

Monophoton signals in light gravitino production at future linear colliders

Bettina Oexl

Vrije Universiteit Brussel and International Solvay Institutes

Eur.Phys.J. **C71** (2011) 1783

K. Mawatari, BO, Y. Takaesu

JHEP 1210 (2012) 008

P. de Aquino, F. Maltoni, K. Mawatari, BO

Eur.Phys.J **C73** (2013) 2580

Neil D. Christensen, P. de Aquino,
N. Deutschmann, C. Duhr, B. Fuks, C. Garcia-Cely,
O. Mattelaer, K. Mawatari, BO, Y. Takaesu

Eur.Phys.J **C74** (2014) 2909

K. Mawatari, BO

In progress (arXiv:1410.xxxx)

F. Maltoni, A. Martini, K. Mawatari, BO

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Vrije
Universiteit
Brussel



New physics particles may show up as
mono-photon plus missing energy

massive gravitons

weakly interacting massive particles

neutralino

gravitino

...

New physics particles may show up as
mono-photon plus missing energy

massive gravitons

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neutralino

gravitino very light: $m_{3/2} = \mathcal{O}(10^{-13} - 10^{-12} \text{ GeV})$

No-scale supergravity: Ellis, Enqvist,Nanopoulos, Phys Lett. B147 (1984) 99
Extra dimensions: Gheretta, Pomarol, Nucl.Phys B586(2000)141([hep-ph/0003129](#))

...

Gravitino production gives mono-photon signal via two processes

Gravitino production at a linear e^+e^- collider gives signal

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

via two processes:

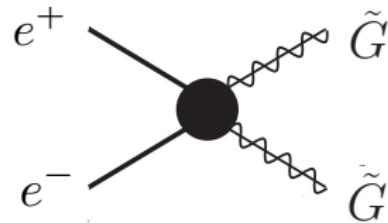
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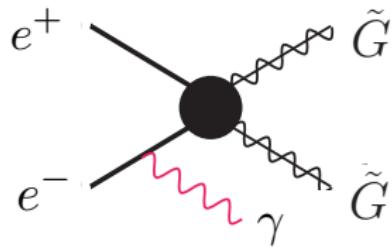
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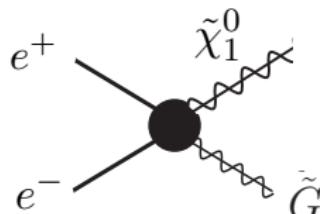
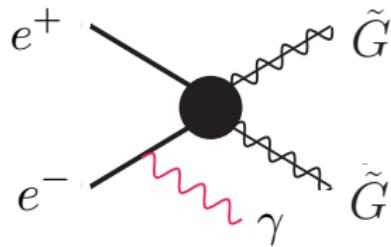
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neutralino gravitino associated production



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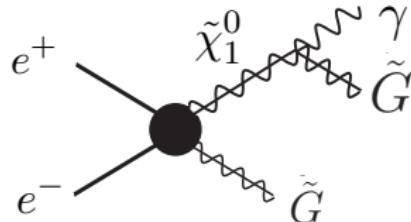
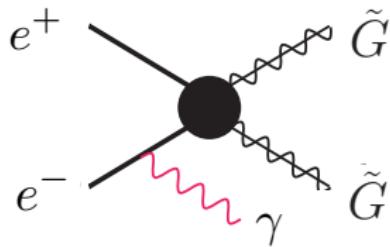
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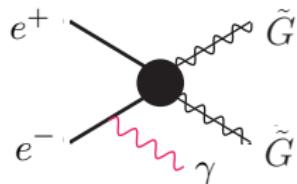
gravitino pair production

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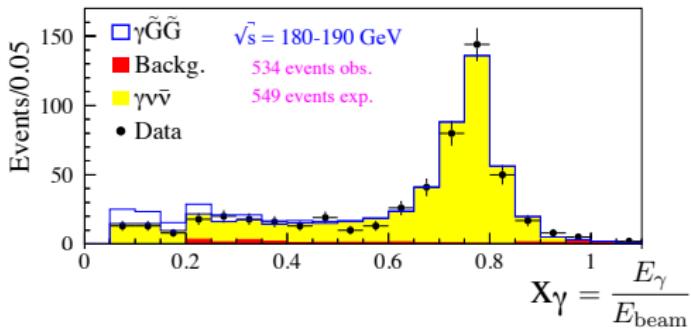


Current interpretation of monophoton signal in terms of single process only

Gravitino-pair production:



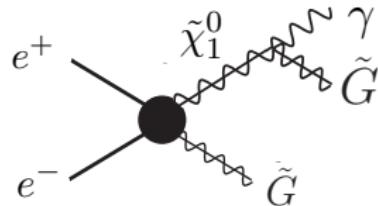
LEP2 SUSY Working group collaboration,
"Single photon, 183-208 GeV"
[http://lepsusy.web.cern.ch/lepsusy/www/photons/
single/single_public_summer04.html](http://lepsusy.web.cern.ch/lepsusy/www/photons/single/single_public_summer04.html)



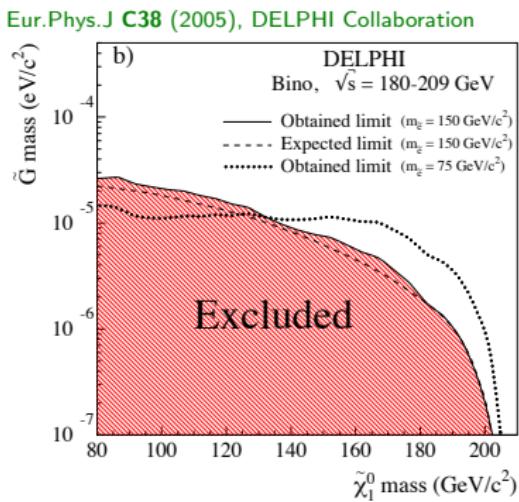
Assuming that other SUSY particles except gravitino are heavy, the bound is $m_{3/2} \geq 1.37 \times 10^{-14} \text{ GeV}$.

Current interpretation of monophoton signal in terms of single process only

Neutralino-gravitino associated production:



For $m_{\tilde{\chi}_1^0} = 140$ GeV and $m_{\tilde{e}} = 150$ GeV, gravitino masses of $m_{3/2} \geq 10^{-14}$ GeV are allowed.



