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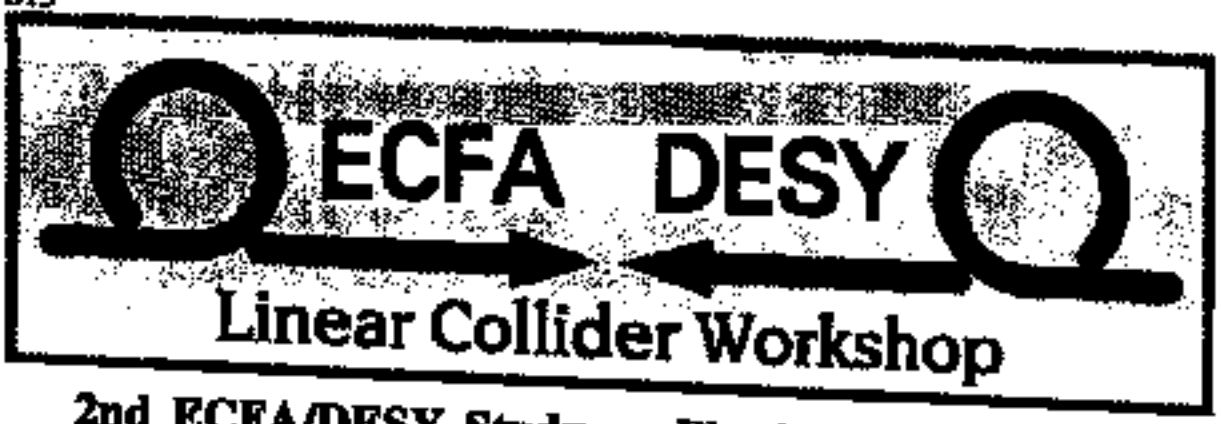


2nd ECFA/DESY Study on Physics and Detectors for a Linear Electron-Positron Collider

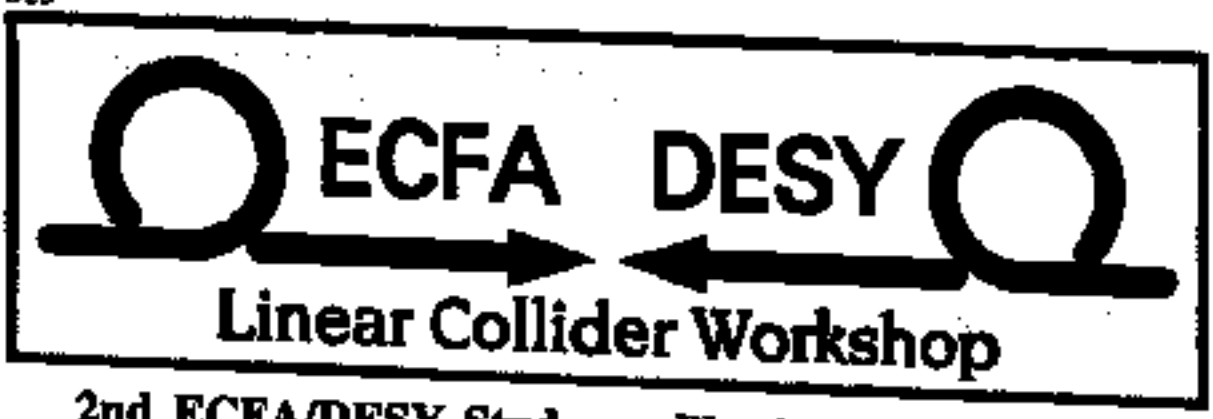
LAL - Orsay - France, April 5-7, 1998

Date : April 6, 1998 - 11:15

Parallel groups to plan tasks :

SUSY

S13



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Parallel groups to plan tasks : SUSY

Introduction

SUSY Working Group*

Convenors: A. Bartl[Th.], G. Blair[Ex.], W. Majerotto[Th.],
H.-U. Martyn[Ex.], Y. Sirois[Ex.]

* SUSY ⇔ Extensions of the Higgs Sector
MSSM Particle Spectra
Tests of SUSY GUTs ... SUGRA and beyond
R-Parity Violation
etc.

- PHYSICS GOALS

Appetizers:

S. Ambrosiano, "Gauge-Mediated SUSY Breaking Models
F. Richard, "Search for SUSY beyond SUGRA

Review existing, short and medium term goals

- Expected CONTRIBUTIONS

Short (June 98) and Medium (November 98) term

- AOB

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• Pierre Lutz	Pierre.Lutz@cern.ch	RPV. fully hadronic final state
• Uriel Nauenberg	uriel@colohe.colorado.edu	Experimental issues
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• H. EBERL	helmut@hepty.soew.sc.at	Squarks in MSSM
• E. Elsen	elsen@desy.de	"experimental" signatures
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S. Ambrosiano

Gauge-Mediated SUSY-Breaking Models @ Linear Collider – Prospects and Open Problems

Signatures of GMSB models depend mainly on:

• a) Characteristic scale of low-energy SUSY Breaking $\sqrt{F} \Longrightarrow$ determines the Gravitino $\tilde{G}$ mass; $\tilde{G}$ is always LSP.
Typical range:

$$\begin{aligned} \text{few } 10\text{'s TeV} \quad &\lesssim \sqrt{F} \lesssim \quad \text{few } 1000\text{'s TeV} \\ \text{few} \times 10^{-5}\,\text{keV} \quad &\lesssim m_{\tilde{G}} \lesssim \quad 1\,\text{keV} \end{aligned}$$

$\sqrt{F}$ sets "shape" and "length scale" of signals.
Characteristic decay length L for NLSP $\rightarrow \tilde{G}$ decays ($\tilde{P} \rightarrow P\tilde{G}$); where $\tilde{P} = \tilde{N}_1, \tilde{\tau}_1 \ldots$ and $P = \gamma \ldots, \tau \ldots$

$$\frac{L}{10^{-2}\,\text{cm}} = \frac{1}{k}\left(\frac{100\,\text{GeV}}{m_{\text{NLSP}}}\right)^5 \left(\frac{\sqrt{F}}{100\,\text{TeV}}\right)^4 \sqrt{\frac{E^2_{\text{NLSP}}}{m^2_{\text{NLSP}}} - 1}$$

where $0.4 \lesssim k \leq 1$ always.
Example: $m_{NLSP} = 100$ GeV (model just out of LEP2/Tevatron reach) @ LC with $\sqrt{s} = 500$ GeV (typical c.m. energy for Phase I).
After $e^+e^- \rightarrow \tilde{P}\tilde{P}^{(*)}$ direct production:

$$\text{few } \frac{1}{10}\text{'s } \mu\text{m} \lesssim L \lesssim \text{few } 100\text{'s m } (\ldots \text{ or more})$$

For instance:
$e^+e^- \rightarrow \tilde{N}_1\tilde{N}_1$ followed by $\tilde{N}_1 \rightarrow \gamma\tilde{G}$.
Photons could both originate from (close to) the interaction point
OR 1 or 2 photons could arise from anywhere in the detector
OR 1 or 2 photons could even be emitted outside the detector
(γ's undetected $\Longrightarrow$ additional $\not{E} \Longrightarrow$ mSUGRA-like scenario)

Gauge-Mediated SUSY-Breaking Models @ Linear Collider – Prospects and Open Problems

• b) Identity of the NLSP (and possibly "co-NLSP's" in more complex scenarios) $\Longrightarrow$ determines "flavor" of signals.

