Searches for Prompt Light Gravitino Production

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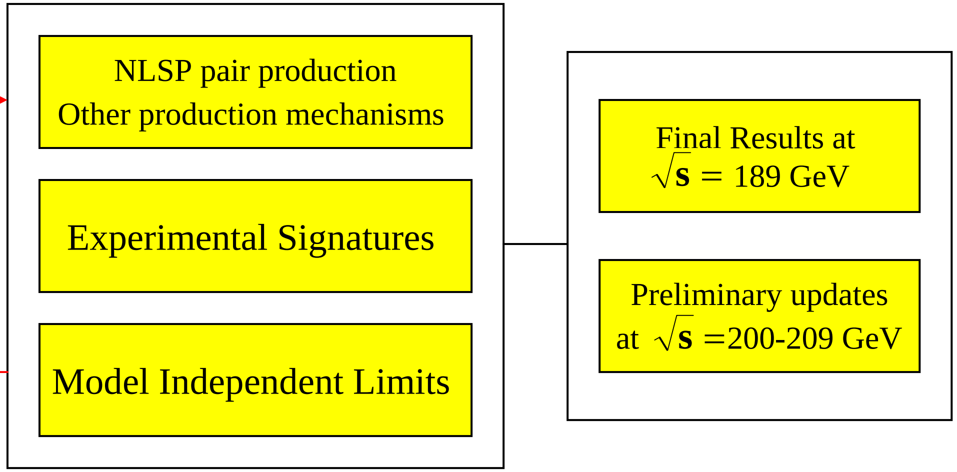
- SUSY models with light gravitinos
- Gauge-Mediated Supersymmetry Breaking

- Neutralino NLSP Scenario
- Slepton NLSP Scenario



- GMSB scan
- Gravitino Pair Production
- GMSB signatures with lifetime
- Summary

SUSY models with a Light Gravitino

- Some SUSY models predict that the LSP is an almost massless gravitino (models with gauge-mediated supersymmetry breaking, no-scale supergravity)
- Richest phenomenology is from GMSB models

Problems with FCNC

Gravitino phenomenologically unimportant

Phenomenology depends on LSP

Gravity

$\mathbf{M} \sim \mathbf{M_P} \sim 10^{18}\,\mathbf{GeV}$

$\sqrt{\mathbf{F}} \sim 10^{11}\,\mathbf{GeV}$

FCNC

$\mathbf{M}_{\tilde{G}} \sim 2.5\ \mathbf{TeV}$

SUSY in hidden sector

$\sqrt{\mathbf{F}} \sim \sqrt{\dfrac{\mathbf{M}}{\mathbf{G_F^{1/2}}}}$

Visible Sector

$\mathbf{e}, \mu, \tau, \ldots\ldots \mathbf{W}^-, \mathbf{Z}^0$

$\tilde{\mathbf{e}}, \tilde{\mu}, \tilde{\tau}, \ldots\ldots \tilde{\mathbf{W}}^-, \tilde{\mathbf{Z}}^0$

Gauge

$10^3 < \mathbf{M} < 10^{15}\,\mathbf{GeV}$

$10^3 < \sqrt{\mathbf{F}} < 10^{10}\,\mathbf{GeV}$

No FCNC

Sspectrum $\Lambda \sim \mathbf{k}\dfrac{\mathbf{F}}{\mathbf{M}}$

$\mathbf{M}_{\tilde{G}} < 1\ \mathbf{GeV}$

Well defined particle spectrum

No FCNC

LSP = light gravitino

Phenomenology depends on NLSP

R-parity conservation assumed throughout this talk

Experimental Signatures

Scale of SUSY breaking $\sqrt{F}$ determines $\tilde{G}$ mass and NLSP lifetime

$$\mathbf{M}_{\tilde{G}} \cong 2.37\times10^{-2}\left(\frac{\sqrt{\mathbf{F}}}{10\ \mathbf{TeV}}\right)^{2}\ \mathbf{eV} \qquad \mathbf{c}\tau(\mathbf{NLSP}) \cong \left(\frac{\mathbf{M}_{\mathbf{NLSP}}}{100\ \mathbf{GeV}}\right)^{-5}\left(\frac{\sqrt{\mathbf{F}}}{10\ \mathbf{TeV}}\right)^{4}\ \mu\mathbf{m}$$

Phenomenology dictated by the NLSP (usually either $\tilde{\chi}_1^0$ or $\tilde{l}^{\pm}$) and on NLSP lifetime (decay length w.r.t detector volume)

NLSP lifetime →

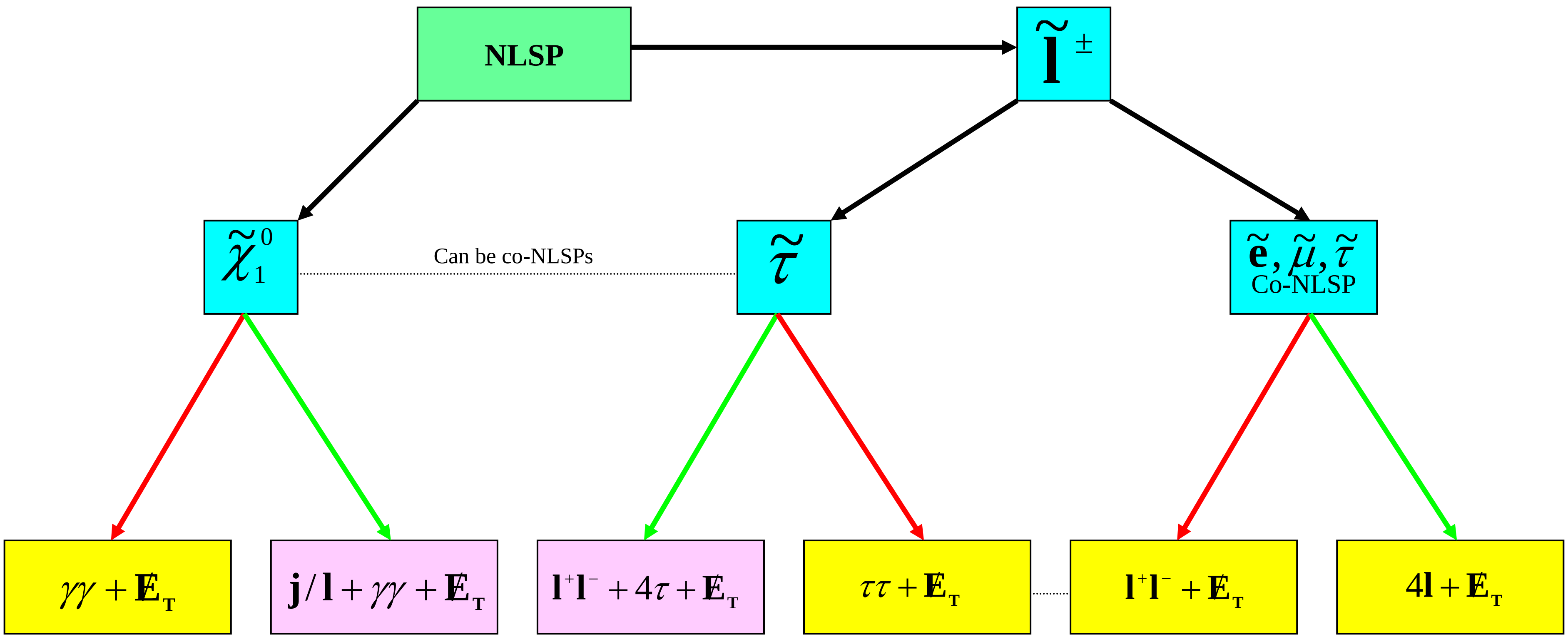
NLSP	short	intermediate	long
$\tilde{\chi}_1^0$	photons + $\not{E}_T$	Non-pointing photons + $\not{E}_T$	as in gravity-mediated SUSY
$\tilde{l}^{\pm}$	leptons + $\not{E}_T$	Kinked charged tracks + $\not{E}_T$	Long-lived heavy charged particles

(Pink cells:) Scenarios with particularly low SM backgrounds

This talk: Prompt Production (→ short)

Unusual signatures in the case of intermediate $\tau_{\mathbf{NLSP}}$ (→ intermediate)