The bounds are obtained independently from gravitino-pair and neutralino-gravitino associated production.

We obtain information about gravitino
and SUSY particle masses

We revisit the mono-photon + \cancel{E} signature
at future linear e^+e^- colliders.

We construct model that allows to simulate both processes
at the same time, for any SUSY parameters.

We show how to extract information about the gravitino and other
SUSY particle masses from simple final state observables.

Outline

The gravitino

A SUSY QED model

The two contributing sub-processes

Gravitino pair production

Gravitino-neutralino associated production

Monophoton plus missing energy signal at the ILC

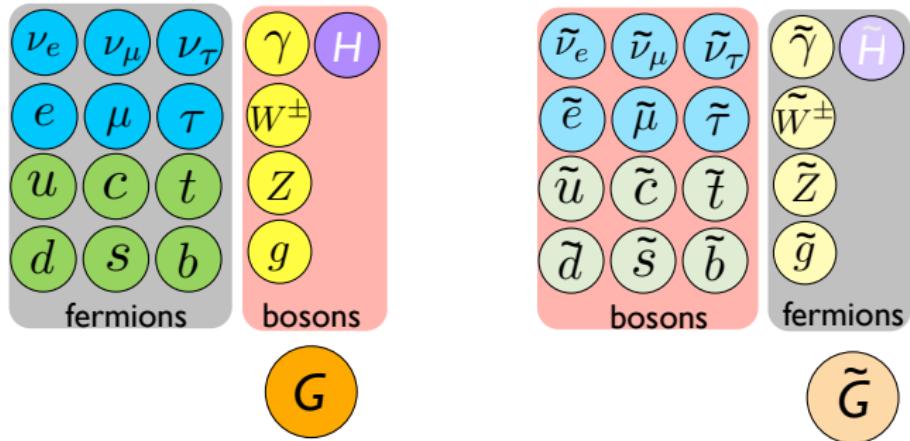
Phenomenological studies

Background reduction

Results

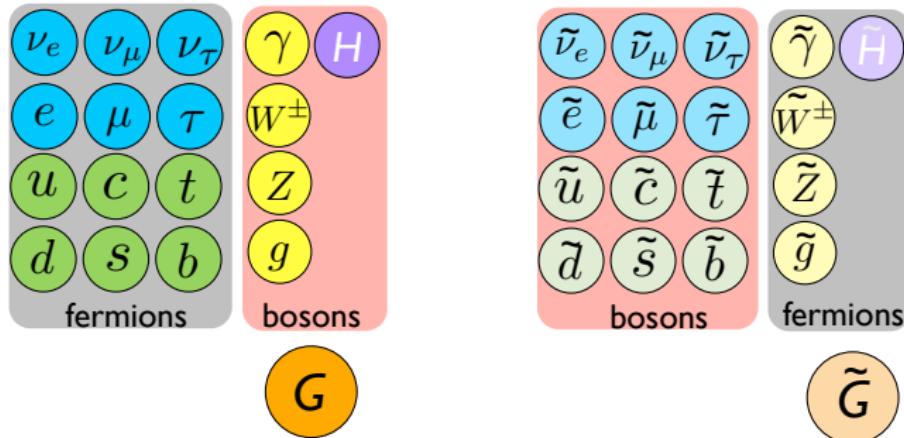
Monophoton plus missing energy signal at the LHC

Local SUSY theories include the gravitino



In local SUSY theories, the gravitino is the spin 3/2 superpartner of the graviton (spin 2).

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The gravitino becomes massive when SUSY is broken spontaneously.

Its interactions might be strong enough to be tested at colliders.

The gravitino mass is proportional to SUSY breaking scale

BEH-mechanism

SU(2)xU(1) gauge symmetry is spontaneously broken.

Massless goldstone bosons appear.

The W and Z absorb the goldstone bosons and become massive.

$$m_W \sim gv$$



g : interaction strength of W boson

v : vacuum expectation value of H field

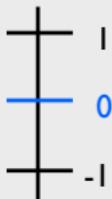
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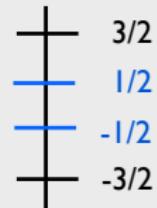
v : vacuum expectation value of H field

Super-Higgs mechanism

SUSY is spontaneously broken.
A massless goldstone fermion (the goldstino) appears.

The gravitino absorbs the goldstino and becomes massive.

$$m_{3/2} \sim \frac{1}{M_{\text{Pl}}} F$$



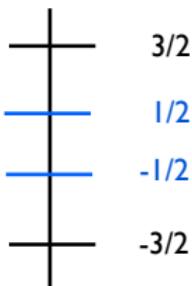
$\frac{1}{M_{\text{Pl}}}$: interaction strength of gravitino

F : vacuum expectation value that breaks SUSY (SUSY breaking scale)

Gravitino interactions can be relevant at colliders

The interactions of the helicity $3/2$ states are suppressed by the Planck scale.

By absorbing the goldstino,
the interactions of the helicity $1/2$ states gain
the interaction strength of the goldstino.
They interact with a strength $\sim 1/\sqrt{F}$.



For low scale SUSY breaking scenarios, the spin $1/2$ components are dominant, and can become relevant at colliders.
The gravitino is well described by the goldstino (gravitino-goldstino equivalence theorem).

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The SUSY QED field content

Our model consists of

one vector superfield describing the photon A^μ and photino λ

$$V = (A^\mu, \lambda, D_V)$$

two chiral superfields describing left- and right-handed electrons $e_{L/R}$ and selectrons $\tilde{e}_{L/R}$

$$\begin{aligned}\Phi_L &= (\tilde{e}_L, e_L, F_L) \\ \Phi_R &= (\tilde{e}_R^*, e_R^c, F_R)\end{aligned}$$

one chiral superfield describing the sgoldstino ϕ and a goldstino \tilde{G} .

$$X = (\phi, \tilde{G}, F_X)$$

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We have a Lagrangian for the **visible sector**, for the **goldstino sector** and **interactions** between the fields of the visible sector and the (s)goldstino.