Two main scenarios are possible:

(A) "neutralino–NLSP" case: $e^+e^- \to \tilde{S}\bar{S}^{(*)} \to X + \tilde{N}_1\tilde{N}_1(\to \gamma\gamma\tilde{G}\tilde{G})$

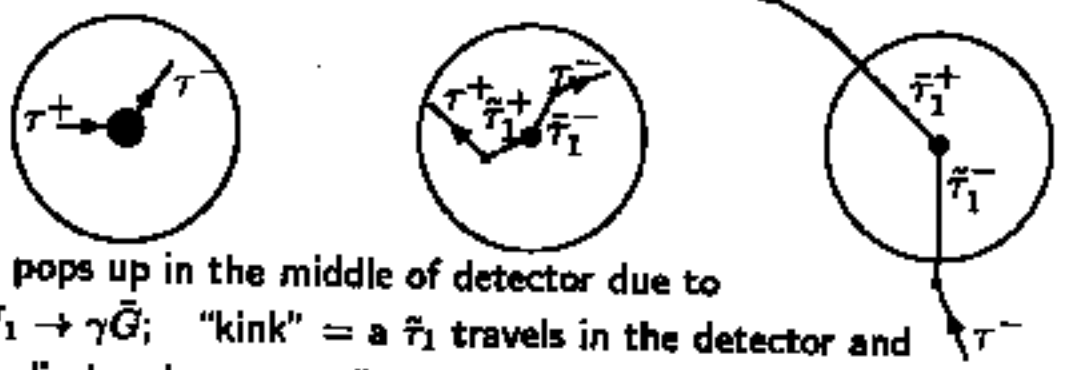
(B) "stau–NLSP" case: $e^+e^- \to X + \tilde{\tau}_1\tilde{\tau}_1\ (\to \tau\tau\tilde{G}\tilde{G})$

[as long as $m_{\tilde{N}_1} \lesssim 200$ GeV $\Longrightarrow$ BR$(\tilde{N}_1 \to \tilde{G}\gamma) \gtrsim 80-90\%$]

L [mm] $\approx$	$10^{-4} - 10^{-1}$	(?)$1 - 10^3$	$10^3 - 10^5$
$\sqrt{F}$ [TeV] $\approx$	$15 - 100$	$200 - 10^3$	$< 1 - 3 \times 10^3$
(A)	$\gamma\gamma X \not{E}$	γ "γ" $X \not{E}$ "γ" "γ" $X \not{E}$	"γ" $X \not{E}$ (large) $X \not{E}$ (LARGE)
(B)	$\tau^+\tau^- X \not{E}$	$\tau^\pm$ "kink" $X \not{E}$ 2 "kinks" $X \not{E}$	"kink" "track" $X \not{E}$(sm.) 2 "tracks" X

(A)

(B)



"γ" = a photon pops up in the middle of detector due to delayed decay $\tilde{N}_1 \to \gamma\tilde{G}$; "kink" = a $\tilde{\tau}_1$ travels in the detector and decays to τ with displaced vertex; "track" = a $\tilde{\tau}_1$ produces a μ-like "stable" charged track, possibly w/ anomalous ionization.

(B): If $\tilde{\tau}_1$'s are misinterpreted as μ's $\Rightarrow$ Multilepton Signals or $e - \mu$ universality violation.

Gauge-Mediated SUSY-Breaking Models @ Linear Collider – Prospects and Open Problems

DISCOVERY @ LC (if LHC has not done the job yet!) certainly not a problem, provided e.g., $m_{NLSP} \lesssim 245$ GeV for $\sqrt{s} = 500$ GeV.

• Signatures are clear and spectacular, often very low or no SM bkgd.
For instance: $\tilde{N}_1 =$ NLSP; $m_{\tilde{N}_1} = 100$ GeV; $\sqrt{s} = 500$ GeV.
Our simulation with a typical GMSB model in this class (see table):
[$N_{\rm mess} = 1$, $\Lambda = 74$ GeV; $M_{\rm mess} = 150$ TeV; $\tan\beta = 3$; sgn$(\mu) = -$]
gave the following result (before detection/ID cuts):

$$\sigma_{\rm inclusive}(\gamma\gamma + X + \not{E}) \sim 1\ {\rm pb}$$

$\Longrightarrow$ 500000 evts./year for high luminosity $\int_{year} \mathcal{L} = 500\ {\rm fb}^{-1}$!!
(from: $\tilde{N}_1\tilde{N}_1$, $\tilde{C}_1^+\tilde{C}_1^-$, $\tilde{N}_1\tilde{N}_2$, $\tilde{N}_2\tilde{N}_2$, $\tilde{e}_R^+\tilde{e}_R^-$, $\tilde{\mu}_R^+\tilde{\mu}_R^-$, $\tilde{\tau}_1^+\tilde{\tau}_1^-$, $\tilde{e}_L^\pm\tilde{e}_R^\mp$.)
Of course, if $\Lambda \nearrow \Longrightarrow m_{\tilde{N}_1}$ and the whole MSSM spectrum $\nearrow$
(GMSB: only a single mass scale sets spectrum, to a large extent.)
Ex.: $m_{\tilde{N}_1} \gtrsim 170$ GeV $\Longrightarrow$ only $\tilde{N}_1\tilde{N}_1$ (and possibly R-slepton pairs) can be produced!

• However: LC detector might be challenged by unusual signals (e.g. displaced photons) $\Longrightarrow$ Detector design should aim to:
◇ Not to miss such weird signals!
◇ Allow unconventional measurements of fundamental GMSB parameter (e.g. $\sqrt{F}$)

• Notice: LC might potentially be a better machine for GMSB searches than LHC seems to be. Possible reasons:
◇ GMSB $\Longrightarrow$ large squark–slepton mass splitting
(e.g. in the model above: $m(\tilde{q}) \simeq 800$ GeV; $m(\tilde{g}) \simeq 640$ GeV)
◇ Drell-Yan σ for producing $\tilde{N}$'s, R-sleptons, etc. are "low" at LHC
◇ LHC detectors are mainly designed for catching Higgs(es) or conventional SUSY and not for unusual GMSB event shapes...

Gauge-Mediated SUSY-Breaking Models @ Linear Collider – Prospects and Open Problems

Two main questions to be answered by theorists/phenomenologists:

Q # 1 If SUSY with GMSB is not discovered @ LHC, can it be discovered @ LC and how?

(Suppose, e.g., $\tilde{N}_1 =$ NLSP and $m_{\tilde{N}_1} \geq 200$ GeV with $N_{mess} = 1$ $\Longrightarrow m(\tilde{q}), m(\tilde{g}) > 1$ TeV. Then, LC can still look for $\gamma\gamma\not{E}$ events from $\tilde{N}_1\tilde{N}_1$ production with sizeable σ and low/no SM bkgd.)

Q # 2 After GMSB is discovered @ LHC or LC, how well can we measure low-energy MSSM parameters (masses, mixings) $\Longrightarrow$ infer high-energy messenger-scale param's.? (GMSB vs. mSUGRA)

• Ex: Typical model with $\tilde{N}_1 =$ NLSP.