Experimental Signatures



Contriubute to exclusion regions from GMSB scan

NLSP Pair Production

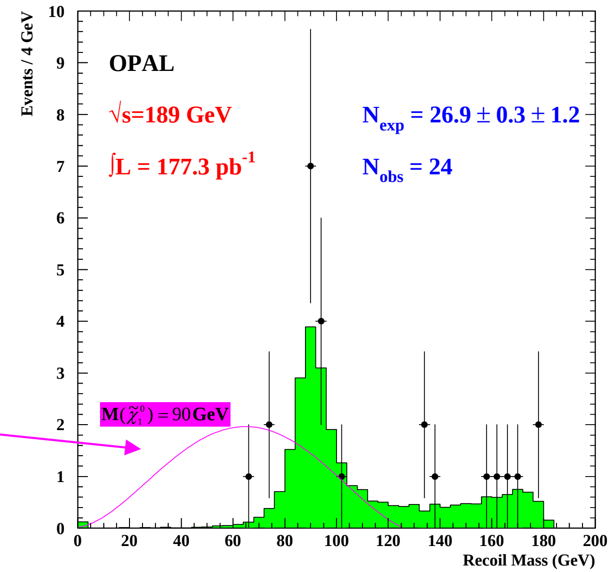
Other sparticle pair production, associated pair production

Neutralino NLSP Pair Production

Acoplanar photons

$$e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow (\tilde{G}\gamma)(\tilde{G}\gamma) \Longrightarrow \gamma\gamma + \not{E}_T$$

Irreducible SM background from $e^+e^- \rightarrow \nu\bar{\nu}\gamma\gamma$

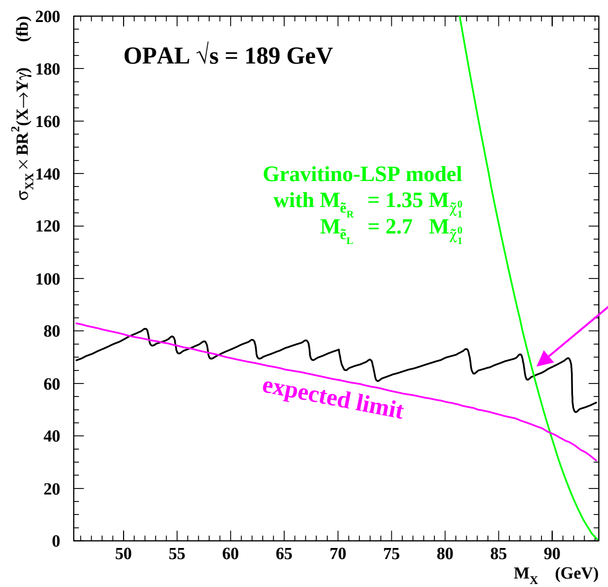


Large fraction of signal contribution expected at M_{recoil} values well below the Z peak

Selected events can be classified according to maximum mass for which they remain kinematically consistent with the above decay sequence (M_X^{max})

OPAL published results from $\sqrt{s}$ =189 GeV

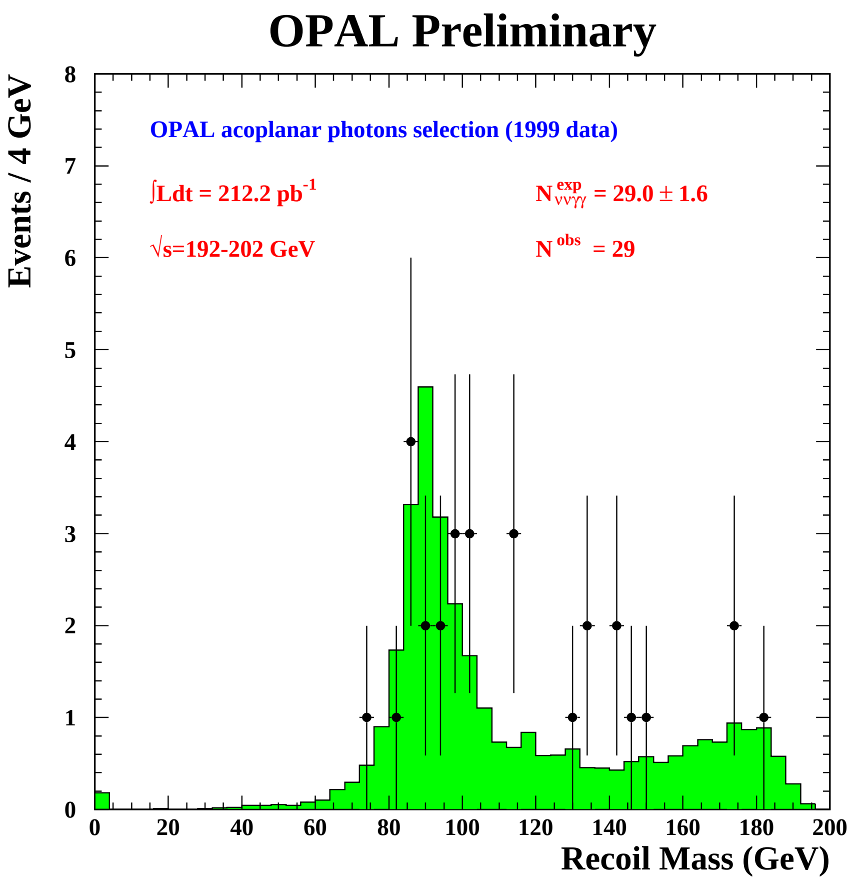
M_X(GeV)	Selection Efficiency (%)	Selection efficiency with $M_X^{max} > M_X - 5$ GeV	N_{data}	$N_{\nu\bar{\nu}\gamma\gamma}$
50	70.2 +/- 1.2	67.7 +/- 1.3	14	13.67 +/- 0.20
60	74.0 +/- 1.1	71.1 +/- 1.2	11	10.05 +/- 0.18
70	71.4 +/- 1.2	69.2 +/- 1.2	9	7.22 +/- 0.15
80	72.3 +/- 1.2	68.7 +/- 1.4	7	4.81 +/- 0.13
90	71.3 +/- 1.2	67.5 +/- 1.3	5	2.40 +/- 0.09
94	72.2 +/- 1.2	70.4 +/- 1.2	3	1.34 +/- 0.07

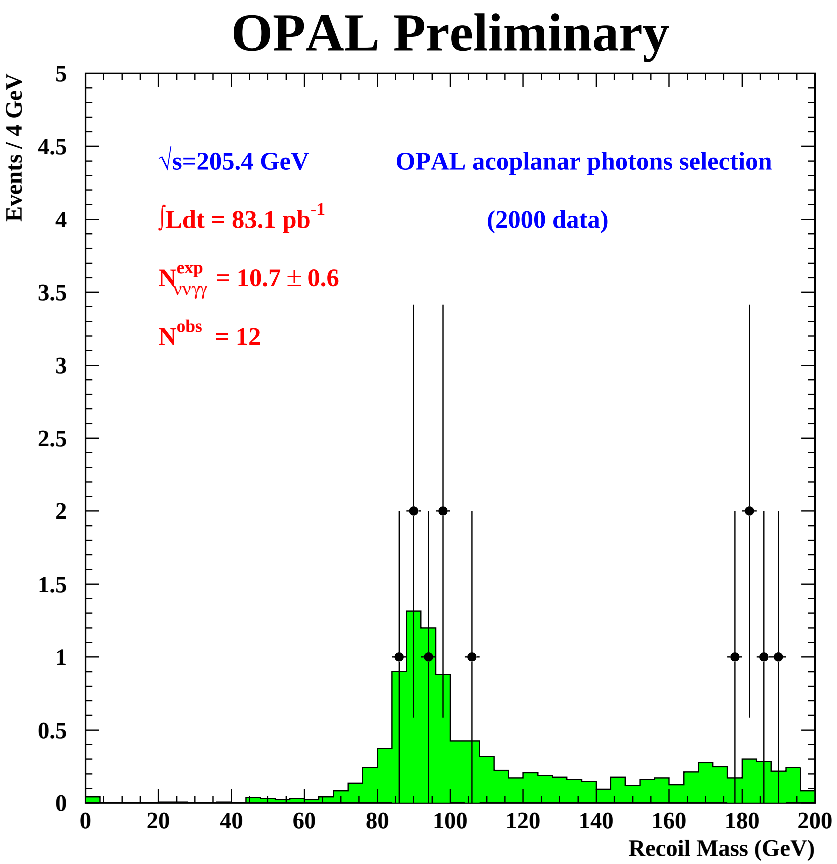


NLSP = $\tilde{B}$

$M(\tilde{\chi}_1^0) > 88.3$ GeV @95% CL

Update of OPAL Acoplanar Photons Selection





No evidence for non-Standard Model contributions (especially in low recoil-mass region)

