New Physics with photon signatures

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- Gauge-mediated SUSY Breaking (GMSB)
- Unparticles

Gauge-mediated SUSY Breaking (GMSB) models are distinguished by having a very light Gravitino ($\tilde{G}$) as the Lightest SUSY Particle (LSP).

In the Minimal GMSB model, the Next-Lightest SUSY Particle (NLSP) is a neutralino ($\tilde{N}_1$). The dominant decay mode is:

$$\tilde{N}_1 \to \gamma \tilde{G}$$

with a decay width:

$$\Gamma = 20\kappa \left(\frac{m_{\tilde{N}_1}}{100\ \mathrm{GeV}} \right)^5 \left(\frac{\sqrt{F}}{10\ \mathrm{TeV}} \right)^{-4} \text{ eV}$$

Here κ is a neutralino-photino mixing angle of order 1, and

$$\sqrt{F} = \text{mass scale of SUSY breaking}$$

This is a number we would **really** like to know!

The probability for $\tilde{N}_1$ with energy E to decay before traveling a distance x is

$$P(x) = 1 - e^{-x/L}$$

where

$$L = \frac{10^{-6}}{\kappa} \left(\frac{m_{\tilde{N}_1}}{100\ \mathrm{GeV}} \right)^{-5} \left(\frac{\sqrt{F}}{10\ \mathrm{TeV}} \right)^{4} (E^2/m_{\tilde{N}_1}^2 - 1)^{1/2}\ \text{cm}$$

This could be anything from less than a micron to many kilometers, depending on $\sqrt{F}$.

After LHC, we should know a great deal about these models. What can a Linear Collider add?

The most detailed study of the ILC side that I know of is:

AB = S. Ambrosanio and G.A. Blair, `hep-ph/9905403`.

Discussion here is based on that paper.

See also the LEP2 version, and a nice comprehensive review of GMSB:

S. Ambrosanio, G.D. Kribs, SPM, `hep-ph/9703211`

G.F. Giudice, R. Rattazzi, `hep-ph/9801271`

ILC can add a very precise measurement of $m_{\tilde{N}_1}$, and perhaps more importantly, $\sqrt{F}$.

Conservatively, suppose $\tilde{N}_1$ is the only superpartner that can be produced at the ILC for a given $\sqrt{s}$. Then the observable signal is:

$$e^+e^- \rightarrow \tilde{N}_1\tilde{N}_1 \rightarrow \gamma\gamma + \not{E}$$

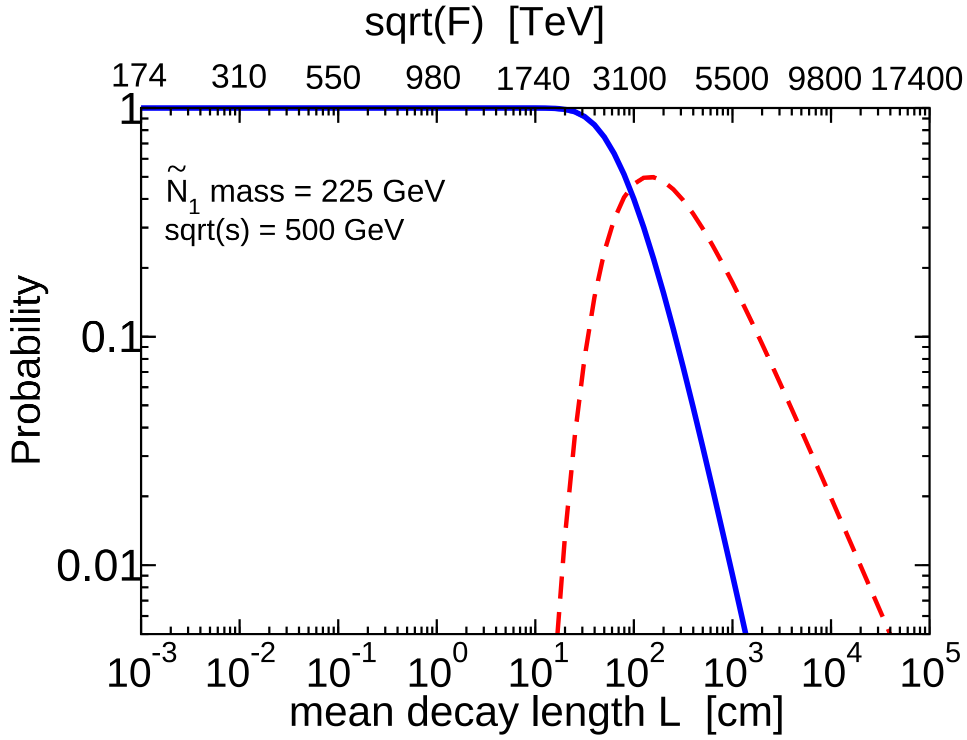
The photon energies have a flat spectrum, with

$$E_\gamma^{\text{max, min}} = \frac{1}{4}\left(\sqrt{s} \pm \sqrt{s - 4m^2_{\tilde{N}_1}}\right)$$

Measuring the endpoint of the more energetic photon gives a precise measurement of $m_{\tilde{N}_1}$.