Exclusive analysis of $\gamma\gamma\not{E}$ events ($X =$ nothing) from $\tilde{N}_1\tilde{N}_1$ production $\Longrightarrow$ Photon spectra are flat with end points fixed by $m_{\tilde{N}_1}$ and $\sqrt{s}$. If $\sqrt{s} = 500$ GeV:

$$10\ \text{GeV} \lesssim E_{\gamma_1,\gamma_2} \lesssim 240\ \text{GeV} \text{ if } m_{\tilde{N}_1} = 100\ \text{GeV}$$
$$50\ \text{GeV} \lesssim E_{\gamma_1,\gamma_2} \lesssim 200\ \text{GeV} \text{ if } m_{\tilde{N}_1} = 200\ \text{GeV}$$

it is possible a direct measurement of $m_{\tilde{N}_1}$ (which gives info on the whole spectrum, thanks to GMSB). Events with the highest E_γ (upper end point) especially useful: $m^2_{\tilde{N}_1} = 2E_\gamma^{max}(\sqrt{s} - 2E_\gamma^{max})$

Reasons:

◇ less or no contamination from SM bkgd $\gamma\gamma\nu\bar{\nu}$ (softer γ spectra)

◇ less or no contamination from other SUSY processes producing $e^+e^-\gamma\gamma + X + \not{E}$ (where X is undetectable or missed.)

Also useful (exploting LC flexible characteristics):

◇ Beam polarization $\Longrightarrow$ kills W-exchange contribution to SM bkgd.

◇ Ability to change $\sqrt{s}$ to approach threshold for $\tilde{N}_1\tilde{N}_1$ production (and other processes) $\Longrightarrow$ kills (part of) the SUSY "noise."

Gauge-Mediated SUSY-Breaking Models @ Linear Collider – Prospects and Open Problems

Once $m_{\tilde{N}_1}$ is measured and the overall MSSM mass scale is roughly singled out, there is still dependence of the rest of the spectrum mainly on $N_{\rm mess}$ and (logarithmic) on $M_{\rm mess}$.
$N_{\rm mess}$ is especially crucial $\Longrightarrow$ sets sfermion/gaugino mass ratio $\Longrightarrow$ Important for distinguishing GMSB vs. mSUGRA $\Longrightarrow$
Next step: Let's measure $m_{\tilde{e}_R}$ (or any other R-slepton mass)!
Let's look at the inclusive signal $e^+e^-\gamma\gamma\not{E}$.
In our typical model with $m_{\tilde{N}_1}$ = NLSP of 100 GeV (see table):

$$\sigma(\tilde{e}_R^+\tilde{e}_R^- \to e^+e^-\tilde{N}_1\tilde{N}_1 \to e^+e^-\gamma\gamma\tilde{G}\tilde{G}) \simeq 280\ \text{fb}$$

since BR($\tilde{e}_R^\pm \to e\tilde{N}_1$) $\simeq$ BR($\tilde{N}_1 \to \gamma\tilde{G}$) $\simeq 100\%$.
$e^\pm$ spectra flat $\Longrightarrow$ measure $\tilde{e}_R$ mass from end points and $m_{\tilde{N}_1}$!!
SM bkgd to such events is essentially ZERO, irrespective of where the γ's appear in the detector
• However: There is contamination from other SUSY processes:
◇ $e^+e^- \to \tilde{e}_L^\pm\tilde{e}_R^\mp \to e^+e^-\gamma\gamma\not{E}$ with $\sigma \simeq 40$ fb in our typical model (through complex decay chains involving $\tilde{N}_1$, $\tilde{N}_2$, $\tilde{C}_1^\pm$, $W^\pm$ and Z)
◇ $e^+e- \to \tilde{N}_1\tilde{N}_2$, $\tilde{C}_1^\pm\tilde{C}_1^\pm$, $\tilde{N}_2\tilde{N}_2$ etc. $\to e^+e^-\gamma\gamma\not{E}$ ($\sigma \sim 10$ fb)
To isolate interesting signal $\Longrightarrow$ work with $e^\pm$ angular distributions, invariant mass cuts and possibly again with beam polarization and threshold-approaching techniques.
OR: Consider R-smuon production to measure $m_{\tilde{\mu}_R} = m_{\tilde{e}_R}$
[$e^+e^- \to \mu\mu\gamma\gamma\not{E}$ (~ 60 fb) – less events, but less contamination!]
Next step: Let's measure $m_{\tilde{C}_1^\pm}$ and/or $m_{\tilde{N}_2}$ to verify gaugino mass unification (GMSB generally implies $\tilde{N}_1 \simeq \tilde{B}$ and $\tilde{N}_2$, $\tilde{C}_1^\pm \simeq \tilde{W}$, with $m_{\tilde{N}_2} \simeq m_{\tilde{C}_1^\pm} \simeq 2m_{\tilde{N}_1}$)
Further step: Let's measure $m_{\tilde{e}_L}$ and verify typical GMSB large $m_{\tilde{e}_L} - m_{\tilde{e}_R}$ splitting...(more difficult, $\tilde{e}_L$ may easily be out of kinematical reach $\Longrightarrow$ c.m. energy upgrade, Phase II!)

Gauge-Mediated SUSY-Breaking Models @ Linear Collider – Prospects and Open Problems

Many detector dependent questions to be answered by experimenters and designers. (Mainly about how to measure the fundamental scale of SUSY breaking $\sqrt{F}$.) GMSB – and in general low-energy SSB $\Longrightarrow$ unique opportunity to measure this parameter $\Longrightarrow$ info about the so-called "hidden" or "secluded" sector of SUSY models.
Also: If $\sqrt{F}$ can be measured (because not too small or not too large) $\Longrightarrow$ mSUGRA can be quickly ruled out!

Q # 1 If $\tilde{N}_1$ = NLSP; $\sqrt{F} \approx 50 - 200$ TeV $\Longrightarrow L \approx 10^{-2} - 10$ mm
Can we do anything at the level of the vertex detector to detect and recognize a displaced photon? With the present proposed design? Alternative designs?

Q # 2 If $\tilde{N}_1$ = NLSP; $\sqrt{F} \approx 200 - 800$ TeV $\Longrightarrow L \approx 10^{-2} - 1$ m
What is the efficiency (if any) for detecting displaced γ's in external parts of detector [ϵ_γ as a function of $\vec{p}_\gamma$ AND $(z, \theta, \varphi)_\gamma$ point where delayed NLSP decay takes place and γ originates] ?
In EM calorimeter? In hadronic calorimeter? In (modified) μ chambers?

Q # 3 Once a displaced γ is detected wherever in the detector, what info is then available about it? What's the accuracy for distinguishing it from a "prompt" photon coming from the int'n. point? Directional info (impact parameter measurement) from EM calorimeter? Timing info (late energy deposit in EM calorimeter $\Longrightarrow$ flight time before the NLSP decays to the $\tilde{G}$) – especially for heavy, moderately-relativistic NLSP? Notice: after having measured $m_{\tilde{N}_1}$ (see above) measure flight time and/or impact parameter$\Longrightarrow \sqrt{F}$.
Also: If both 2 "prompt" γ and displaced γ('s) signals are present, their relative rates are a measure of $c\tau$.

Gauge-Mediated SUSY-Breaking Models @ Linear Collider – Prospects and Open Problems

Q # 4 What if $\sqrt{F} \gtrsim 500$ TeV $\Longrightarrow L \gtrsim$ 10's cm?

Can we hope to catch delayed $\tilde{N}_1$ decays if they occur in the outer muon chambers or even outside? First of all, one could investigate the possibility of having "modified" (sections of the) μ chambers to do this job. Secondly, one could imagine placing additional external dedicated detectors. There have already been proposals for a "roof-array" (a two-layer detector) to be placed on the roof of the existing D0 building at FNAL, as well as a special purpose detector for the LHC to be located far away from the interaction point (possibly with shielding). $\Longrightarrow$ Simulations at toy LC detector? What directional and timing info could we get out of such detector?
Notice: Some cosmological models suggest $\sqrt{F} \lesssim 2000 - 3000$ TeV (otherwise stable $\tilde{G}$'s may overclose the universe!) $\Longrightarrow L \lesssim 100$ m...