Other Channels: Neutralino NLSP

Other production channels:

$$\mathbf{e^+e^-} \rightarrow \tilde{\mathbf{l}}^+\tilde{\mathbf{l}}^- \rightarrow (\mathbf{l}^+\tilde{\chi}_1^0)(\mathbf{l}^-\tilde{\chi}_1^0) \rightarrow (\mathbf{l}^+\gamma\tilde{\mathbf{G}})(\mathbf{l}^-\gamma\tilde{\mathbf{G}})$$

⇒ $\mathbf{l^+l^-}\gamma\gamma + \not{\mathbf{E}}_\mathbf{T}$

$$\mathbf{e^+e^-} \rightarrow \chi_1^+\chi_1^- \rightarrow (\mathbf{W}^{(*)+}\tilde{\chi}_1^0)(\mathbf{W}^{(*)-}\tilde{\chi}_1^0) \rightarrow (\mathbf{W}^{(*)+}\gamma\tilde{\mathbf{G}})(\mathbf{W}^{(*)-}\gamma\tilde{\mathbf{G}})$$

⇒ Leptons and/or jets $+\gamma\gamma + \not{\mathbf{E}}_\mathbf{T}$

$$\mathbf{e^+e^-} \rightarrow \chi_2^0\chi_1^0 \rightarrow \mathbf{Z}^{(*)}\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow (\mathbf{Z}^{(*)}\gamma\tilde{\mathbf{G}})(\gamma\tilde{\mathbf{G}})$$

⇒ Leptons or jets $+\gamma\gamma + \not{\mathbf{E}}_\mathbf{T}$

Separate selections into high/low multiplicity parts (depending on W,Z final states)

Efficiencies depend on mass-difference of NLSP and produced particles

⇒ Limits in $[\mathbf{M}(\mathbf{X}),\mathbf{M}(\tilde{\chi}_1^0)]$ plane: $\mathbf{X} = \tilde{\mathbf{l}}^+, \tilde{\chi}_1^+, \tilde{\chi}_2^0$

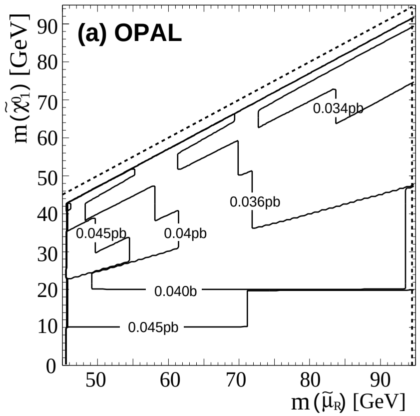
Other Channels: Neutralino NLSP

~ model independent cross-section limits at $\sqrt{s} = 189\,\mathbf{GeV}$

$$\sigma(\mathbf{e}^+\mathbf{e}^- \to \tilde{\mu}^+\tilde{\mu}^-)$$
$$\tilde{\mu}^\pm \to \mu^\pm\tilde{\chi}_1^0 \to \mu^\pm\gamma\tilde{\mathbf{G}}$$

Efficiency ~ 30-50%

$$\mu^+\mu^-\gamma\gamma + \not{\mathbf{E}}_\mathbf{T}$$



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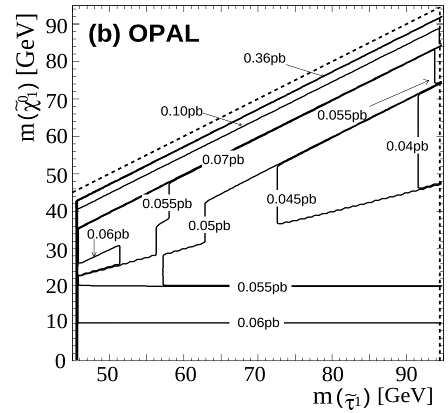


40 - 360 fb

$$\sigma(\mathbf{e}^+\mathbf{e}^- \to \tilde{\tau}^+\tilde{\tau}^-)$$
$$\tilde{\tau}^\pm \to \tau^\pm\tilde{\chi}_1^0 \to \tau^\pm\gamma\tilde{\mathbf{G}}$$

Efficiency ~ 20-40%

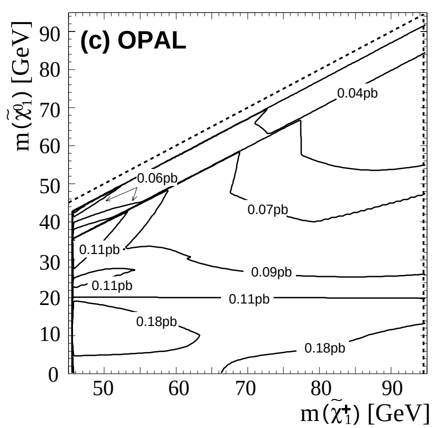
$$\tau^+\tau^-\gamma\gamma + \not{\mathbf{E}}_\mathbf{T}$$

$$\sigma(\mathbf{e}^+\mathbf{e}^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-)$$
$$\tilde{\chi}_1^\pm \to \mathbf{W}^{(*)\pm}\tilde{\chi}_1^0 \to \mathbf{W}^{(*)\pm}\gamma\tilde{\mathbf{G}}$$

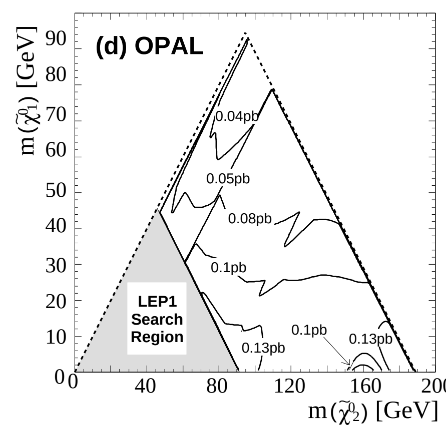
Efficiency ~ 20-50%

$$\mathbf{W}^{(*)+}\mathbf{W}^{(*)-}\gamma\gamma + \not{\mathbf{E}}_\mathbf{T}$$

40 - 180 fb



40 - 130 fb



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

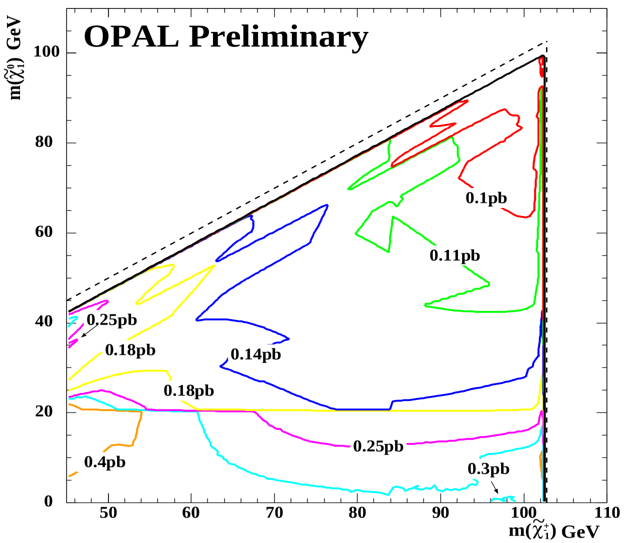
Efficiency ~ 20-50%

$$\mathbf{Z}^{(*)}\gamma\gamma + \not{\mathbf{E}}_\mathbf{T}$$

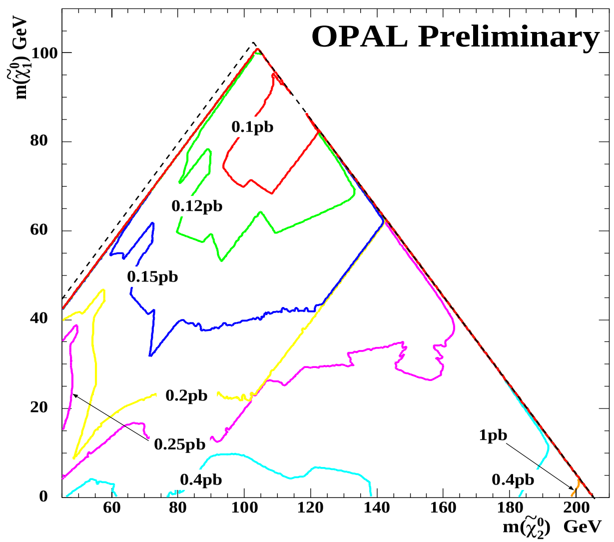
Other Channels: Neutralino NLSP (Update)