SUSY QED Lagrangian: visible sector

The usual SUSY interactions are described by

$$\mathcal{L}_{\text{vis}} = \sum_{i=L,R} \int d^4\theta \Phi_i^\dagger e^{2g_e Q_i V} \Phi_i + \frac{1}{4} \left(\int d^2\theta W^\alpha W_\alpha + \text{h.c.} \right).$$

kinetic terms of (s)electrons
and (SUSY) gauge interactions

kinetic terms
of photon and photino

W_α : SUSY $U(1)_{\text{em}}$
field strength tensor

SUSY QED Lagrangian: visible sector + goldstino sector

The usual SUSY interactions are described by

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kinetic terms of (s)electrons
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W_α : SUSY $U(1)_{\text{em}}$
field strength tensor

The kinetic terms and self-interactions of the gravitino result from

$$\mathcal{L}_X = \int d^4\theta X^\dagger X - \left(F \int d^2\theta X + \text{h.c.} \right) - \frac{m_\Phi^2}{4F^2} \int d^4\theta (X^\dagger X)^2.$$

kinetic terms

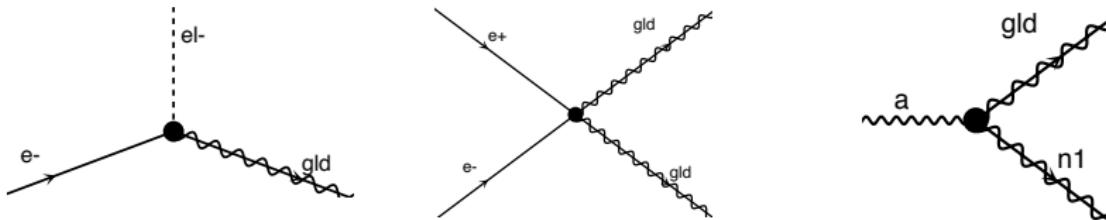
SUSY breaking

(s)goldstino
interactions

SUSY QED Lagrangian: interactions

The interactions between the SUSY fields and the (s)goldstino arise from

$$\mathcal{L}_{\text{int}} = - \sum_{i=L,R} \frac{m_{\tilde{e}_i}^2}{F^2} \int d^4\theta X^\dagger X \Phi_i^\dagger \Phi_i - \left(\frac{m_\lambda}{2F} \int d^2\theta X W^\alpha W_\alpha + \text{h.c.} \right).$$



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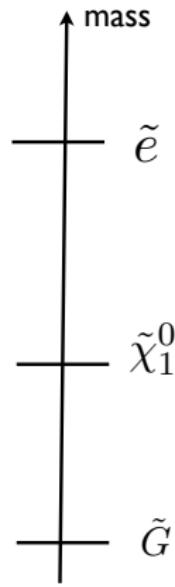
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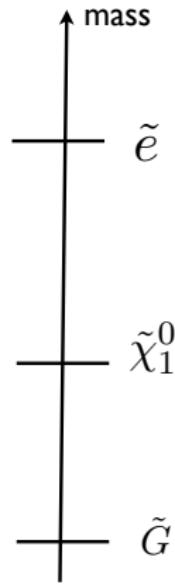
Monophoton plus missing energy signal at the LHC

The setup



The gravitino is the lightest SUSY particle.
 $m_{3/2} = \mathcal{O}(10^{-13})$ GeV

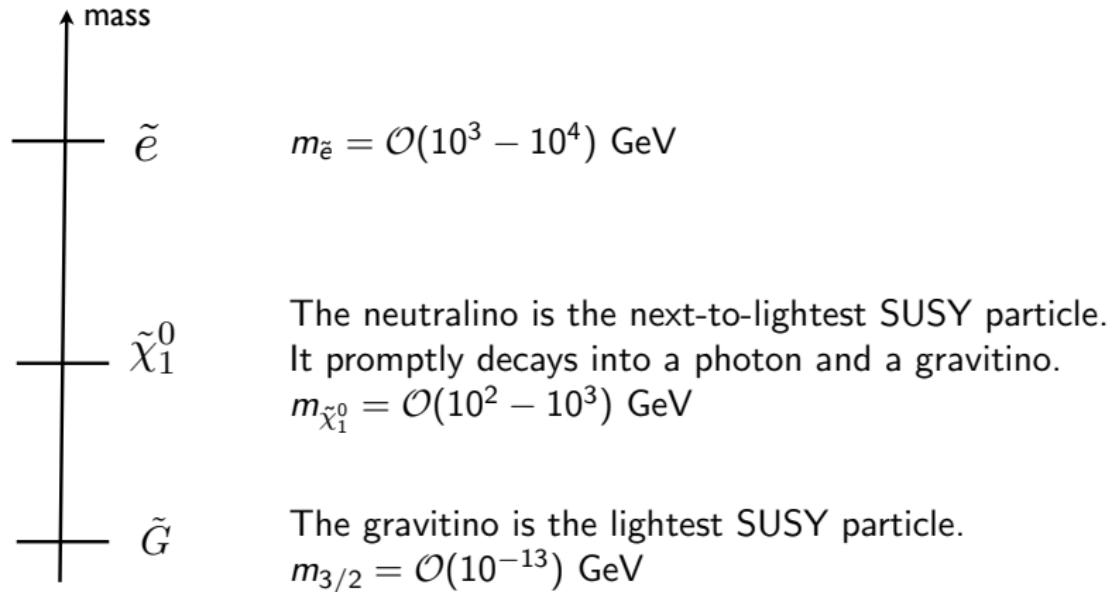
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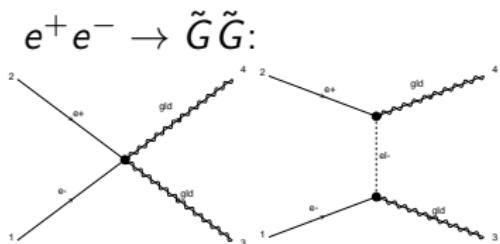
The neutralino is the next-to-lightest SUSY particle.
It promptly decays into a photon and a gravitino.
 $m_{\tilde{\chi}_1^0} = \mathcal{O}(10^2 - 10^3) \text{ GeV}$