Q # 5 If $\tilde{\tau}_1$ = NLSP; $\sqrt{F} = 50 - 500$ TeV. (Poss. $\tilde{e}_R$, $\tilde{\mu}_R$ co-NLSP's)

What is the minimum resolution on the transverse impact parameter in vertex detector for delayed $\tilde{\tau}_1 \to \tau\tilde{G}$ $[(\tilde{e}_R, \tilde{\mu}_R) \to (e, \mu)\tilde{G}]$ decays? What can be done in tracking chambers? In EM/had calorimeter? In μ chambers? Timing info?

Q # 6 How can we recognize a $\tilde{\ell} \to \ell\tilde{G}$ decay kink and measure its distance from interaction point? E.g., what is the minimum detectable deviation $\Delta\theta_{kink}$ on a μ-like charged track as a function of β_{track}, Θ_{track}, z_{kink}, in the various parts of the detector?

Typical GMSB signals @ NLC ($\sqrt{s} = 500$ GeV): Neutralino=NLSP; $m_{\rm NLSP} > 100$ GeV				
Sparticle Production	Range[1] σ_{TOT} (fb)	Mass Range[2] $m_{\tilde{N}_1}$ (GeV)	Typical Signal(s)	Special Features and Comments
$\tilde{N}_1\tilde{N}_1$	'1' – 350	< 240...250 >	"γ" "γ" $\not{E}$	"γ": { int. point γ, if $\tilde{N}_1 \to \tilde{G}\gamma$ prompt ($\sqrt{F}$ low); displaced γ in detector (moderate); add. $\not{E}$ outside (large) } γ('s) are hard, central; spectra are flat
$\tilde{e}_R^+\tilde{e}_R^-$	'1' 380	< 150...248 >	e^+e^-"γ" "γ" $\not{E}$	γ have softer, non-flat spectra; flat $e^\pm$ spectra
$\tilde{\mu}_R^+\tilde{\mu}_R^-$	'1' – 80	< 150...248 >	$\mu^+\mu^-$"γ" "γ" $\not{E}$	see $\tilde{e}_R^+\tilde{e}_R^-$ (but diff.ang.distr.: only s-channel prodn.)
$\tilde{\tau}_1^+\tilde{\tau}_1^-$	'1' 80	< 150...248 >	$\tau^+\tau^-$"γ" "γ" $\not{E}$	see $\tilde{e}_R^+\tilde{e}_R^-$ (but diff.ang.distr.: only s-channel prodn.)
$\tilde{N}_1\tilde{N}_2$	'1' – 80	< 160...180 >	X "γ" "γ" $\not{E}$	$X = jj$, $\tau^+\tau^-$, $\ell^+\ell^-$ ($\ell = e, \mu$), or add. $\not{E}$ only
$\tilde{e}_L^\pm\tilde{e}_R^\mp$	'1' – 220	< 115...180 >	e^+e^-"γ" "γ" $\not{E}$ $e^\pm jj$"γ" "γ" $\not{E}$ $e^\pm\tau^\mp$"γ" "γ" $\not{E}$ X "γ" "γ" $\not{E}$	γ and $e^\pm$ have non-flat spectra softer γ's; on shell $W \to jj$ via $\tilde{e}_L^\pm \to \tilde{C}_1^\pm \to \tilde{N}_1 W^\pm$ via $\tilde{e}_L^\pm \to \tilde{C}_1^\pm \to \tilde{\tau}_1\tilde{N}_1$ $X = e^+e^-jj$; $e^+e^-\tau^+\tau^-$; $e^+e^-e^+e^-$ etc.
$\tilde{\tau}_1^\pm\tilde{\tau}_1^\mp$	'1' – 5	< 115...180 >	X "γ" "γ" $\not{E}$	$X = \tau^\pm$+ leptons and/or jets
$\tilde{C}_1^+\tilde{C}_1^-$	'1' – 120	< 120...140 >	$jjjj$"γ" "γ" $\not{E}$ $\tau^\pm jj$"γ" "γ" $\not{E}$ $\ell^\pm jj$"γ" "γ" $\not{E}$ X "γ" "γ" $\not{E}$	jets from on-shell W's after $\tilde{C}_1^\pm \to \tilde{N}_1 W^\pm$ via $W \to jj$ and $\tilde{C}_1^\pm \to \tilde{\tau}_1\tilde{N}_1$ ℓ ($\ell = e, \mu$) and jj via W decays $X = \tau^+\tau^-$; $e^\pm\tau^\mp$; $\ell^+\ell^-$, etc.
$\tilde{N}_2\tilde{N}_2$	'1' – 50	< 120...140 >	X "γ" "γ" $\not{E}$	$X = \tau^+\tau^-jj$, $jjjj$, $\tau^+\tau^-\tau^+\tau^-$, $\ell^+\ell^-jj$, $\ell^+\ell^-\tau^+\tau^-$, jj, $\tau^+\tau^-$
$\tilde{e}_L^+\tilde{e}_L^-$	0 70	≪.....140 >	X "γ" "γ" $\not{E}$	mainly $X = jjjj$ or e^+e^-
$\tilde{\mu}_L^+\tilde{\mu}_L^-$	0 – 30	≪.....140 >	X "γ" "γ" $\not{E}$	mainly $X = jjjj$ or $\mu^+\mu^-$
$\tilde{\tau}_2^+\tilde{\tau}_2^-$	0 30	≪.....140 >	X "γ" "γ" $\not{E}$	mainly $X = jjjj$ or $\tau^+\tau^-$
$\tilde{N}_1\tilde{N}_3$	0 – 20	≪.....140 >	X "γ" "γ" $\not{E}$	$X = \ell$'s and/or j's; complex cascade decays; poss. h involved
$\tilde{N}_1\tilde{N}_4$	0 – 5	≪.....125 >	X "γ" "γ" $\not{E}$	$X = \ell$'s and/or j's; complex cascade decays; poss. h involved
$\tilde{N}_2\tilde{N}_3$	0 15	≪.....105 >	X "γ" "γ" $\not{E}$	$X = \ell$'s and/or j's; complex cascade decays: poss. h involved

Gauge-Mediated SUSY-Breaking Models @ Linear Collider – Prospects and Open Problems

Q # 7 If $\tilde{\tau}_1$ = NLSP; $\sqrt{F} \gtrsim 500$ TeV. (Poss. $\tilde{e}_R$, $\tilde{\mu}_R$ co-NLSP's)

[Here one can only get a lower bound on $\sqrt{F}$ unless additional external dedicated detectors are used...]

How and with what efficiency can we distinguish b/w a charged track from μ and a massive "stable" charged track from sleptons?

- If $m_{\tilde{e}_R} = m_{\tilde{\mu}_R} \simeq m_{\tilde{\tau}_1} \gtrsim 200$ GeV, sleptons might be "slow" (moderately relativistic) $\Longrightarrow$ Anomalous Ionization ($\frac{dE}{dx} \nearrow$ rapidly when $\beta \searrow$ for low β.)

Measure in tracking chambers, require also isolation.

- What about if sleptons are "fast" (highly relativistic)?

– Different curvature of trajectory in μ chambers? Difficult, can it work for $m \gtrsim 50$ GeV??

– Careful analysis of angular distributions (scalar vs. non-scalar)? (Warning: charged tracks would come out of any SUSY process after cascade decays, with complex distributions $\Longrightarrow$ threshold-approaching techniques?)