If the supersymmetry breaking mass scale $\sqrt{F}$ is large enough, then the macroscopic decay length of $\tilde{N}_1$ can be measured.

Probability of exactly one (dashed line) or both (solid line) photon from the decays $\tilde{N}_1 \to \gamma\tilde{G}$ occuring within 1 meter of the Interaction Point:



Determining the mean decay length and thus $\sqrt{F}$ may be feasible for (tens of microns) $\lesssim\ L\ \lesssim$ (tens of meters)

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ILC can add a very precise measurement of $m_{\tilde{N}_1}$, and perhaps more importantly, $\sqrt{F}$.

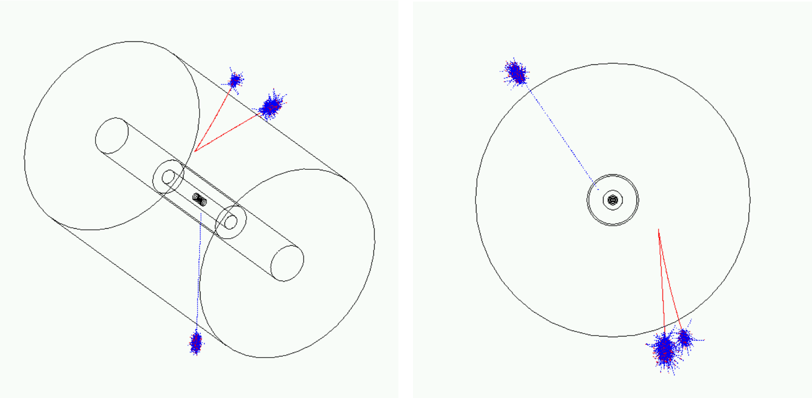
Photons can appear in the detector in several ways:

- photon impacts on preshower detector(s), ECAL energy deposit distributions give direction
- photon converts in the detector material to e^+e^- or other charged tracks
- slightly off-shell photon decays: $\gamma^{(*)} \to e^+e^-$, again giving tracks with pointing information. Happens at the percent level.

Depending on the decay length, different strategies can be used. Here I will briefly review the methods considered by Ambrosanio and Blair.

Method 1: 2-dim Projective Tracking

Require one photon in the ECAL and one off-shell photon decay (or photon conversion) tracks.



(Ambrosanio and Blair)

Project tracks onto the transverse plane, because of large z size of interaction region.

Applicability: tens of microns $\lesssim L \lesssim$ 0.1 cm

Method 2: 3-dim Vertexing

For decay lengths larger than the interaction region size (in z), reconstruct the 3-dim vertex position for off-shell photon decays or photon conversions.

Cut on the invariant mass of the track pair to improve vertexing by requiring a larger opening angle:

$$20\ \mathrm{MeV} < M_{\mathrm{pair}} < 10\ \mathrm{GeV}$$

This favors off-shell photon decays over conversions.

Applicability: 0.1 cm $\lesssim L \lesssim$ tens of cm

Method 3: Preshower and ECAL pointing

Finely segmented ECAL and preshower hit used to infer the photon impact parameter with respect to the interaction point.

More than one preshower layer helps (gives 2 points along photon path).

Applicability: few cm $\lesssim L \lesssim$ few meters

Method 4: ECAL timing

Decaying $\tilde{N}_1$ is heavy and slow.

AB assumed timing resolution in nanoseconds of $0.5 + 2/\sqrt{E/\text{1 GeV}}$.

This implies ~ 15 cm impact parameter resolution.

This method is more a “sanity check” than a best measurement.

