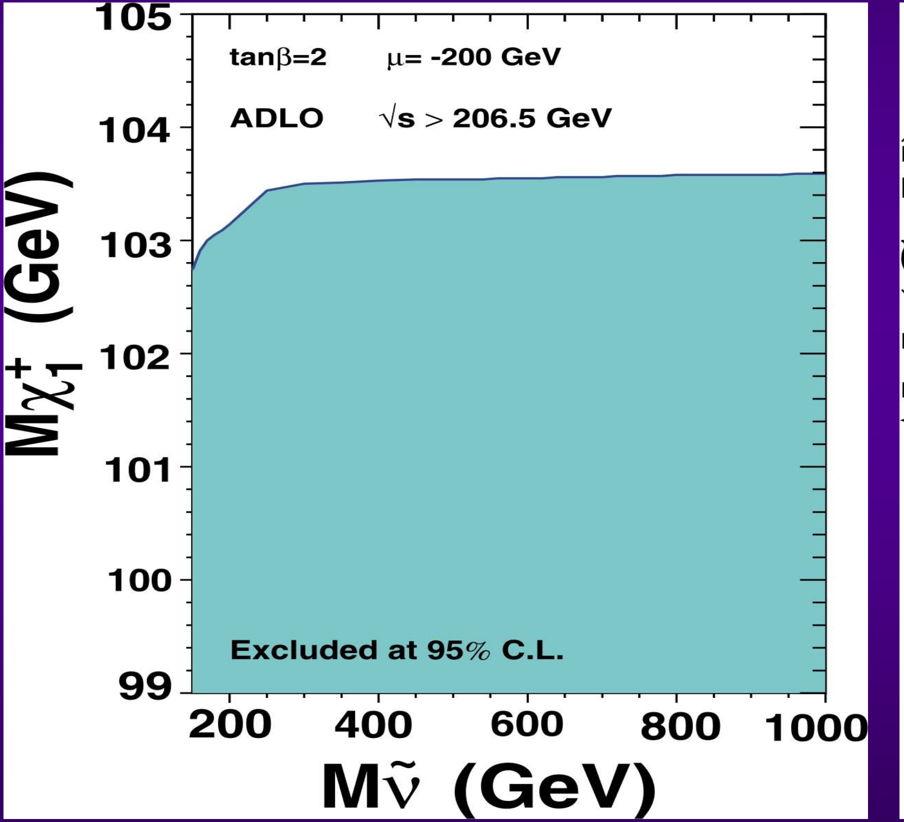
Mass limits for 40 GeV $\tilde{\chi}^0$ (ADLO)

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:

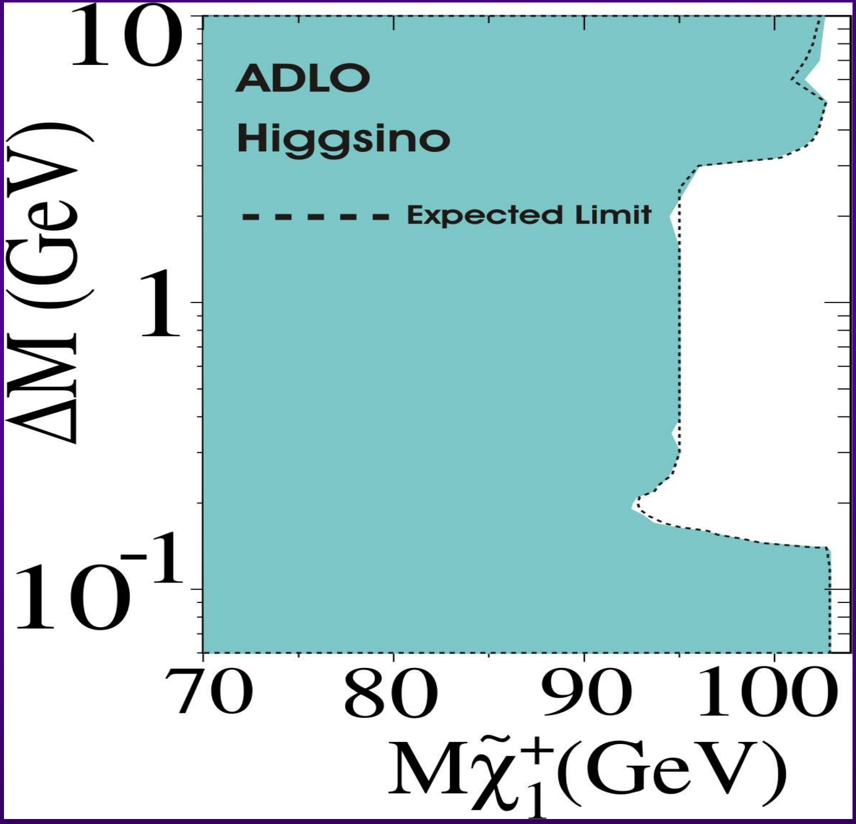
(Benchmark: tanβ=2, μ=-200 GeV)