– For small $\tan\beta \Longrightarrow$ small splitting $(m_{\tilde{e}_R} - m_{\tilde{\tau}_1})$ and heavy spectra $(m_{\tilde{e}_R} \gtrsim 200$ GeV) $\Longrightarrow$ Measure excess of di-muon like events $\Longrightarrow$ apparent violation of $e - \mu$ universality!

– For larger $\tan\beta$ (and possibly lighter spectra) $\Longrightarrow$ Multilepton events from three-body decays $(\tilde{e}_R, \tilde{\mu}_R) \to (e, \mu)\tau\tilde{\tau}_1$ (and gaugino production + cascade decays through L-sleptons)!!

Summary:

A LOT OF UNUSUAL AND INTERESTING SIGNALS IN ALL POSSIBLE SCENARIOS! A LOT OF WORK TO DO ...AND FUN TO HAVE!!

[1] Lower limit '1' stands for a number at the level of 1/10's to few fb. This ensures unambiguous signal (at least 50 events before cuts) at NLC in a "500 fb^{-1} year." Such lower limit holds only if the condition for the lower end on the $m_{\tilde{N}_1}$ range (in green, next column) is met. The upper limit is a consequence of imposing $m_{\tilde{N}_1} > 100$ GeV (model out of LEP2/Tevatron reach).

[2] The lower end of the range (in green) is a sufficiently low (non-necessary condition) NLSP mass level to ensure in typical cases kinematical accessibility for the channel with σ_{TOT} at the level '1'. A consistent signal may be however present for a heavier NLSP as well, but not in the whole parameter space. Here, "$\ll$" means that there is no lower bound to be possibly forced on m_{NLSP} which implies that a detectable signal for the channel xmust necessarily be present. In other words, one can build models with $\tilde{N}_1$ = NLSP, $m_{\tilde{N}_1} = 100$ GeV where that channel is kinematically forbidden at NLC. However, a consistent signal may be present in particular models. The condition on the upper end of the range (in red) is a sufficiently high (non-necessary condition) NLSP mass level for which it is no longer possible to build any models where the channel is kinematically allowed at NLSP. However, in some cases, the channel may already be forbidden in particular models with lower values of m_{NLSP}. SUSY production processes not listed here are always kinematically forbidden in this class of GMSB models.

S13

2nd ECFA/DESY Study on Physics and Detectors for a Linear Electron-Positron Collider

LAL - Orsay - France, April 5-7, 1998

Date : April 6, 1998 - 11:15

Parallel groups to plan tasks : SUSY

W. Majerotto

W. Majerotto, Vienna

Some suggestions for this Workshop

- $e^+e^- \to \tilde{\chi}_i^+ \tilde{\chi}_j^-$, $\tilde{\chi}_1^+ \to W \tilde{\chi}_1^0 \to e\nu \tilde{\chi}_1^0, \ldots$

  $\tilde{\chi}_2^0 \tilde{\chi}_2^0$, $\tilde{\chi}_2^0 \to Z \tilde{\chi}_1^0 \to ll \tilde{\chi}_1^0, \ldots$

  with <u>spin correlations</u> in production & decay

  → decay distributions, asymmetries

  → additional information to determine SUSY-parameters (Würzburg-Vienna)

- $e^+e^- \to \tilde{t}_i \tilde{t}_j$ $\quad \tilde{t}_i \to \tilde{\chi}^+ b, \ldots$

  $\tilde{b}_i \tilde{b}_j$ $\quad \tilde{b}_i \to b \tilde{\chi}_k^0, \ldots$

  → <u>new</u>: SUSY-QCD corrections to production <u>and</u> decay

  → <u>include</u> three-body decays

  $\tilde{t} \to b e \tilde{\nu}$, $b \tilde{e} \nu$

  $bW \tilde{\chi}_i^0$, $bH^0 \tilde{\chi}_i^0$

- $\not{R}$: (Vienna)

  Minimal extension of MSSM: $W \sim \ldots \epsilon L H_2$

  (Valencia - Vienna)

$\not{R}$ in • $e^+e^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^-$

$\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 W$

$\hookrightarrow \nu_e Z, eW$

$\tilde{\chi}_1^+ \not\to \nu_e W, eZ$

• $e^+e^- \to \tilde{\chi}_2^0 \tilde{\chi}_1^0$, $\tilde{\chi}_2^0 \to \nu_e Z, eW$

• $e^+e^- \to \tilde{t}_1 \bar{\tilde{t}}_1$

$\hookrightarrow b\bar{c}$

• $\not{CP}$ due to complex parameters: $M_{e\nu}, M', A$ complex

in $e^+e^- \to t\bar{t}$

$\tilde{\chi}^+ \tilde{\chi}^-$ and decays

$\tilde{\chi}_1^0 \tilde{\chi}_2^0$

using 'optimal' variables (→ Berreuther, Nachtmann, ..)

• Other suggestions welcome !

S13

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Parallel groups to plan tasks : SUSY

C. Heusch

SUSY

C. Heusch
U. of California
Santa Cruz

IF SUPERSYMMETRY IS DISCOVERED,
MEASURING SPARTICLE
MASSES, COUPLINGS, MIXINGS
WILL BE A MAJOR CONCERN.

PRECISION SUSY MEASUREMENTS
CAN DRAW ON e^-e^-
$\mu^+\mu^+/\mu^-\mu^-$ COLLISIONS
FOR VITAL INFORMATION!

MASS DETERMINATION FOR SLEPTONS:

$$\left.\begin{array}{l} e^-e^- \to \tilde{e}^-\tilde{e}^- \\ \mu^-\mu^- \to \tilde{\mu}^-\tilde{\mu}^- \end{array}\right\} \text{LOW BACKGROUND}$$

POLARIZATION CAN MAKE A PIVOTAL DIFFERENCE

TAKE A HINT FROM SELECTRON CASE:

searches for $\tilde{e}^-$ production were considered by

Cuypers, von Oldenborgh, + Rückl

hep-ph / 9305287

$$e^-e^- \to \tilde{e}^-\tilde{e}^- \to e^-e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$$

also include $e^-\tilde{\chi}_2^0$, $\nu\tilde{\chi}_1^-$ where almost neutralino / chargino } mass determ'n

SM backgrounds:

$$e^-e^- \to e^-e^-Z^0 \hookrightarrow \nu\bar{\nu}$$

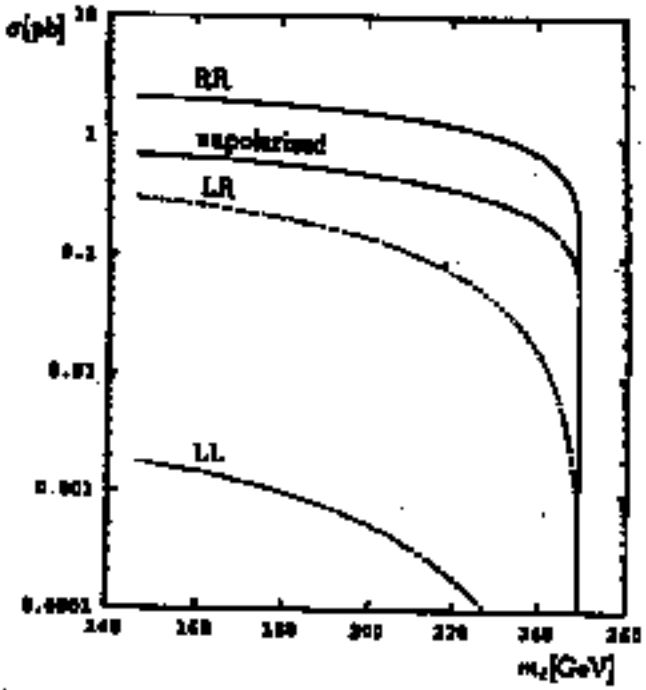
$$e^-e^- \to e^-\nu W^- \hookrightarrow e^-\bar{\nu}$$