The gravitino is the lightest SUSY particle.
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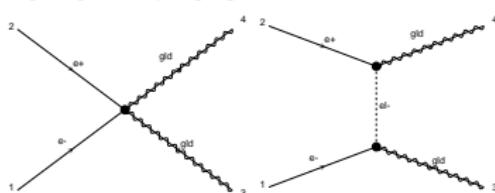


The cross section depends on CM energy
and selectron mass

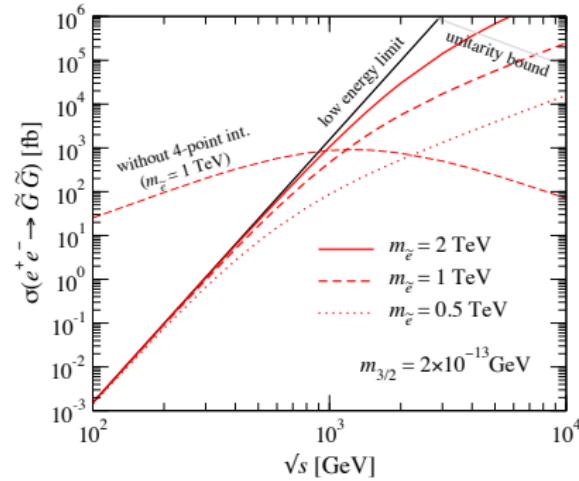


The cross section depends on CM energy and selectron mass

$e^+ e^- \rightarrow \tilde{G} \tilde{G}$:

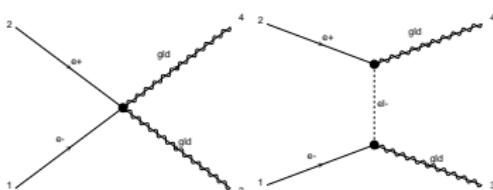


$$\sigma = \frac{1}{192\pi F^4} \sum_{\lambda=\pm} \frac{m_{\tilde{e}\lambda}^4}{s^2} \left[s^3 - 3m_{\tilde{e}\lambda}^2 s^2 + 9m_{\tilde{e}\lambda}^4 s \right. \\ \left. + 3m_{\tilde{e}\lambda}^6 \left(1 - \frac{m_{\tilde{e}\lambda}^2}{s + m_{\tilde{e}\lambda}^2} + 4 \log \frac{m_{\tilde{e}\lambda}^2}{s + m_{\tilde{e}\lambda}^2} \right) \right]$$

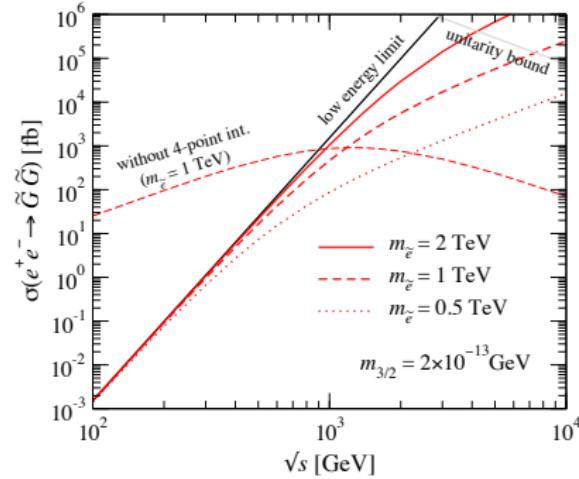


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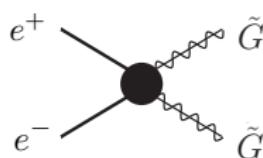
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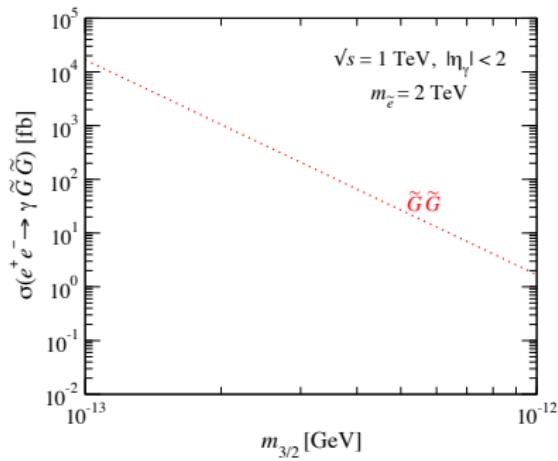
In low-energy limit, $\sqrt{s} \ll m_{\tilde{e}\pm}$, cross section increases with CM energy as $\sigma = \frac{s^3}{160\pi F^4}$.

Low energy limit may not be adequate for current collider energies.

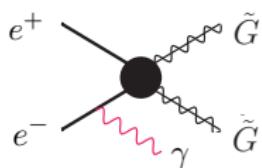
The cross section scales with gravitino mass



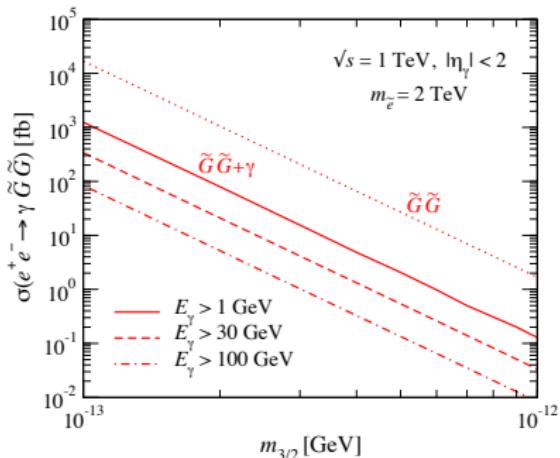
$$\sigma(\tilde{G}\tilde{G}) \propto \frac{1}{m_{3/2}^4}$$



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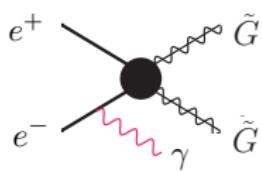


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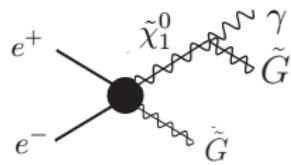
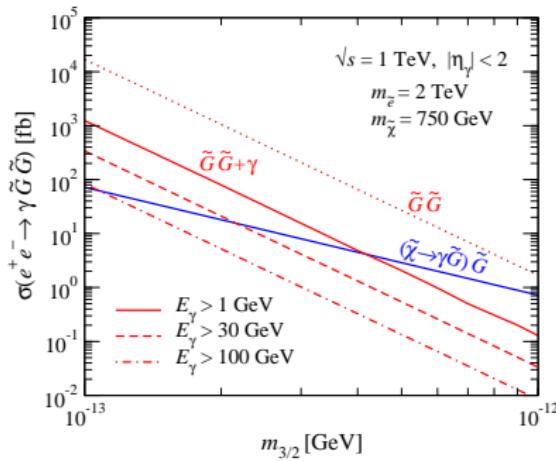
The cross section depends on cut on photon energy.