Applicability: 15 cm $\lesssim L \lesssim$ 1 meter

Method 5: Photon counting statistics

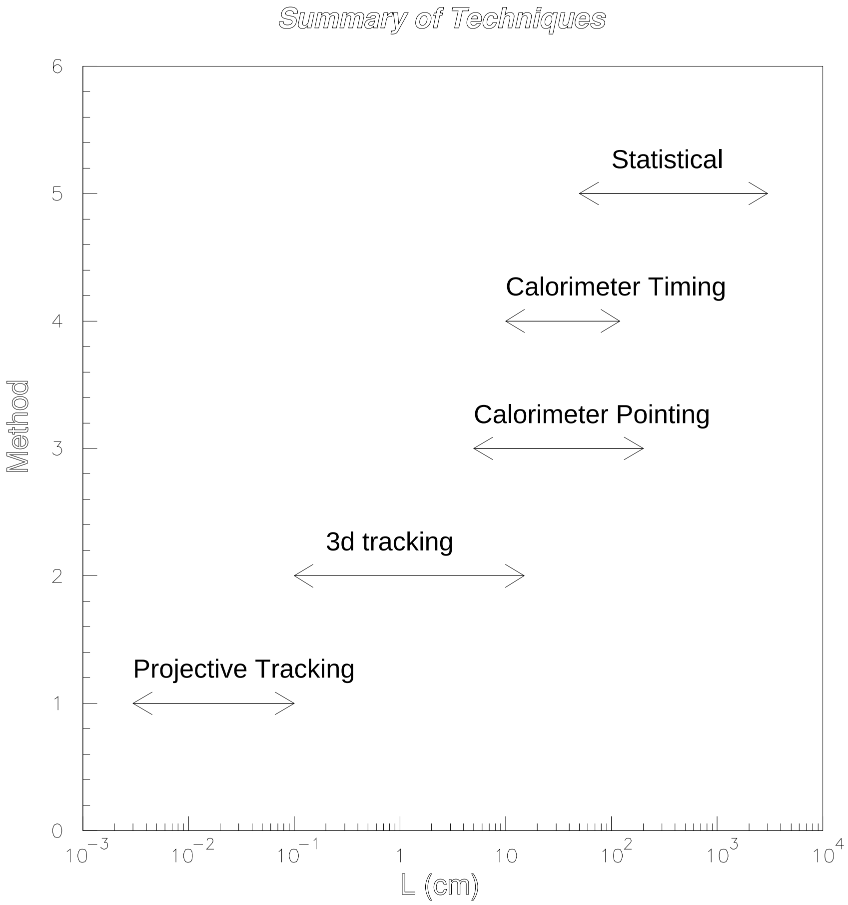
The ratio of 1-photon to 2-photon events consistent with large decay lengths gives a measure of the decay length.

Works best for large decay lengths, where 1 photon can escape the ECAL.

Depends in a complicated way on the detector configuration.

Applicability: tens of cm $\lesssim L \lesssim$ tens of meters

Summary of methods studied in Ambrosanio and Blair `hep-ph/9905403`:



Taking into account LHC results and updated ILC design parameters will require these analyses to be reconsidered.

“Unparticles”

H. Georgi, `hep-ph/0703260, 0704.2457`

Suppose there is a sector of fields with:

- Nearly exact scale invariance (an infrared-stable fixed point)
- very weak couplings to the Standard Model

This sector will have no particles with definite mass!

“Unparticle stuff” is (nearly) invisible, but carries energy, momentum.

Unparticle operators that couple to the Standard Model feature non-integer scaling dimension $d_{\mathcal{U}}$.

For example, Unparticle stuff might interact like:

$$\mathcal{L}_{int} \;=\; \frac{\lambda}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}-1}}\bar{e}\gamma_{\mu}e\,\mathcal{O}_{\mathcal{U}}^{\mu}$$

Here:

$\mathcal{O}_{\mathcal{U}}^{\mu}$ is a spin-1 Unparticle composite field

λ is a dimensionless coupling

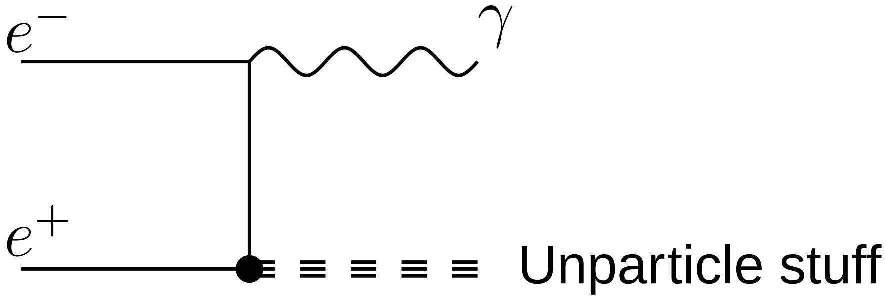
$\Lambda_{\mathcal{U}}$ is the effective mass scale for Unparticle interactions with electrons and positrons.