(e_L^- only)

in both cases, one e^- must be close to the beam energy

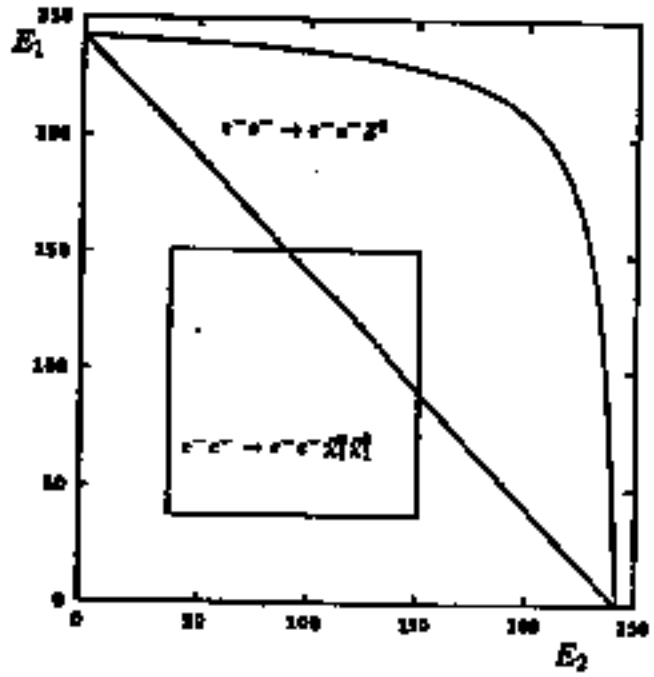
can easily be eliminated:

cut in E, E_0 plane



IMPORTANCE OF POLARISATION!

Figure 12: Cross-section of selectron pair production for a given SUSY parameter set, as a function of selectron mass, for different helicity combinations of the incoming e^- beams, at a 500 GeV NLC/ pr Collider



for e^-e^- case, analogous in pp.

Figure 13: The allowed electron ranges for a pair of 200 GeV selectrons decaying into e^-e^- plus a pair of 100 GeV neutralinos (box) and for the principal background, Z "bremsstrahlung" ($e^-e^- \to e^-e^-Z$). This example illustrates the relative ease with which backgrounds can be removed by cuts on the final-state electrons (from ref. 26).

Cuypers et al.

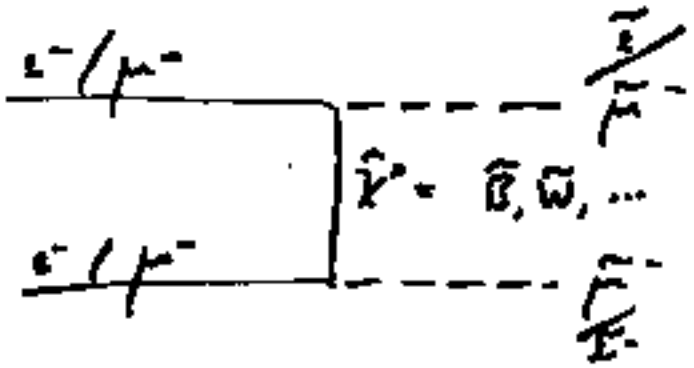
$e^-e^- \begin{pmatrix} \mu^+\mu^+ \\ \mu^-\mu^- \end{pmatrix}$ CAN LEAD TO A PRECISE

$\tilde{\nu}(\tilde{\mu})$ MASS MEASUREMENT:

S WAVE TURN-ON AT KINEMATICAL THRESHOLD GIVES $m(\tilde{\mu})$ TO FEW $\overset{100}{\Lambda}$ MeV;

ALL SUSY MODELS CONTAIN MAJORANA FERMIONS THAT COUPLE TO $\mu^\pm$:

$B^\mu, W^\mu \longrightarrow \tilde{B}, \tilde{W}$, gauginos



Kamp, Litenberg

→ NEUTALINO MASS MEASUREMENT

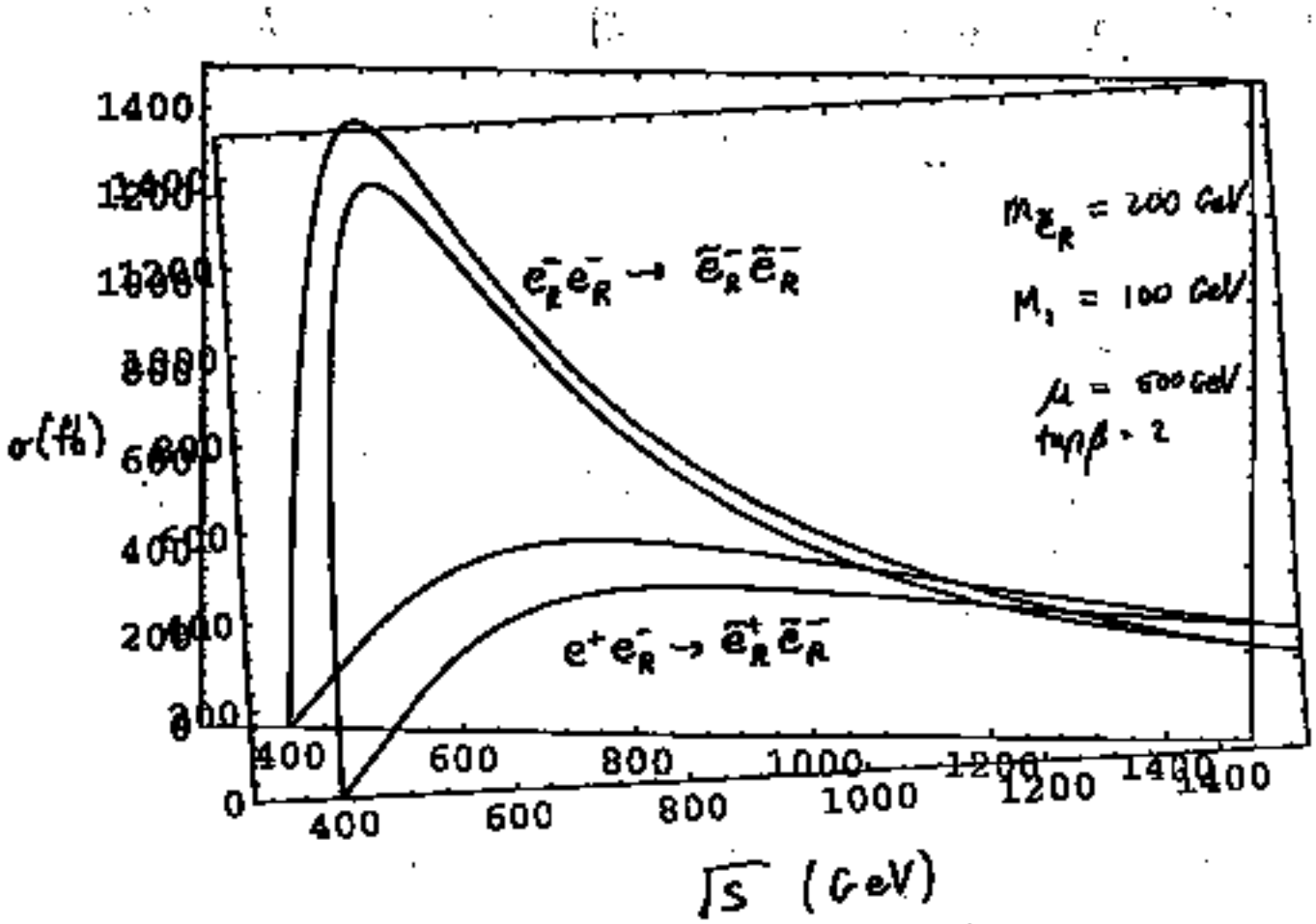
PHASE IN NEUTRALINO MASS MATRIX ?