M > 103 GeV

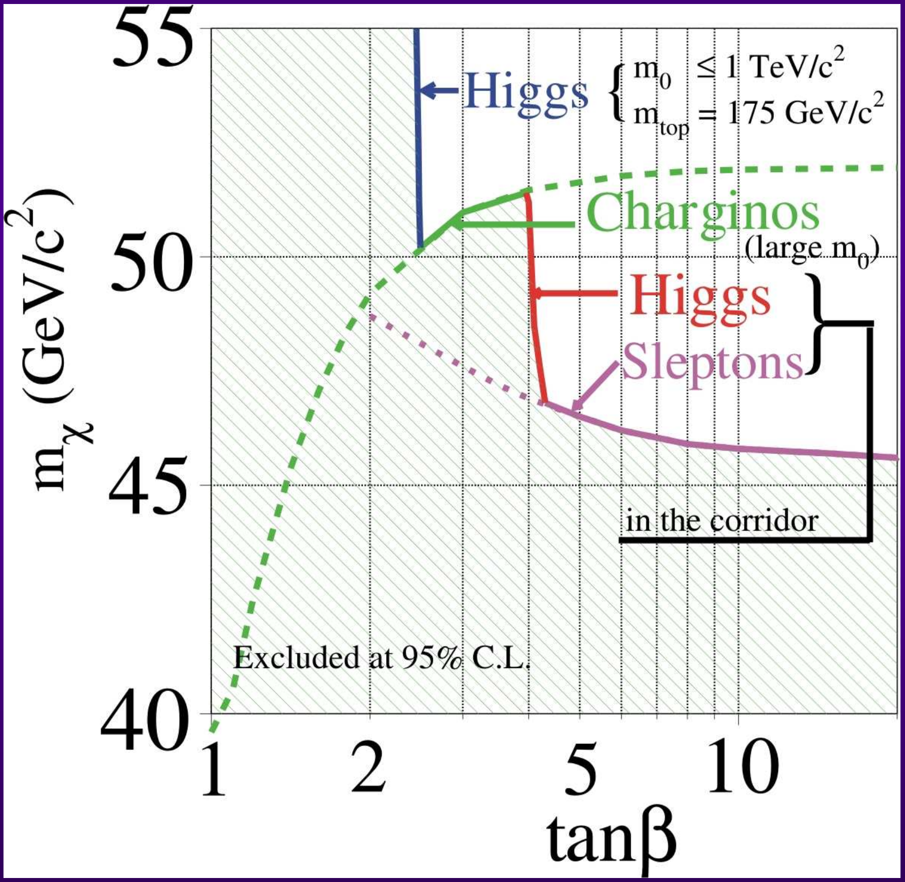
Even small ΔM

(Deep Higgsino Region)