$d_{\mathcal{U}}$ is the (non-integer) scaling dimension

This Unparticle interaction has been investigated by Cheung, Keung, and Yuan (CKY) in `hep-ph/0704.2588` and `0706.3155`.

Monophoton signature from Unparticle Stuff

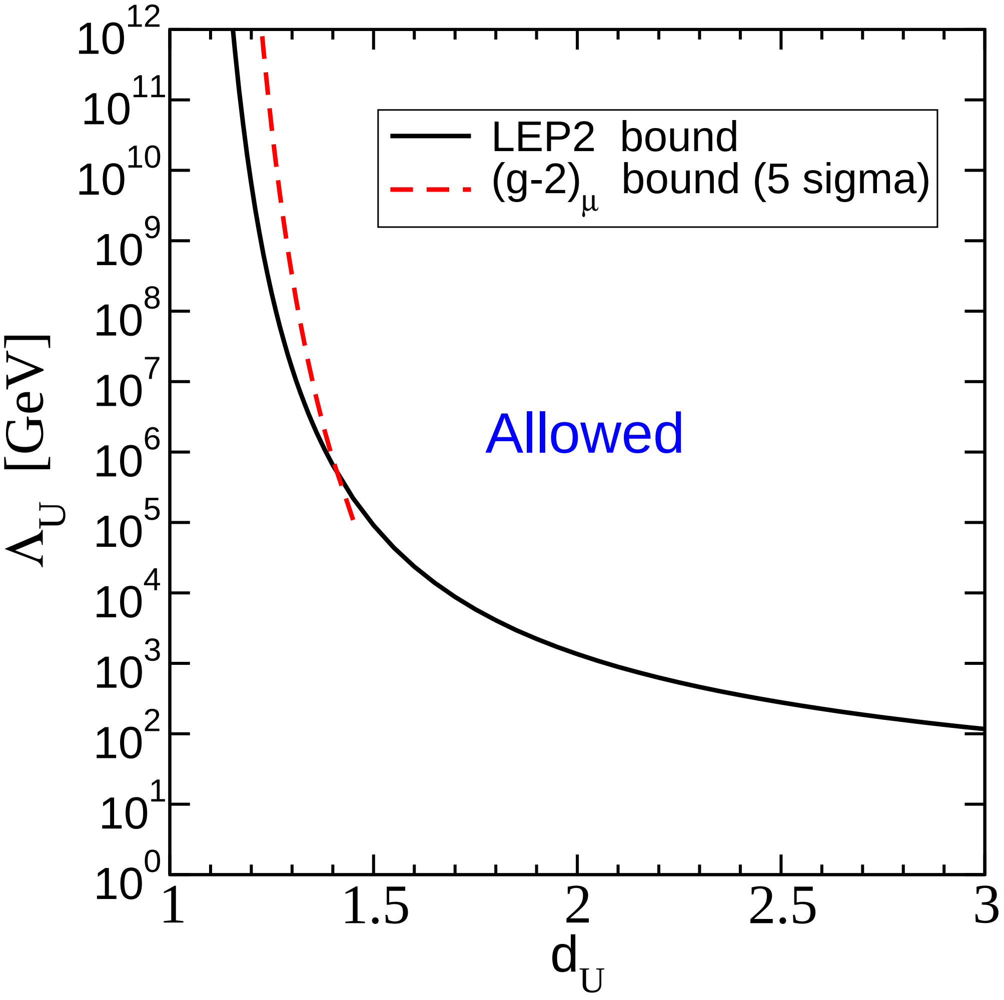
$$\sigma \propto \frac{\lambda^2}{\Lambda_{\mathcal{U}}^{2d_{\mathcal{U}}-2}}$$



Strongest bounds on this version of Unparticles come from LEP2 monophoton search, and (assuming lepton universality) $(g-2)_\mu$.