IN ANALOGOUS SELECTRON CASE,

Mass Measurement

Threshold: $\overrightarrow{e_R^-}$ $\overleftarrow{e_R^-}$

S wave, β behavior!

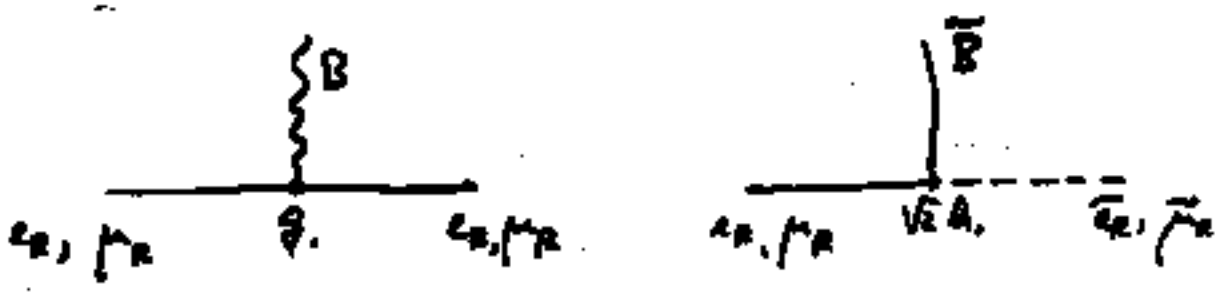


NOTE: IMPORTANCE OF POLARIZATION.

J. FENG
H.-C. CHENG

MEASUREMENT OF SPARTICLE COUPLINGS

RELATED TO ORDINARY GAUGE COUPLINGS BY SUSY



$g_1 = \lambda_1$ IN EXACT SUSY ?

A PRECISE MEASUREMENT OF THESE RELATIONS CAN

- TEST SUPERSYMMETRY
- PROBE FOR HEAVIER S-PARTICLES BEYOND KINEMATICAL REACH

$\Rightarrow$ TEST OF SUSY FLAVOR STRUCTURE

("HEAVY QCD MODELS
2-1 MODELS, ...)

A COMPARISON OF $\mu^-\mu^- \to \tilde{\mu}^-\tilde{\mu}^-$
$e^-e^- \to \tilde{e}^-\tilde{e}^-$ MAY BE
VERY INSTRUCTIVE

LOOK FOR FLAVOR VIOLATION

$\mu^-\mu^- \to e^-\mu^-\tilde{B}\tilde{B}$

S13

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Parallel groups to plan tasks : SUSY

F. Richard

New trends in SUSY
Consequences on LC detectors

- Large variety of SUSY schemes
  - SUGRA without M_i universality
    - → Degenerate scenario $M_1 \sim M_2$ possible
    - → $\tilde{g}$ as LSP ?
  - GMSB
    - → $\tilde{G}$ LSP
    - → NLSP ? $\tilde{\ell}_R$ X long-lived, visible decay
  - SUSY with phases A, μ, M_i
    - → Spin parity aspects POLARISATION

  ...

⇒ Can these anomalous signals be detected at future colliders ?

- What special features are allowed by a LC ?
- What are the consequences for a detector design ?

Non minimal SUGRA

- $\tilde{g}$ as an LSP J.F. Gunion h-ph 9801442
  - Very light $\tilde{g}$ comes out (α_s running) and should be excluded by LEP$_2$
  - $m_{\tilde{g}} > 5$ GeV still possible (Strong coupled)

$R = \tilde{g}g$ Long lived, stopped in HCAL

→ Low $\not{E}$, not easy, better if $m_{\tilde{g}}$ ↗

- Degenerate scenario

$m_{\chi^\pm} \sim m_{\chi_1}$ or $\sim m_{\tilde{\nu}}$

$(m_{\tilde{e}_R} \sim m_{\chi_1})$

→ Low threshold for triggering

→ Not easy to separate from $\gamma\gamma\varphi$

For $\chi^+\chi^-$, with large σ, use a neutrino-counting method

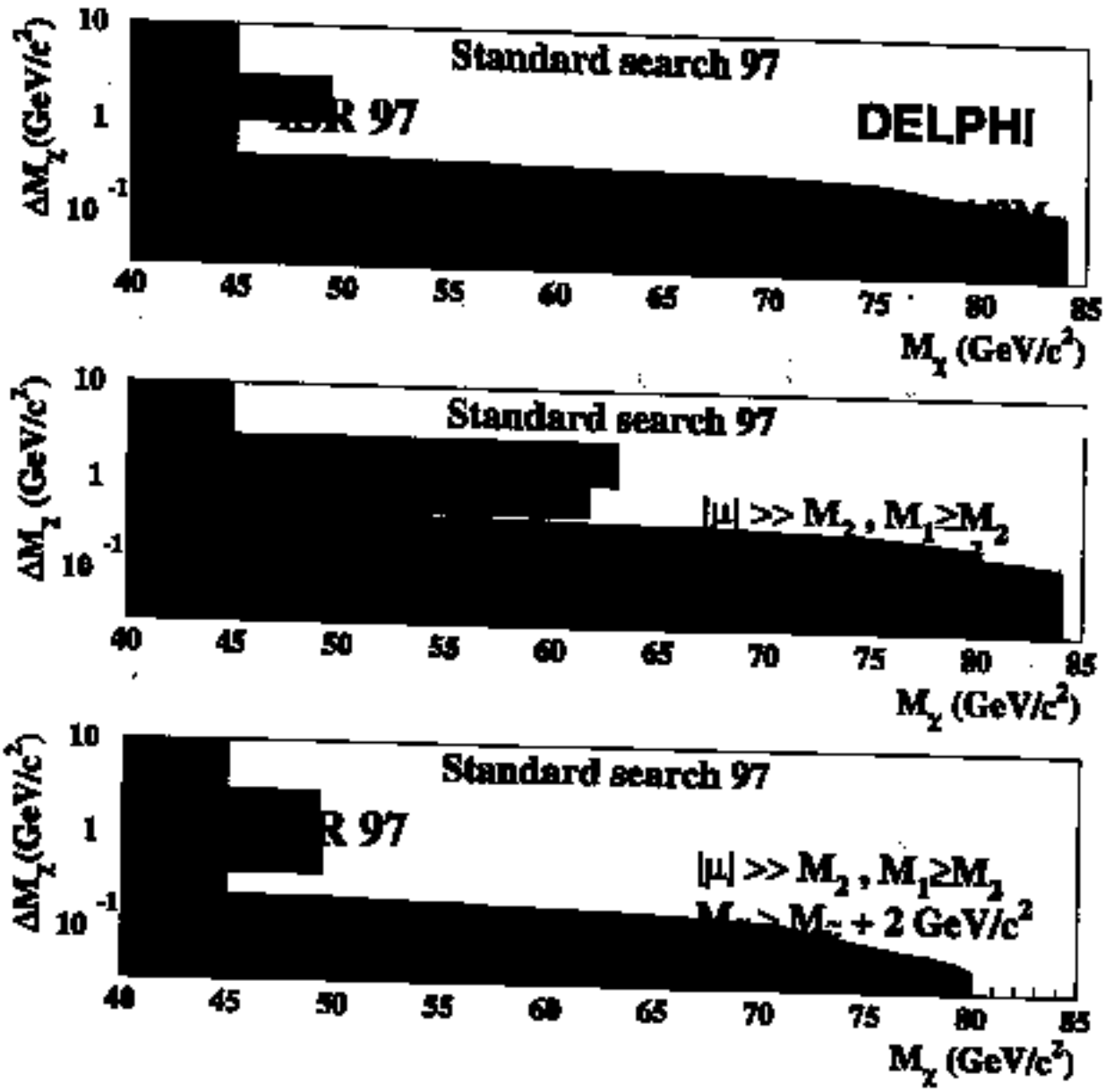
γ + small fragments

RATE

Ex. DELPHI at LEP$_2$

small Δm:

Search for ISR-photons with little energy in the detector



Gaugino with heavy $\tilde{\nu}$: $m(\chi_1^{\pm}) > 61$GeV for all Δm
Higgsino or light $\tilde{\nu}$ needs more luminosity

GMSB

- χ NLSP : long lived if $m_{\tilde{G}} > 1\,\mathrm{keV}$ (cosmology ?)
  If not $\chi \to \tilde{G}\gamma$ can be detected
  → OFFsets : longitudinal segmentation ECAL

- $\tilde{l}_e$ dE/dx cf. LEP_2
  ↳ $\tilde{G}l$ kinks

- Invisible Higgs (not necessarily 100%)
  $h \to \tilde{G}\chi$ Djouadi et al h-ph 9703452
  Also: $h \to JJ$ Valle et al h-ph 9601269
  $\to \tilde{\nu}\tilde{\nu}$ Murayama et al 9712515
  $\to \chi\chi$ Djouadi et al 9712334

  Can be observed by measuring Z decay in hZ

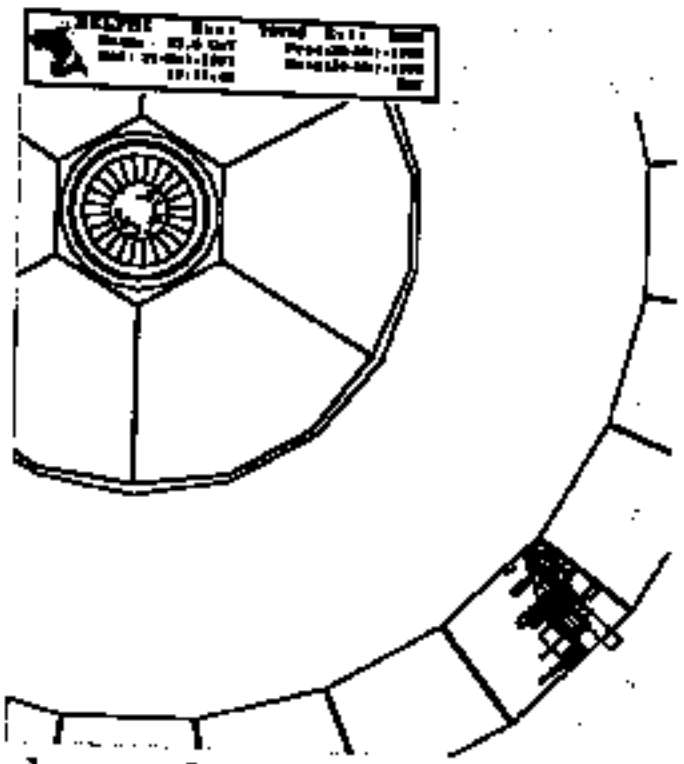
  Discriminate from WW ↳ $(\tau\nu)$ W $(e\nu)$ ZZ ↳ $\nu\bar{\nu}$

  → Good MM resolution or forget about $Z \to q\bar{q}$ and use $l\bar{l}$ (Rate) HIGH $\mathcal{L}$.

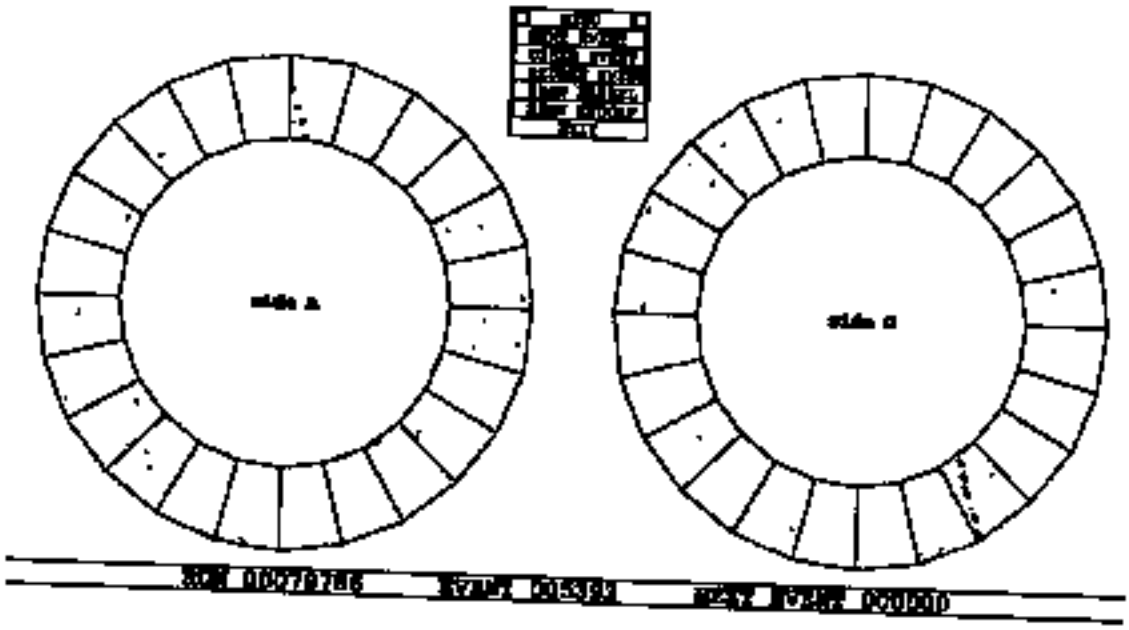
Neutralino search with photons

Long lived Neutralino: Search for "non pointing" photons (0 cand., 0.4 exp.)

Possible candidate: HPC:



HCAL cathode readout:



DETECTOR ASPECTS

- dE/dx for stables Si – TPC
- γ angles L-Sampling in ECAL, large lever arm $\chi \lesssim 20$ m (OR for $\chi\chi$)
  $\hookrightarrow \tilde{G}\gamma$ $m_{\tilde{G}} < 1$ keV (cosmol.)
- Fine granularity of HCAL + good σ_E $\tilde{g}_{LS}$
- Invisible Higgs: Hermeticity, σ_E
- Degenerate scenario:
  - Moderate ΔM $\cancel{\ell\ell} > \theta_{TAG}$ E_e ($\gamma\gamma\varphi$)
    θ_{TAG} as small as possibl
    + Large TRIGGER rate
  - Very low ΔM
    TRIGGER on single γ (+ low energy tracks)

CONCLUSION

- Various SUSY schemes can lead to various types of signatures and require a powerful detector and an open trigger
- The present scheme seems to cover the possibilities discussed in this presentation
- It is important to underline that TESLA can cope with these scenarios (complementarity with LHC