~ model independent cross-section limits at $\sqrt{s} = 205.5\,\mathbf{GeV}$

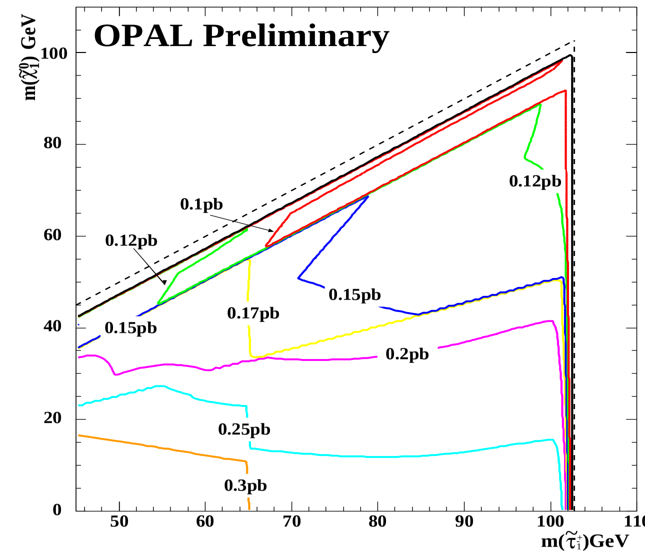
$\mathbf{W}^{(*)+}\mathbf{W}^{(*)-}\gamma\gamma + \not{\mathbf{E}}_T$



$\mathbf{Z}^{(*)}\gamma\gamma + \not{\mathbf{E}}_T$



$\tau^+\tau^-\gamma\gamma + \not{\mathbf{E}}_T$

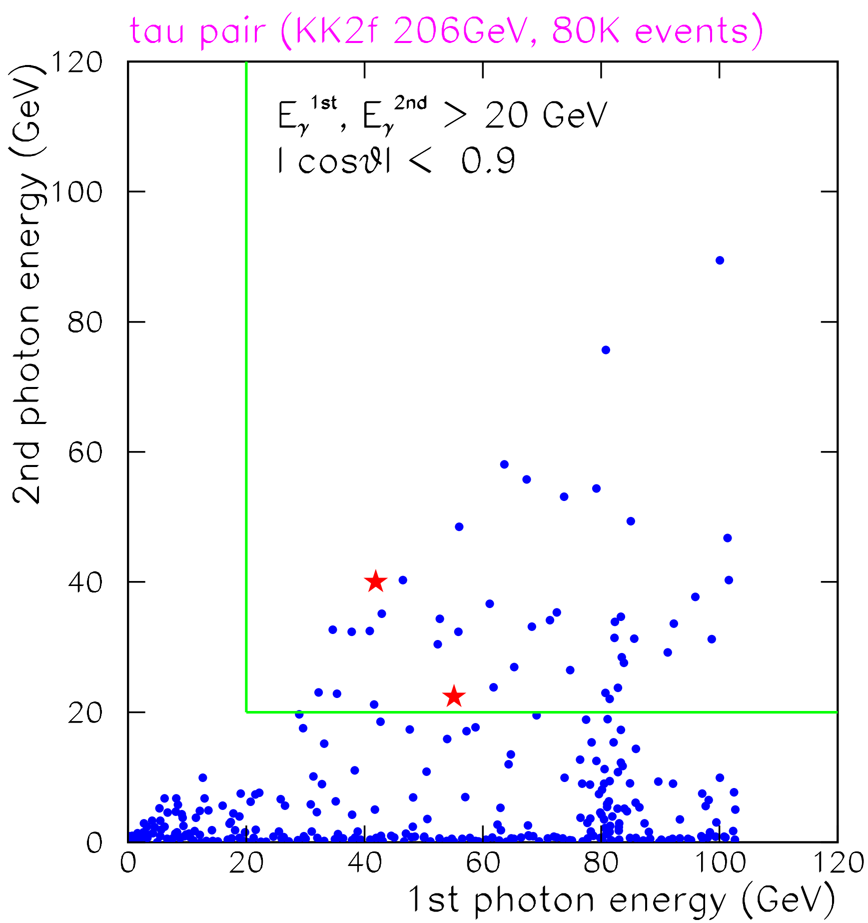


For slepton co-NLSP scenario with large $\mathbf{M}(\tilde{\mathbf{l}}) - \mathbf{M}(\tilde{\chi}_1^0)$

see 4 events where 1.3 +/- 0.3 are expected from SM

$\mathbf{M}(\tilde{\mathbf{l}}) - \mathbf{M}(\chi)$	N(data)	N_{SM}(MC)
$3-10\,\mathbf{GeV}$	1	0.5 +/- 0.2
$10\,\mathbf{GeV} - \mathbf{M}(\tilde{\mathbf{l}})/2$	2	0.7 +/- 0.2
$\mathbf{M}(\tilde{\mathbf{l}})/2 - \mathbf{M}(\tilde{\mathbf{l}})$	4	1.3 +/- 0.3

$l^+l^-\gamma\gamma$ Events



2/4 events have a single high-energy photon consistent with radiative return to the Z^0

Other 2 each have 2 high energy photons

(55 GeV, 22 GeV) **(42 GeV, 40 GeV)**

Background in this kinematic regime is essentially $\mathbf{e^+e^-} \rightarrow \tau^+\tau^-\gamma\gamma$

Prob of two events with 2 photons > 20 GeV estimated from $\mathbf{e^+e^-} \rightarrow \tau^+\tau^-\gamma\gamma$ Monte Carlo (assuming only SM background)

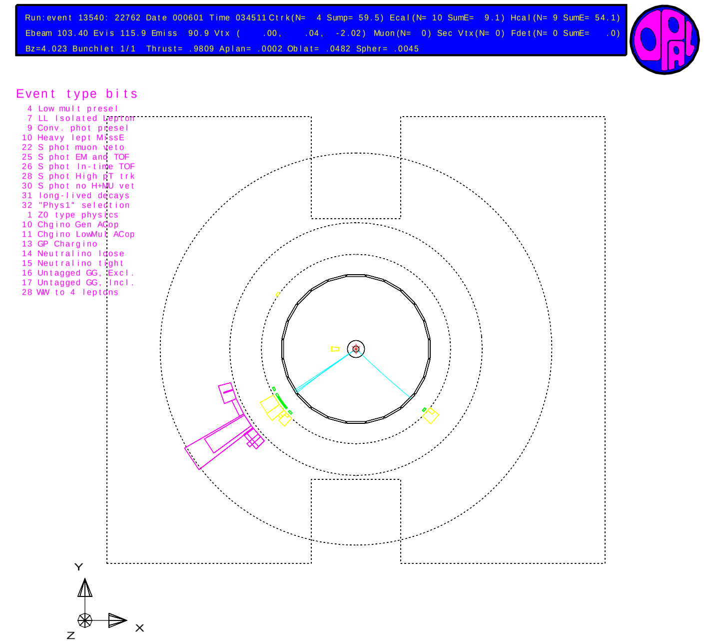
Prob ~ 3 x 10^{-4}

Slepton NLSP Pair Production

Acoplanar leptons

$$e^+e^- \rightarrow \tilde{l}^+\tilde{l}^- \rightarrow (l^+\tilde{G})(l^-\tilde{G}) \Longrightarrow l^+l^- + \not{E}_T$$