The cross section scales with gravitino mass



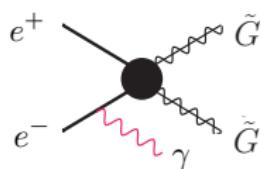
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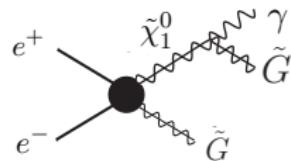
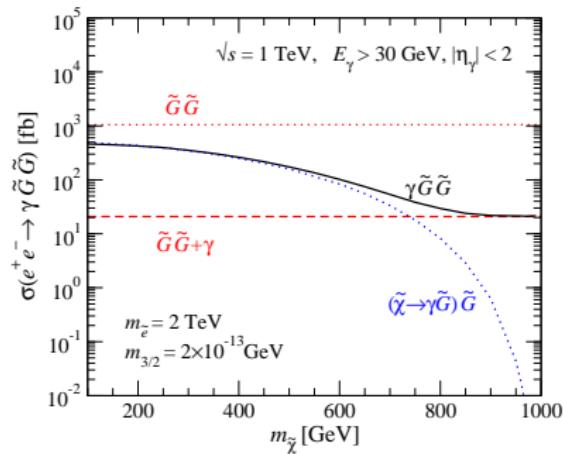


$$\sigma(\tilde{\chi}\tilde{G}) \propto \frac{1}{m_{3/2}^2}$$

Neutralino gravitino associated production depends also on neutralino mass



$$\sigma(\tilde{G}\tilde{G}) \propto \frac{1}{m_{3/2}^4}$$



$$\sigma(\tilde{\chi}\tilde{G}) \propto \frac{1}{m_{3/2}^2}$$

Neutralino gravitino production cross section drops due to phase space closure.

Depending on SUSY parameters, a different sub-process dominates.
We choose parameters such that both processes are comparable.

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The work-flow of our phenomenological study

$$\mathcal{L} = \bar{\psi} i \not{D} \psi$$

FeynRules

<http://feynrules.irmp.ucl.ac.be/>

Feynman rules

$$-ig\gamma^\mu$$

UFO model: vertices.py, parameters.py, ...

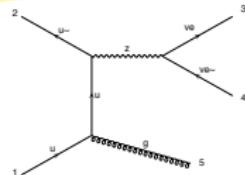
Process

$$pp \rightarrow j\nu\bar{\nu}$$

MadGraph

<https://launchpad.net/mg5amcnlo>

Feynman diagrams



Helicity amplitudes

$$i\mathcal{M} \sim \bar{v}(p_2, \lambda_2)\gamma^\nu(p_1 - p_5)\gamma^\mu u(p_1, \lambda_1) \dots$$

Unweighted events

2	-1	0	0	502	0	0.00000000000E+00	0.00000000000E+00
-2	-1	0	0	501	0	0.00000000000E+00	0.00000000000E+00
23	2	1	2	0	0	-0.10517156134E+03	-0.10962553294E+02
14	1	3	3	0	0	-0.12058574507E+03	-0.12149486638E+02
-14	1	3	3	0	0	0.15414183729E+02	0.11869333442E+01
21	1	1	2	502	501	0.10517156134E+03	0.10962553294E+02
...							

With *FeynRules*, we construct consistent model

It contains 4 fermion interactions,

and the sgoldstino.

We can cover the whole parameter space of SUSY particle masses,

we can treat both contributing sub-processes within one model file.

A 1-minute tutorial to *MadGraph5_aMC@NLO*

With *MadGraph5*, we can simulate any process with gravitinos.

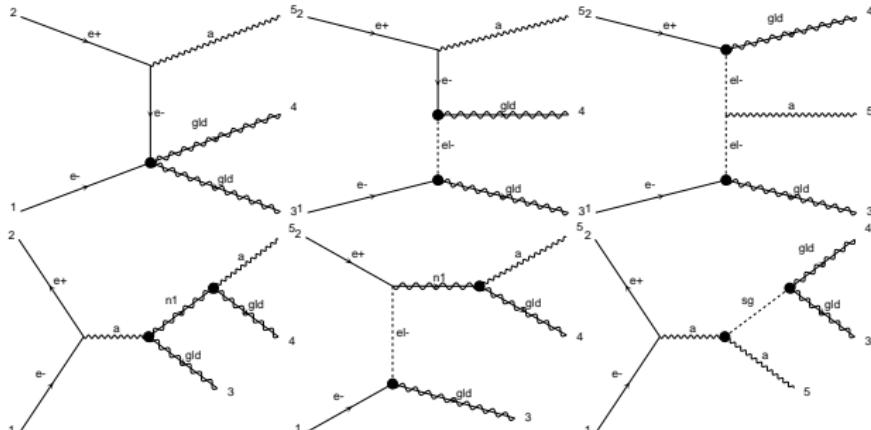
Download <https://launchpad.net/mg5amcnlo>.

.\bin\mg5_aMC	→ start MadGraph in a shell
> import model MSSM_GLD	→ import the model
> generate e+ e- > gld gld a	→ generate process
> output	→ write the code
> launch	→ generate events

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```



SM background is efficiently reduced by cuts and polarized beams

The SM background is $e^+e^- \rightarrow \gamma\nu\bar{\nu}$.