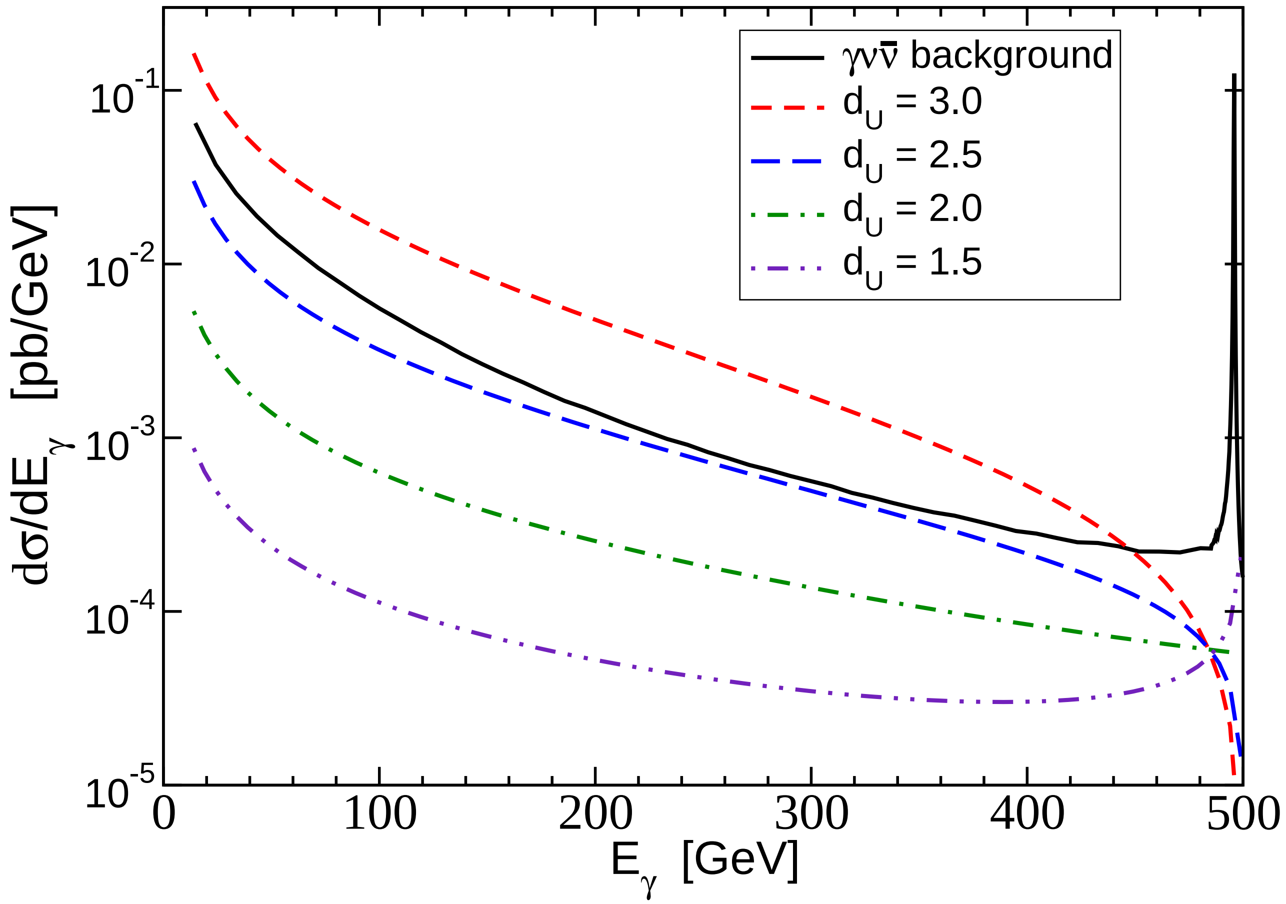
CKY used LEP2 constraint: $\sigma(e^-e^+ \to \gamma + \not{E}) < 0.2$ pb for $E_\gamma > 5$ GeV, $|\cos(\theta_\gamma)| < 0.97$ at $\sqrt{s} = 207$ GeV.

Constraints from LEP2 monophotons and $(g-2)_\mu$, taking $\lambda_1 = 1$:



This constrains what a LC can do with this particular Unparticle operator. . .

Here is what a 1 TeV LC can do for various d_U, taking the smallest value for Λ_U allowed by LEP2 in each case:



A realistic study should be done.

The Unparticle idea doesn’t solve any particular problem.

However, Unparticles can peacefully coexist with every other idea for New Physics, including SUSY, technicolor, extra dimensions, etc.

The particular scenario shown above cannot be constrained by LHC.

ECAL assumptions in Ambrosanio and Blair:

Angular Coverage: $|\cos\theta| < 0.95$

Barrel r size (cm): $172 < r < 210$

Endcap z size (cm): $280 < |z| < 330$

Energy resolution (per cent): $0.6 + 10.3/\sqrt{E/\text{1 GeV}}$

Spatial resolution (cm): $2 + 4/\sqrt{E/\text{1 GeV}}$

Angular pointing resolution (mrad): $50/\sqrt{E/\text{1 GeV}}$

Time resolution (ns): $0.5 + 2/\sqrt{E/\text{1 GeV}}$