Large irreducible SM background from W pair production



Published results at 183-189 GeV CERN EP/99-122

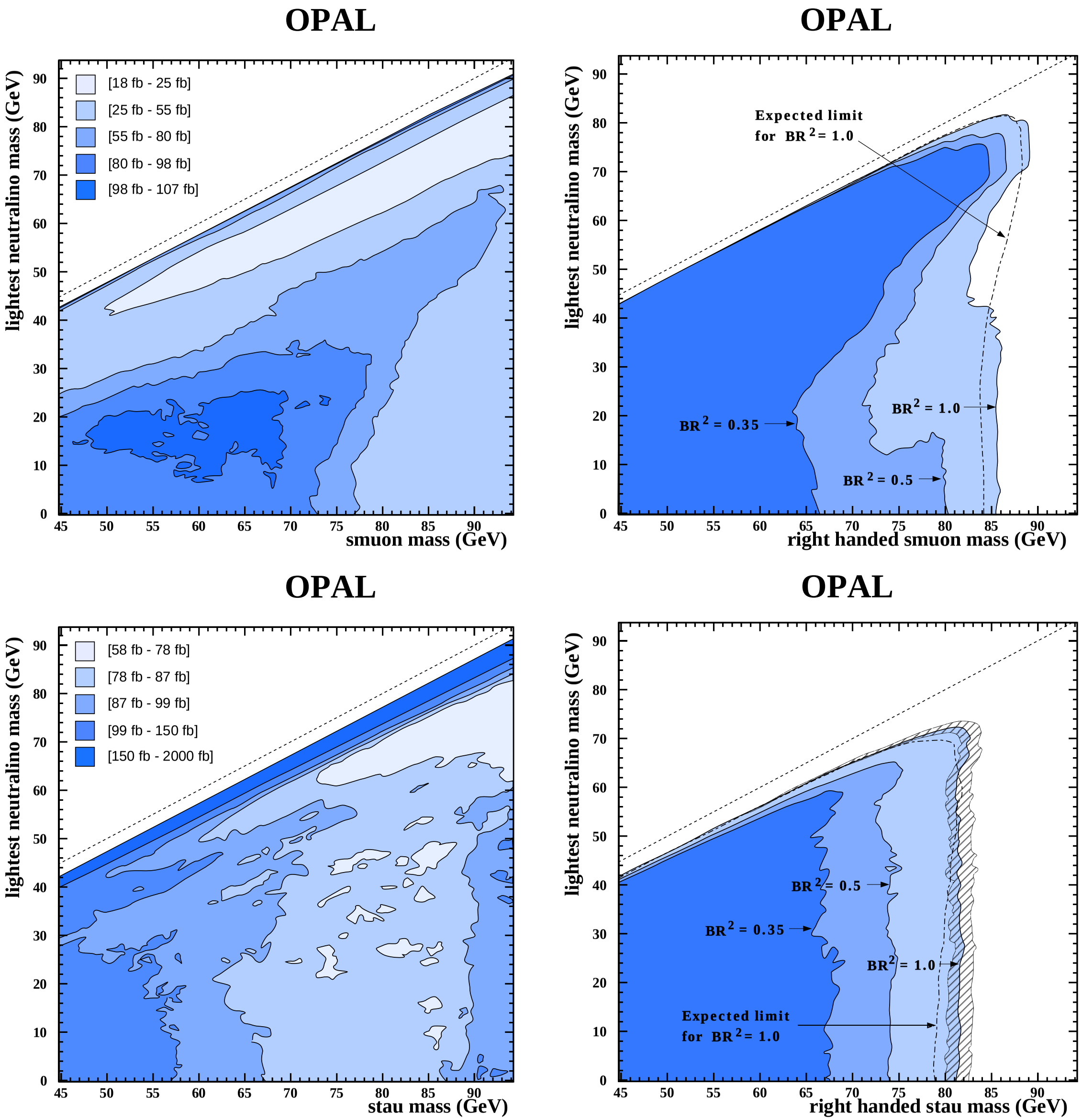
	selectrons			smuons			staus		
Mass	Limit	Expected Limit	CL(%)	Limit	Expected Limit	CL(%)	N	Expected Limit	CL(%)
45 GeV	81.4	81.9	38.2	83.5	50.6	3.4	115.4	118.2	40.6
65 GeV	85.8	76.0	24.9	88.8	52.9	3.9	86.1	112.4	67.4
85 GeV	64.0	71.1	51.2	43.5	56.7	71.3	81.3	113.7	73.3
94 GeV	34.5	38.8	56.0	34.7	39.5	57.1	87.6	114.0	69.6

$\sqrt{s} = 189\,\mathbf{GeV}$

$\int \mathbf{L} = 181.0\,\mathbf{pb}^{-1}$

Good consistency with Standard Model

Limits from Acoplanar Leptons



Limits along $M_{LSP} = 0$ axis applicable to light gravitino scenario

$$\sqrt{\mathbf{s}} = 183 - 189\,\mathbf{GeV}$$

$$\int \mathbf{L} = 237.4\,\mathbf{pb}^{-1}$$

95% CL lower mass limits (for BR=1.0)

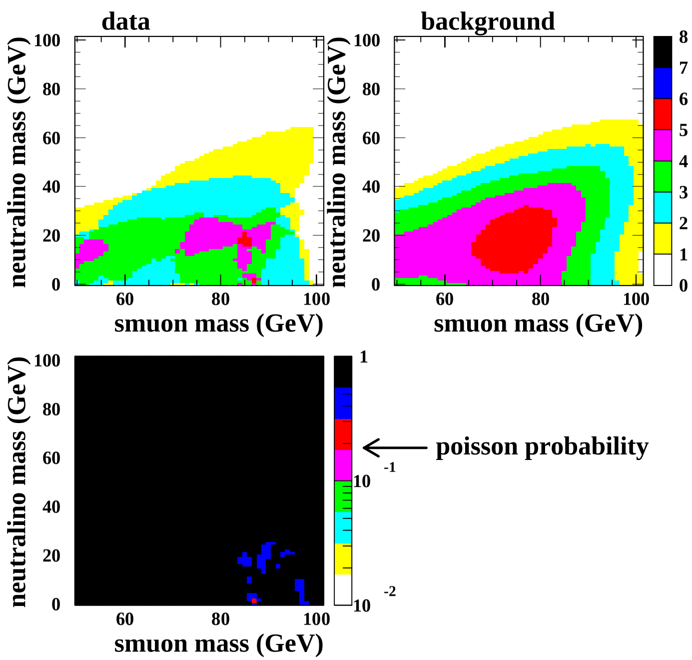
$$\mathbf{M}(\tilde{\mu}_R) > 85.4\ \mathbf{GeV}$$

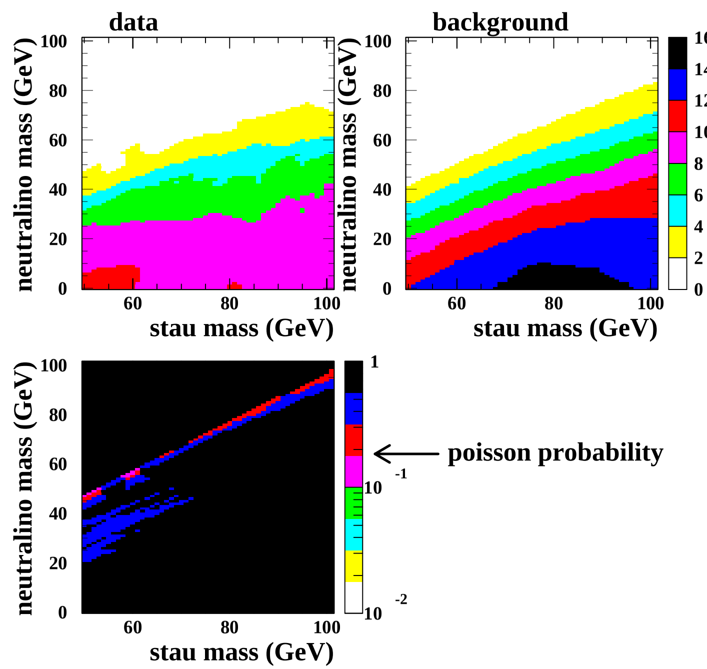
$$\mathbf{M}(\tilde{\tau}_R) > 81.1\ \mathbf{GeV}$$

$$\mathbf{M}(\tilde{\tau}_1) > 80.0\ \mathbf{GeV}$$

for any degree of stau mixing

Slepton NLSP Pair Production @ 205.5 GeV





Preliminary results from OPAL 2000 data

	selectrons			smuons			staus		
Mass	N	N_{SM}(MC)	CL(%)	N	N_{SM}(MC)	CL(%)	N	N_{SM}(MC)	CL(%)
50 GeV	15	16.51 +/-0.25	47.6	2	3.68 +/- 0.09	89.9	10	11.99 +/- 0.23	34.5
70 GeV	20	20.45+/- 0.25	41.8	1	4.37 +/- 0.13	74.3	8	14.16 +/- 0.27	56.5
90 GeV	11	11.22 +/- 0.17	65.8	2	3.11 +/- 0.09	61.3	8	14.25 +/- 0.26	77.7
101 GeV	1	2.63 +/- 0.08	82.9	0	1.17 +/- 0.05	46.8	8	13.68 +/- 0.24	71.7

$\sqrt{s} = 200 - 209\,\mathbf{GeV}$

$\int \mathbf{L} = 83.1\,\mathbf{pb}^{-1}$

Good consistency with Standard Model

Other Channels: Slepton NLSP

Other production channels → Final states with 4 or 6 leptons + missing energy

Slepton co-NLSP

$$e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow (\tilde{l}^{\pm} l^{\mp})(l'^{\pm} l'^{\mp}) \rightarrow l\ l\ l'\ l'\ \tilde{G}\tilde{G}$$

$$l\ l\ l'\ l' + \not{E}_T$$

$$l, l' \equiv e, \mu, \tau$$

Equal branching fractions assumed

$\tilde{\chi}_1^0$ is a Majorana fermion: can lead to same sign for two highest energy leptons (i.e. those from the slepton decays)