Contributions from $e^+e^- \rightarrow \gamma Z \rightarrow \gamma\nu\bar{\nu}$ are removed by requiring

$$E_\gamma < \frac{s - m_Z^2}{2\sqrt{s}} - 5\Gamma_Z.$$

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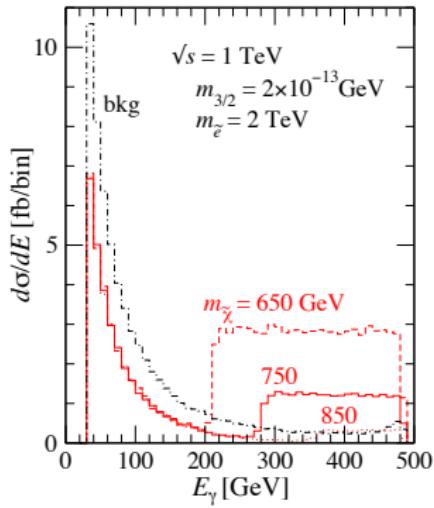
$$E_\gamma < \frac{s - m_Z^2}{2\sqrt{s}} - 5\Gamma_Z.$$

Using polarized beams reduces contributions from W :

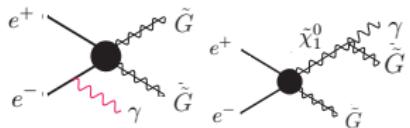
(P_{e^-}, P_{e^+})	$m_{\tilde{\chi}}$ [GeV]	$\tilde{\chi} \tilde{G}$	$\tilde{G} \tilde{G}$	SM bkg	[fb]
(0, 0)	650	49.2			
	750	15.8	21.1		1452
	850	2.5			
$(0.9, -0.6)$	650	75.8			
	750	24.3	32.7		64.9
	850	3.4			

$$\sqrt{s} = 1 \text{ TeV}, m_{3/2} = 2 \times 10^{-13} \text{ GeV}, m_{\tilde{e}} = 2 \text{ TeV}$$

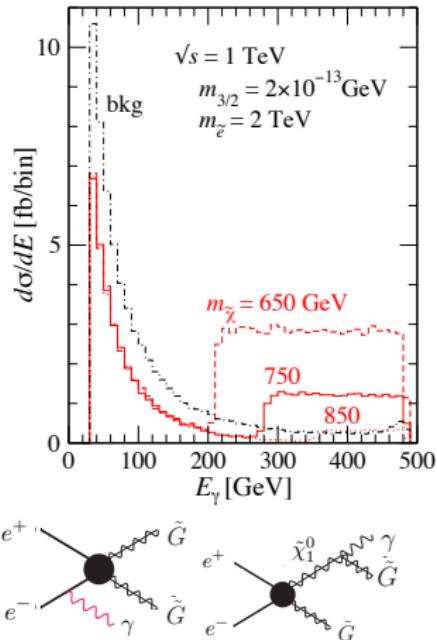
Result: Photon energy distribution



Photon from gravitino pair production is mostly soft.
It is independent of the neutralino mass.



Result: Photon energy distribution



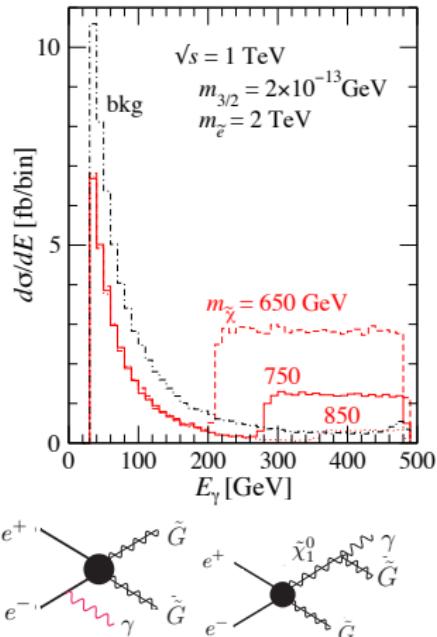
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We can determine neutralino mass.

We can extract information about gravitino mass and other SUSY particle masses.

Outline

The gravitino

A SUSY QED model

The two contributing sub-processes

Gravitino pair production

Gravitino-neutralino associated production

Monophoton plus missing energy signal at the ILC

Phenomenological studies

Background reduction

Results

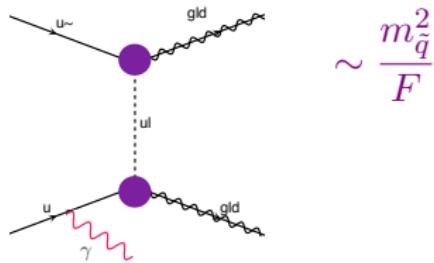
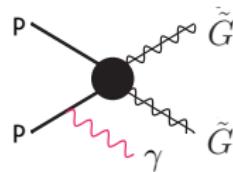
Monophoton plus missing energy signal at the LHC

The cross section is sensitive to the squark masses

We study the process
 $p p \rightarrow \gamma \tilde{G} \tilde{G} \rightarrow \gamma \not{E}_T$.

We assume neutralino to be too heavy to be produced on-shell.
Only gravitino-pair production contributes.

The couplings are sensitive to squark masses.

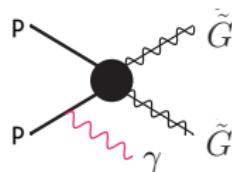


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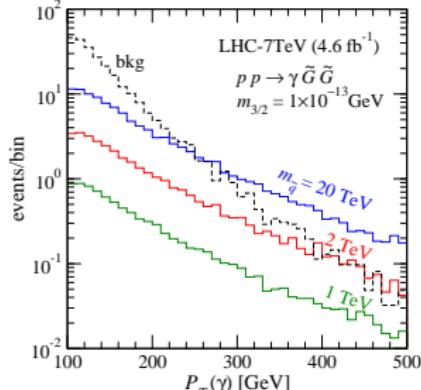
We study the process
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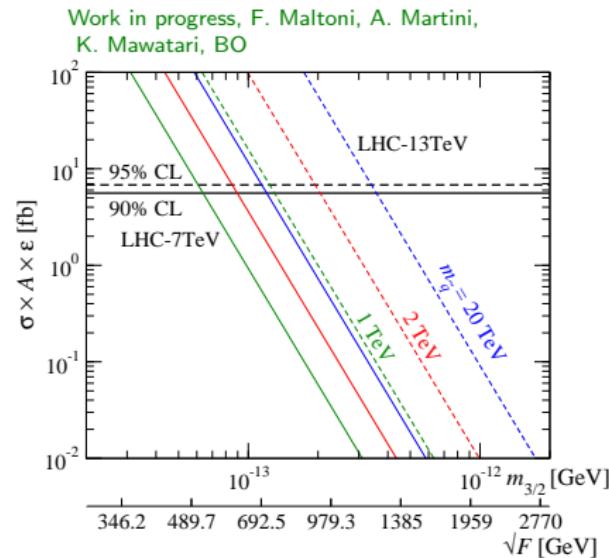
Work in progress, F. Maltoni, A. Martini,
K. Mawatari, BO



We set a lower bound on the gravitino mass

Both ATLAS and CMS set an upper bound in the visible cross section of a new physics process.