M > 92.4 GeV

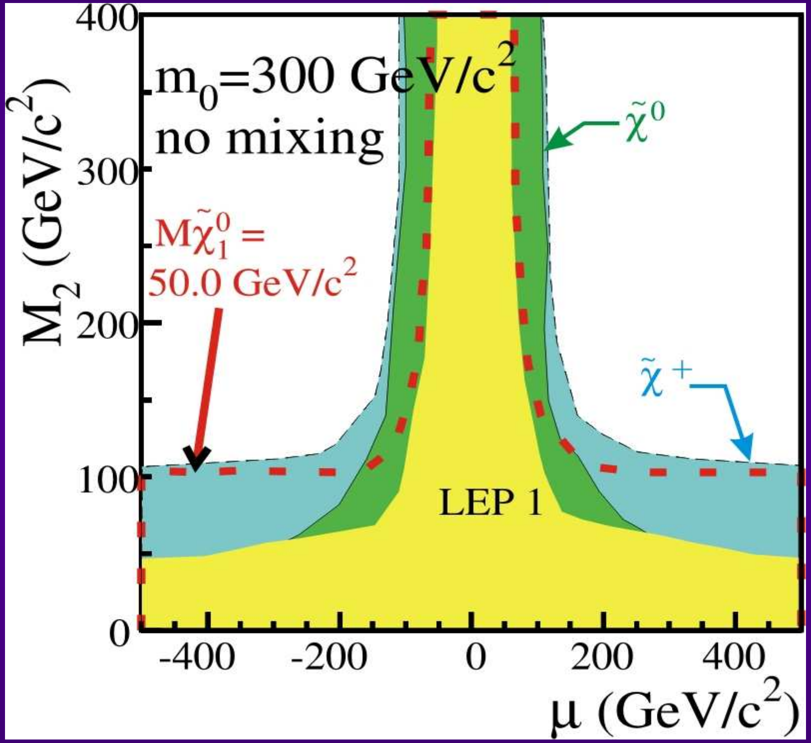
General CMSSM: $\tilde{\chi}^0$ LSP



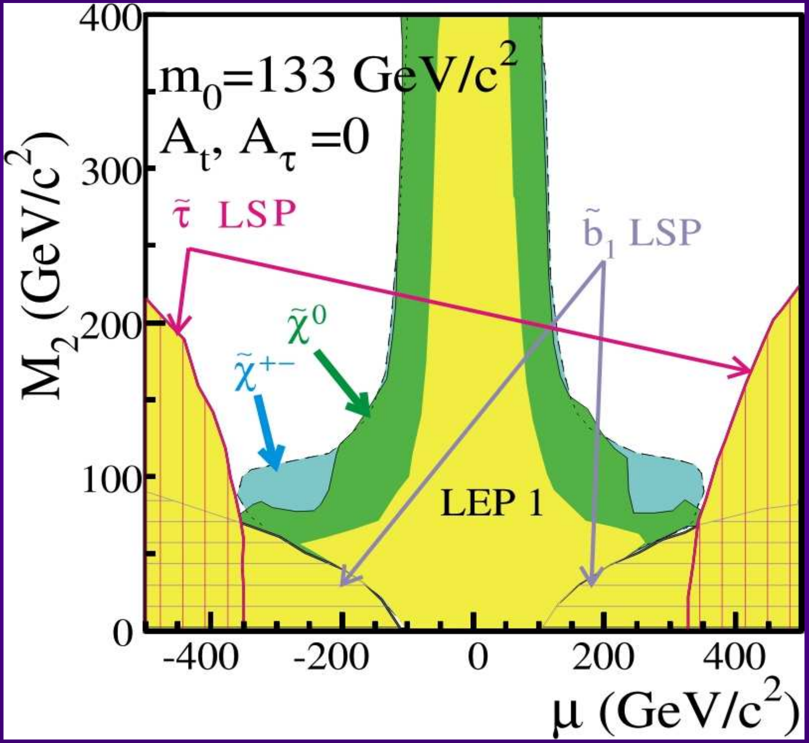
- **Chargino dominant**
  - **Except in "corridor" with $M(\tilde{\nu}) \approx M(\tilde{\chi}^\pm)$**
- **Corridor:**
  - **Sleptons**
- **Higgs:**
  - **$M_h^{95} \Rightarrow M_{\tilde{t}} \Rightarrow M_2(\tan\beta)$**
  - **Corridor stronger: low m_0**
- **Result:**
  - **$M(\tilde{\chi}^0_1) > 45$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