Stau NLSP

$$e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow (\tilde{\tau}^{\pm} \tau^{\mp})(\tilde{\tau}^{\pm} \tau^{\mp}) \rightarrow \tau\tau\tau\tau\ \tilde{G}\tilde{G} \Rightarrow \tau\tau\tau\tau + \not{E}_T$$

$$e^+e^- \rightarrow \tilde{l}^+ \tilde{l}^- \rightarrow (l^+ \tilde{\tau}\tau)(l^- \tilde{\tau}\tau) \rightarrow l^+ l^- \tau\tau\tau\tau\ \tilde{G}\tilde{G} \Rightarrow l^+ l^- \tau\tau\tau\tau + \not{E}_T$$

$$l \equiv e, \mu$$

Other Channels: Slepton NLSP

~ model independent cross-section limits at $\sqrt{s} = 189\,\mathrm{GeV}$

$\mathbf{l^+l^-l'^+l'^-} + \not{E}_T$

$\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0)$

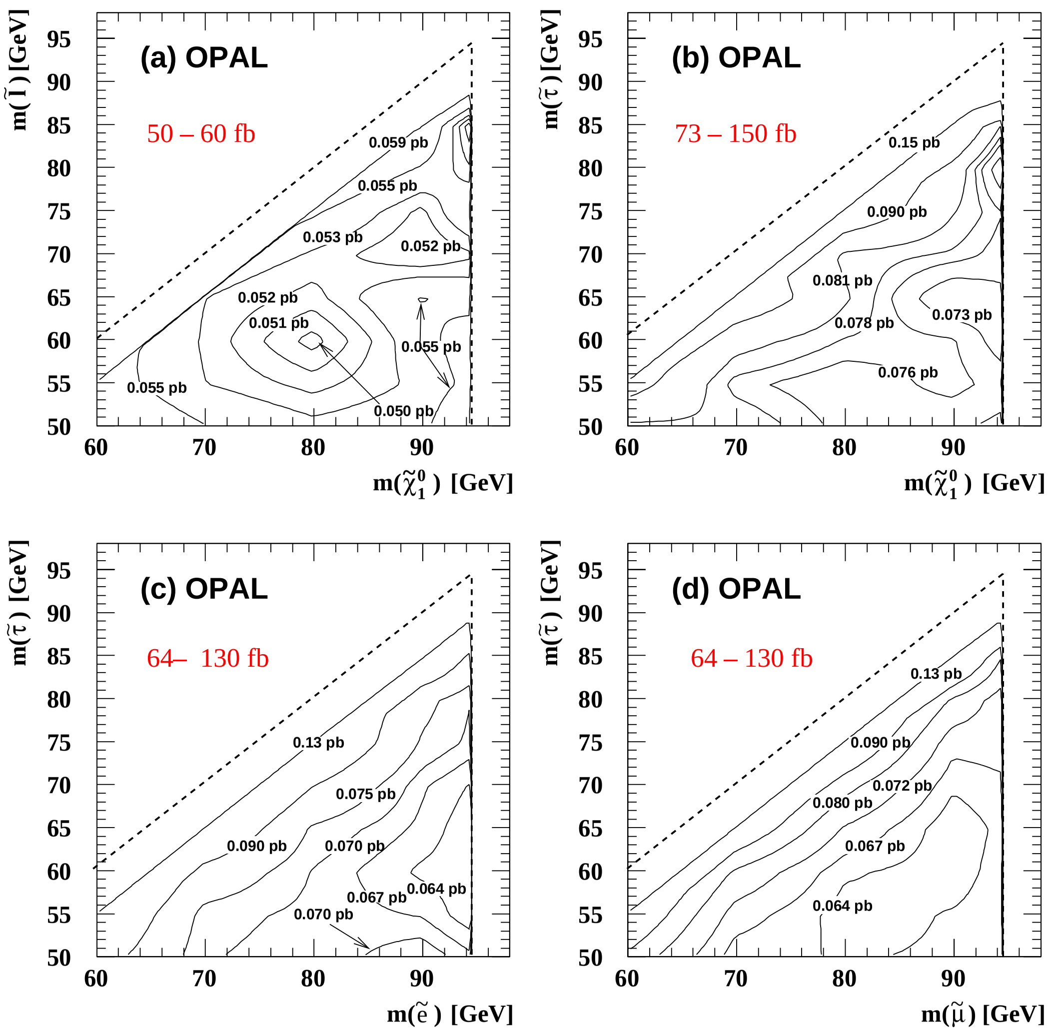
$\tilde{\chi}_1^0 \to \tilde{l}l, \tilde{l} \to l\tilde{G}$

Assumes equal BRs to $\mathbf{e}, \mu, \tau$

$\tau^+\tau^-\tau'^+\tau'^- + \not{E}_T$

$\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0)$

$\tilde{\chi}_1^0 \to \tilde{\tau}^+\tau^-, \tilde{\tau} \to \tau\tilde{G}$



$\mathbf{ee}\tau\tau\tau\tau + \not{E}_T$

$\sigma(e^+e^- \to \tilde{e}^+\tilde{e}^-)$

$\tilde{e} \to \tilde{\tau}\tau e, \tilde{\tau} \to \tau\tilde{G}$

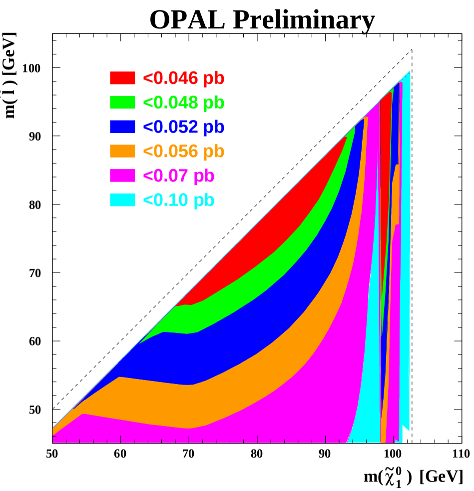
$\mu\mu\tau\tau\tau\tau + \not{E}_T$

$\sigma(e^+e^- \to \tilde{\mu}^+\tilde{\mu}^-)$

$\tilde{\mu} \to \tilde{\tau}\tau\mu, \tilde{\tau} \to \tau\tilde{G}$

Slepton NLSP Results at 200-209 GeV

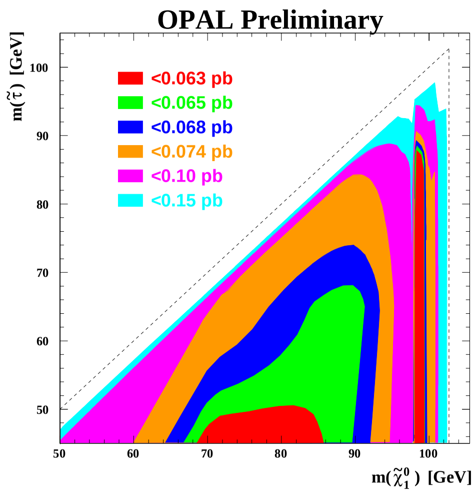
Cross-section limits at $\sqrt{s} = 205.5\,\mathbf{GeV}$



$\sigma(e^+e^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0)$

$\tilde{\chi}_1^0 \rightarrow \tilde{l}l, \tilde{l} \rightarrow l\tilde{G}$

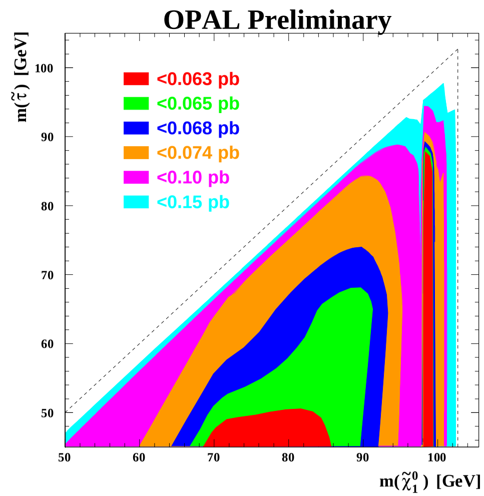
$l^+l^-l'^+l'^- + \not{E}_T$



$\sigma(e^+e^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0)$

$\tilde{\chi}_1^0 \rightarrow \tilde{\tau}^+\tau^-, \tilde{\tau} \rightarrow \tau\tilde{G}$