We interpret this result in terms of light gravitino production.



For the heavy SUSY mass limit, gravitino masses below $m_{3/2} < 1 \times 10^{-13}$ GeV are excluded at 95% CL.

For light squark masses, the limits are lower.

Allowing neutralino to be light can modify the limits.

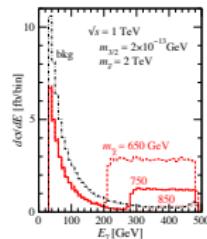
Summary

We revisited the mono-photon+ \cancel{E}_T signal arising from light gravitino production.

Two processes contribute: gravitino pair production and neutralino gravitino associated production.

Their importance varies with the gravitino and neutralino masses as well as with kinematical cuts.

We showed how to extract information about the gravitino mass as well as the other SUSY particle masses from the photon spectrum.



We interpreted the limit on the mono-photon+ \cancel{E}_T signal at the LHC in terms of gravitino production and set a limit on the gravitino mass.

Goldstino gravitino equivalence theorem

Replace the spin-3/2 gravitino field by the spin-1/2 goldstino field as $\psi_\mu \sim \sqrt{2/3} \partial_\mu \psi / m_{3/2}$.

The effective interaction Lagrangian in non-derivative form is

$$\begin{aligned}\mathcal{L}_{\text{int}} = & \pm \frac{i m_{\phi_{L/R}^i}^2}{\sqrt{3} M_{\text{Pl}} m_{3/2}} [\bar{\psi} P_{L/R} f^i (\phi_{L/R}^i)^* - \bar{f}^i P_{R/L} \psi \phi_{L/R}^i] \\ & - \frac{m_\lambda}{4\sqrt{6} M_{\text{Pl}} m_{3/2}} \bar{\psi} [\gamma^\mu, \gamma^\nu] \lambda^a F_{\mu\nu}^a.\end{aligned}$$

The interaction Lagrangian in terms of component fields

$$\mathcal{L}_{\tilde{G}} = \mp \frac{im_{\tilde{e}\pm}^2}{F} (\bar{\psi}_{\tilde{G}} P_{\pm} \psi_e \phi_{\tilde{e}\pm}^* - \bar{\psi}_e P_{\mp} \psi_{\tilde{G}} \phi_{\tilde{e}\pm})$$

$$- \frac{m_{\tilde{\chi}}}{4\sqrt{2}F} \bar{\psi}_{\tilde{G}} [\gamma^\mu, \gamma^\nu] \psi_{\tilde{\chi}} F_{\mu\nu}$$

$$- \frac{m_{\tilde{e}\pm}^2}{F^2} \bar{\psi}_e P_{\mp} \psi_{\tilde{G}} \bar{\psi}_{\tilde{G}} P_{\pm} \psi_e,$$

$$\mathcal{L}_{S,P} = - \frac{m_\phi^2}{2\sqrt{2}F} \bar{\psi}_{\tilde{G}} (\phi_S + i\gamma^5 \phi_P) \psi_{\tilde{G}}$$

$$+ \frac{m_{\tilde{\chi}}}{2\sqrt{2}F} (\phi_S F^{\mu\nu} F_{\mu\nu} - \phi_P F^{\mu\nu} \tilde{F}_{\mu\nu}),$$

$$\begin{aligned} \mathcal{L}_{\text{vis}} = & g_e \bar{\psi}_e \gamma_\mu \psi_e A^\mu + ig_e (\phi_{\tilde{e}\pm}^* \overleftrightarrow{\partial}_\mu \phi_{\tilde{e}\pm}) A^\mu \\ & \mp \sqrt{2} g_e (\bar{\psi}_{\tilde{\chi}} P_{\pm} \psi_e \phi_{\tilde{e}\pm}^* + \bar{\psi}_e P_{\mp} \psi_{\tilde{\chi}} \phi_{\tilde{e}\pm}), \end{aligned}$$

The helicity amplitudes of $e^+e^- \rightarrow \tilde{G}\tilde{G}$

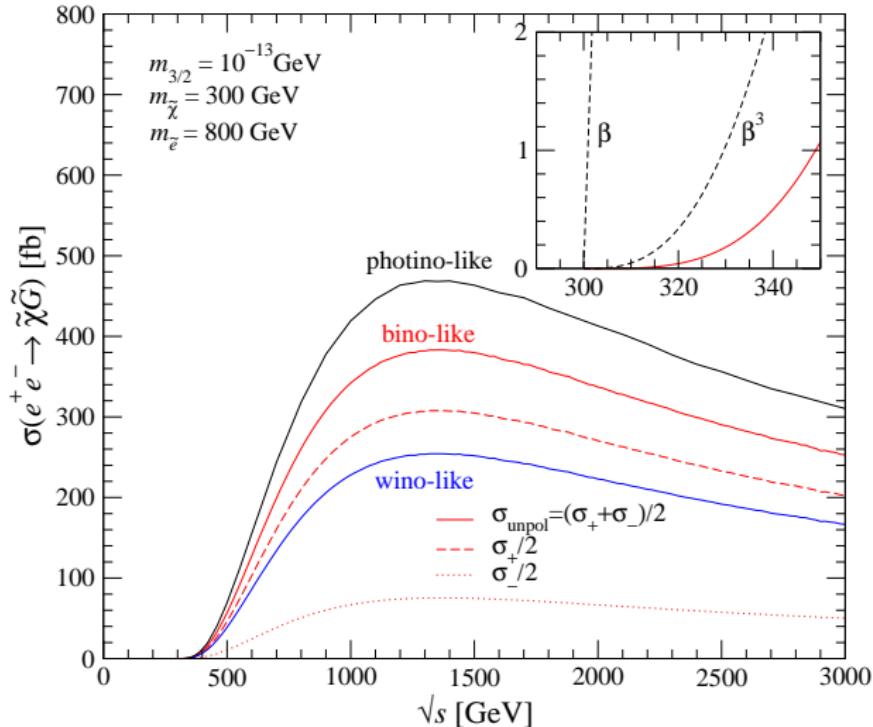
$$e^-\left(p_1, \frac{\lambda_1}{2}\right) + e^+\left(p_2, \frac{\lambda_2}{2}\right) \rightarrow \tilde{G}\left(p_3, \frac{\lambda_3}{2}\right) + \tilde{G}\left(p_4, \frac{\lambda_4}{2}\right),$$

Due to the helicity structure, only amplitudes with $\lambda_2 = -\lambda_1$ contribute.