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

No sfermion mixing

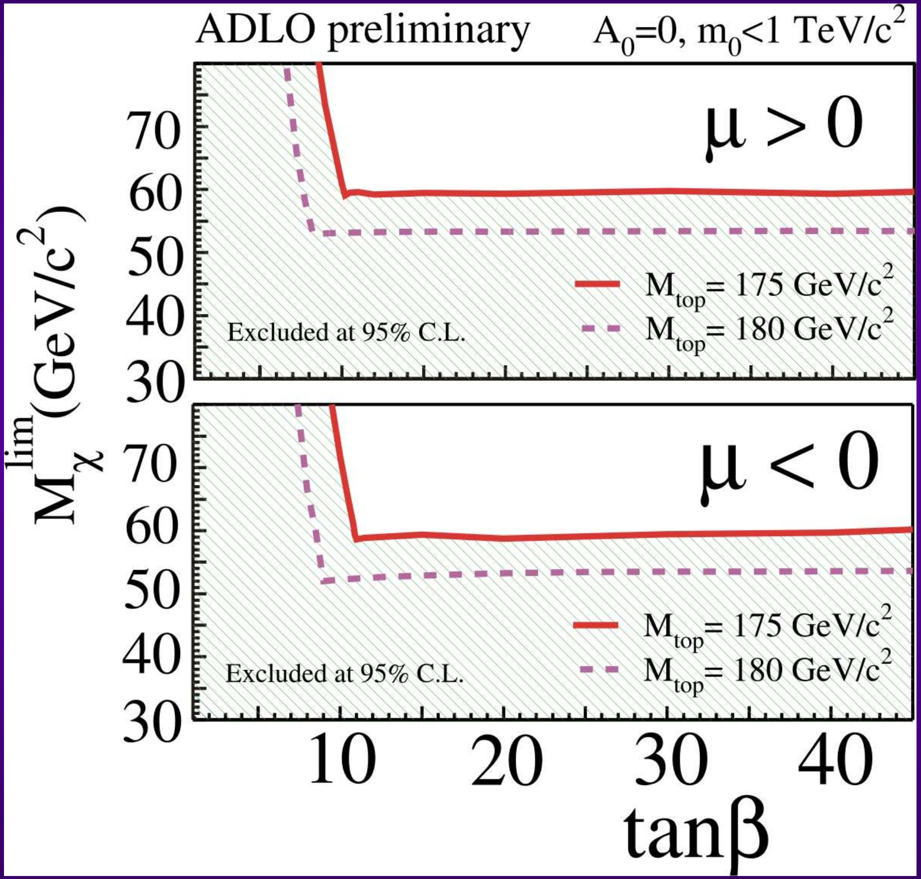


Stau/Sbot Mixing ($A_\tau - \mu \tan\beta$)



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

mSUGRA LSP constraint



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

M_{LSP} > 59 GeV (${M_{top}}$=175 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 ⇒ Null results ⇒ New models ⇒ New searches
- $M(\tilde{\chi}^{\pm}) < E_{beam} \approx 100\ \mathrm{GeV} \Rightarrow M(\tilde{\chi}^{0}) < M(\tilde{\chi}^{\pm})/2 \approx 50\ \mathrm{GeV}$
    - Rather robust constraints with very few loopholes left
- LEP SUSY constraints hard to evade
    - Must look for NLSP beyond our kinematic limit