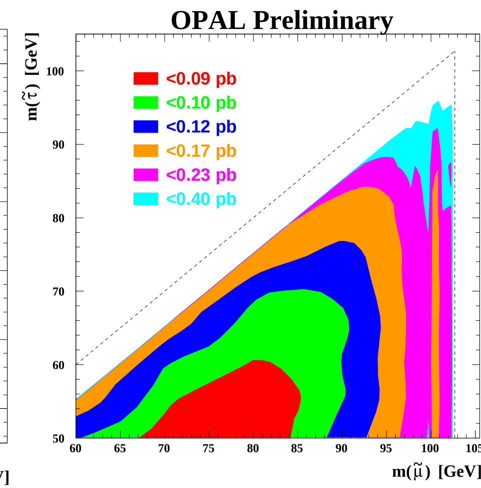
$\tau^+\tau^-\tau'^+\tau'^- + \not{E}_T$



$\sigma(e^+e^- \rightarrow \tilde{e}^+\tilde{e}^-)$

$\tilde{e} \rightarrow \tilde{\tau}\tau e, \tilde{\tau} \rightarrow \tau\tilde{G}$

$ee\tau\tau\tau\tau + \not{E}_T$



$\sigma(e^+e^- \rightarrow \tilde{\mu}^+\tilde{\mu}^-)$

$\tilde{\mu} \rightarrow \tilde{\tau}\tau\mu, \tilde{\tau} \rightarrow \tau\tilde{G}$

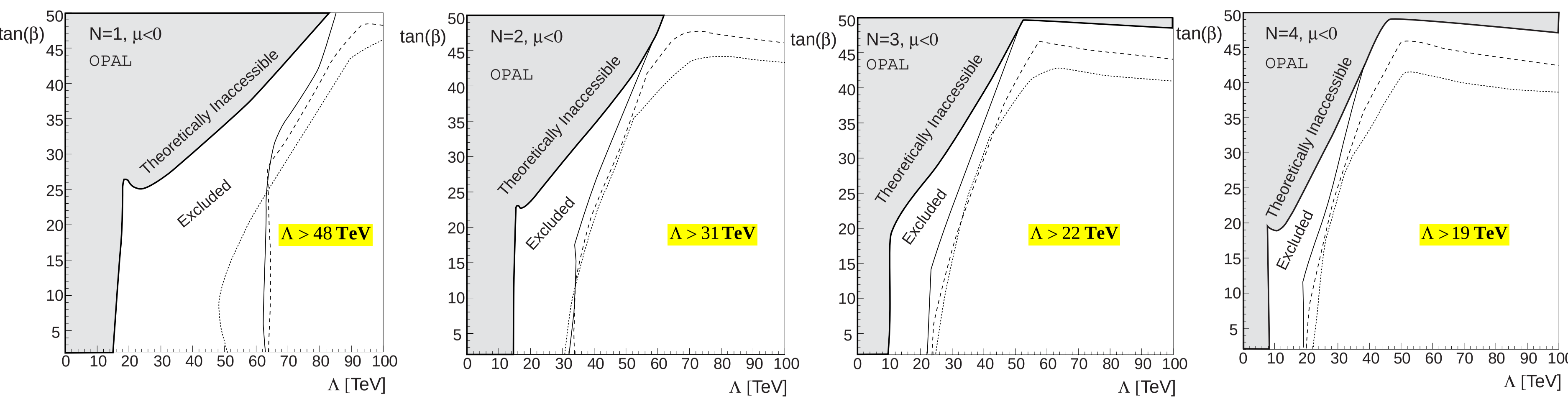
$\mu\mu\tau\tau\tau\tau + \not{E}_T$

channel	data	SM background
$\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow (ll\tilde{G})(l'l'\tilde{G})$	0	0.6 +/- 0.1
$\tilde{l}^+\tilde{l}^- \rightarrow (l^+\tau\tau\tilde{G})(l^-\tau\tau\tilde{G})$	6	2.1+/- 0.2

→ Prob ~ 2%

GMSB Scan: Exclusion regions in $(\tan\beta, \Lambda)$ plane

Parameter	Description	Range for scan
$\sqrt{F}$	**SUSY breaking scale**	**fixed** ⟷ we are assuming prompt decays
Λ	**sets mass scale for sparticles**	$5-200$ **TeV**
M	**mass scale of messengers**	$1.01\Lambda - 10^6$ **TeV**
N	**number of sets of messenger particles**	$1-4$
$\tan\beta$	**as usual**	$2-50$
$\text{sgn}(\mu)$	**as usual**	$+1/-1$



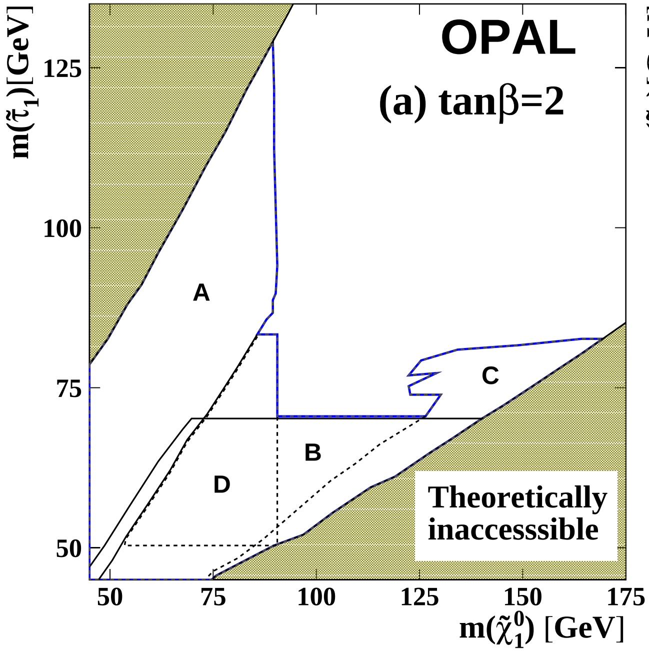
——— $\mathbf{M} = 10^6$ **TeV**

- - - - $\mathbf{M} = 250$ **TeV**

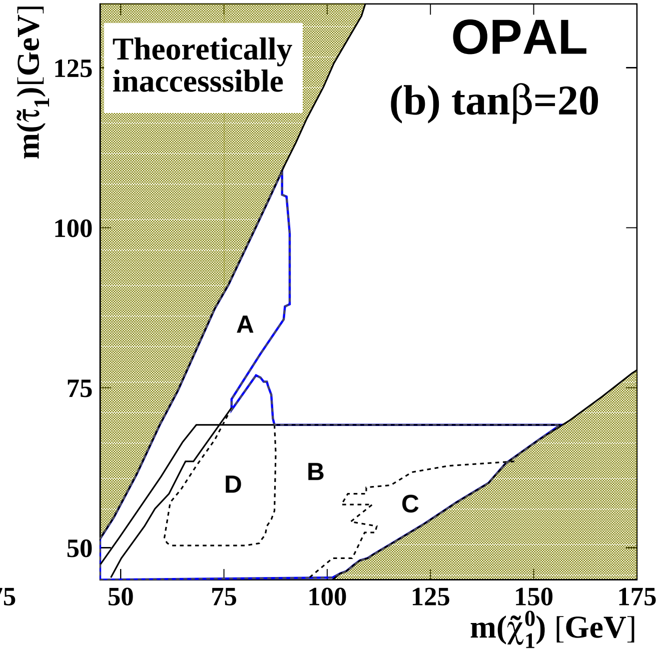
········ $\mathbf{M} = 1.01\Lambda$

Exclusions for $\mu > 0$ are somewhat stronger

GMSB Scan: Exclsusion Regions in $(\mathbf{M}_{\tilde{l}}, \mathbf{M}_{\tilde{\chi}_1^0})$ plane



sleptons ~ degenerate



$\tilde{\tau}_1^{\pm}$ **NLSP**

A	$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \gamma \tilde{G} \gamma \tilde{G}$
B	$\tilde{\tau}^+ \tilde{\tau}^- \rightarrow \tau^+ \tilde{G} \tau^- \tilde{G}$
C	$\tilde{\mu}^+ \tilde{\mu}^- \rightarrow \mu^+ \tilde{G} \mu^- \tilde{G}$
D	$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow l^+ l^- \tilde{G} l'^+ l'^- \tilde{G}$

$\tan\beta = 2$

$\mathbf{M}_{NLSP} > 70$ **GeV** $\tilde{l}^{\pm}$

> 85 **GeV** $\tilde{\chi}_1^0$

$\tan\beta = 20$

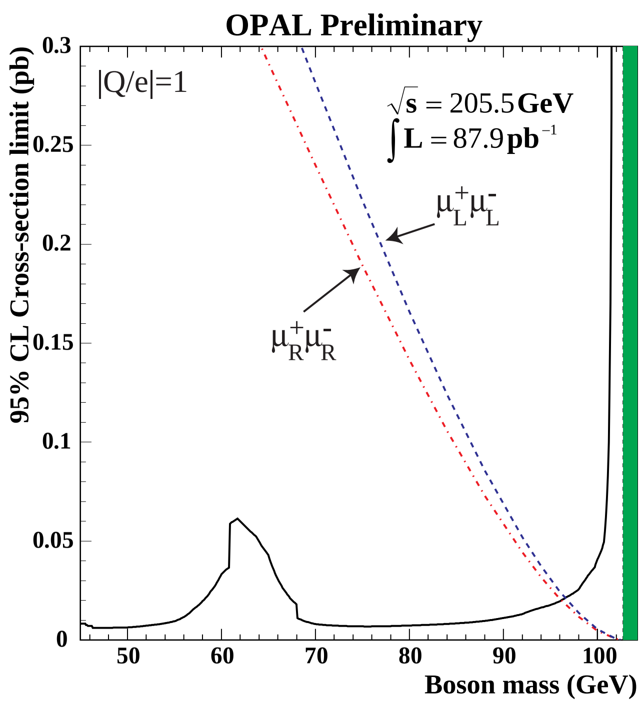
$\mathbf{M}(\tilde{\tau}) > 69$ **GeV**

$\mathbf{M}(\tilde{e}, \tilde{\mu}) > 88$ **GeV**

$\mathbf{M}(\tilde{\chi}_1^0) > 76$ **GeV**

Slepton NLSP with lifetime

- Decay length ~ detector size: kinked charged tracks (analysis in progress)
- Decay length >> detector size: long lived stable charged particles



Includes results from lower energies

$\mathbf{M}(\tilde{l}^+_R) > 96.0$ **GeV** @ 95% **CL**

$\mathbf{M}(\tilde{l}^+_L) > 96.5$ **GeV** @ 95% **CL**

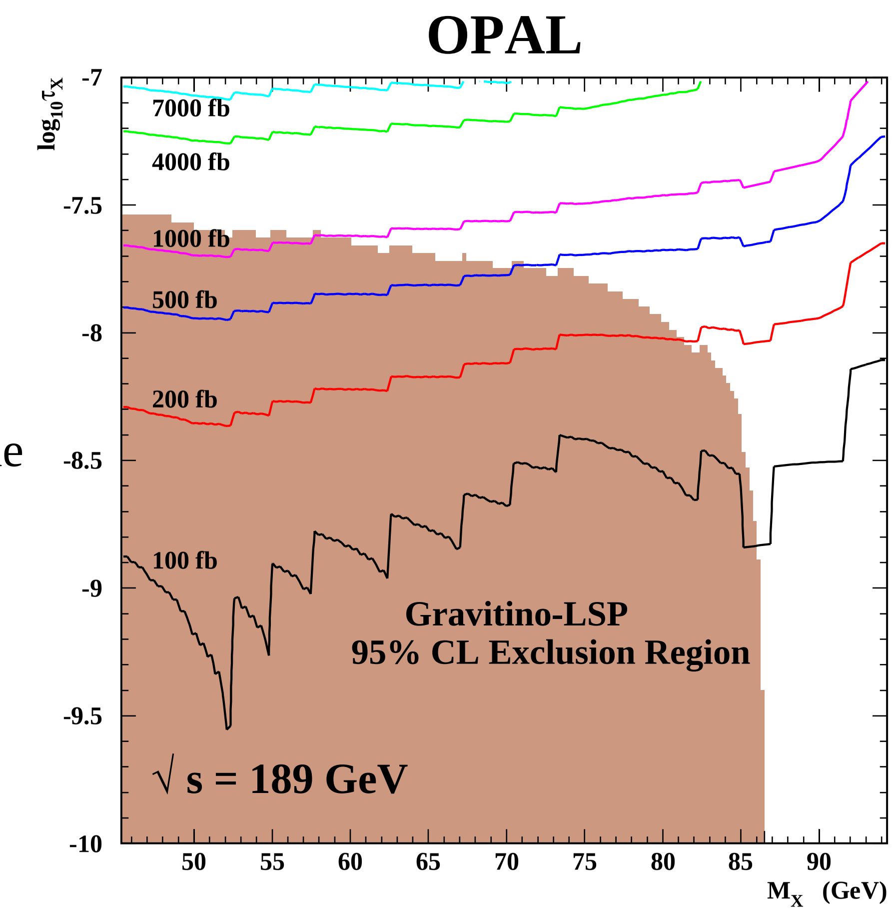
Results valid for lifetimes > 1 us

Neutralino NLSP with Lifetime

- Decay length ~ detector size: non-pointing photons (in progress)
- Decay length >> detector size: conventional SUSY signatures

Can quantify sensitivity of $\gamma\gamma + \not{E}_T$ analysis to finite lifetime

Evaluate selection efficiency as function of lifetime for $\tau = 10^{-15} - 10^{-7}$ **s** $(\mathbf{c}\tau \sim 30\ \mathbf{m})$



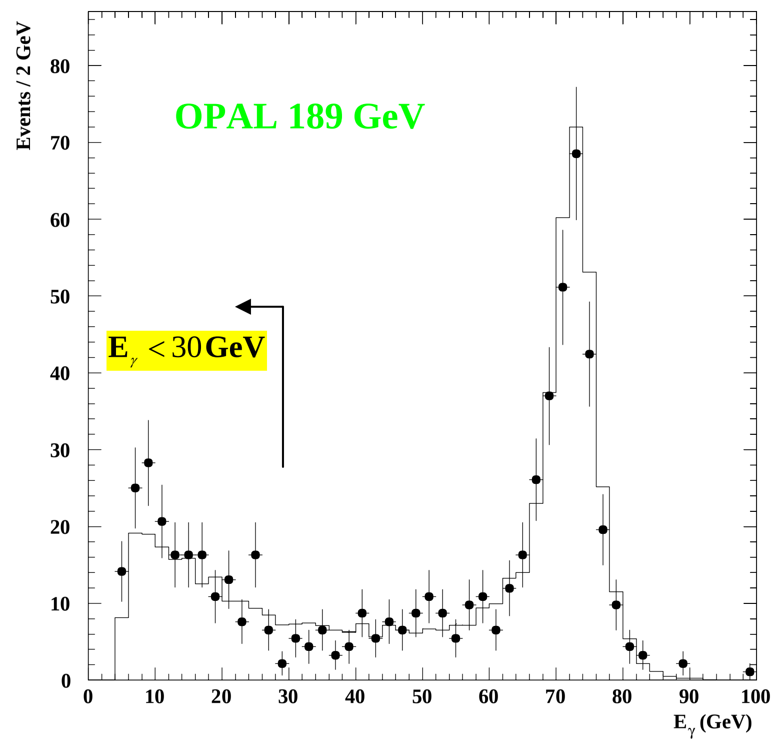
Gravitino Pair Production $e^+e^- \to \tilde{G}\tilde{G}\gamma$

Brignole, Feruglio and Zwirner: models with superlight gravitino

→ single photon + $\not{E}_T$ signature

$$\frac{d^2\sigma}{dx_\gamma\, d\cos\vartheta} = \left(\frac{\alpha G_N^2}{45}\right)\frac{s^3}{m_{\tilde{G}}^4} f_{\tilde{G}\tilde{G}\gamma}(x_\gamma, \cos\theta)$$

$$f_{\tilde{G}\tilde{G}\gamma}(x,y) = 2(1-x)^2 \left[\frac{(1-x)(2-2x+x^2)}{x(1-y^2)} + \frac{x(-6+6x+x^2)}{16} - \frac{x^3(1-y^2)}{32}\right]$$



Soft photon spectrum:
event counting in region
$E_\gamma < 30$ **GeV**

195 events observed

179.6 ± 5.4 expected $\nu\bar{\nu}\gamma(\gamma)$ from **KORALZ**

↓

$\sigma_{95} \to m_{\tilde{G}} > 8.7\,\mu eV$ @95%CL

Conclusions

- The end of LEP draws near: still no signs of SUSY
- Lots of work to still be done:
  - Update to highest energies and maximum luminosity
  - Results on intermediate / long lifetimes in progress
- Still some hope for discovery at LEP ?
  - Wait a few months ……..
  - Or wait a few years