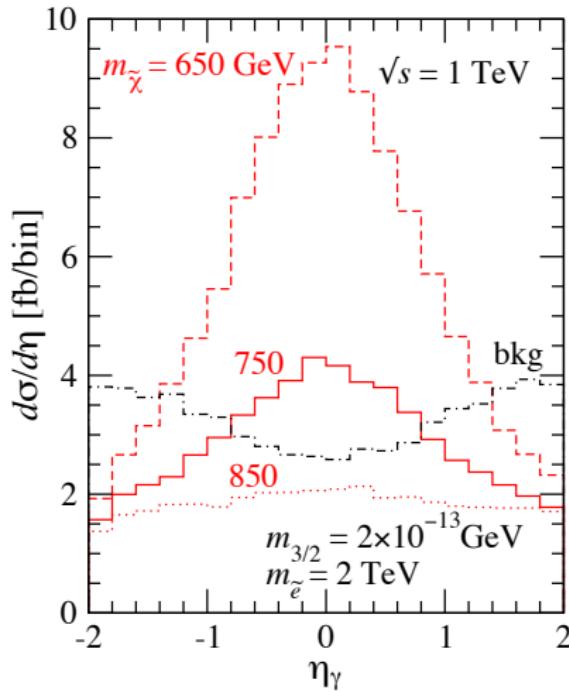
$\lambda_1 \lambda_3$		\mathcal{M}^c	\mathcal{M}^t	\mathcal{M}^u
$\pm \mp$	$-\frac{s m_{\tilde{e}_{\lambda_1}}^2}{2F^2} (1 - \cos \theta)$	$[1]$	$+\frac{m_{\tilde{e}_{\lambda_1}}^2}{t - m_{\tilde{e}_{\lambda_1}}^2}$	
$\pm \pm$	$-\frac{s m_{\tilde{e}_{\lambda_1}}^2}{2F^2} (1 + \cos \theta)$	$[1]$		$+\frac{m_{\tilde{e}_{\lambda_1}}^2}{u - m_{\tilde{e}_{\lambda_1}}^2}$

The cross section can be enhanced with polarized beams.

The neutralino mixing affects cross section



The rapidity distribution

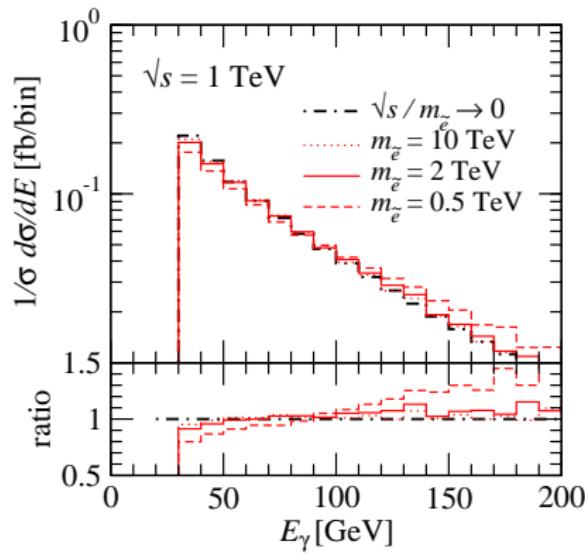


The selectron mass dependence

Overall cross section varies with different selectron masses:

(P_{e^-}, P_{e^+})	$m_{\tilde{\chi}} \text{ [GeV]}$	$(m_{\tilde{e}} = 1 \text{ TeV})$		$(m_{\tilde{e}} = 2 \text{ TeV})$		[fb]
		$\tilde{\chi} \tilde{G}$	$\tilde{G} \tilde{G}$	$\tilde{\chi} \tilde{G}$	$\tilde{G} \tilde{G}$	SM bkg
$(0, 0)$	650	19.7		49.2		
	750	6.0	10.4	15.8	21.1	1452
	850	1.0		2.5		
$(0.9, -0.6)$	650	30.4		75.8		
	750	9.2	16.1	24.3	32.7	64.9
	850	1.5		3.4		

The selectron mass dependence



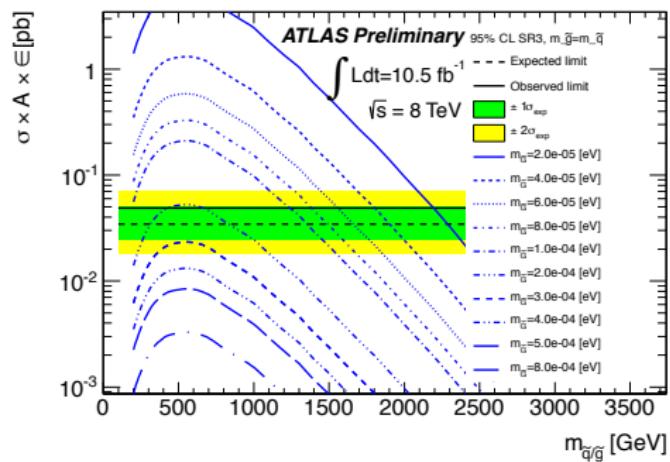
Also shape varies with selectron mass.

The neutralino decay width

$$\Gamma(\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}) = \frac{|C^{\gamma \tilde{\chi}_1^0}|^2 m_{\tilde{\chi}_1^0}^5}{48\pi \overline{M}_{\text{Pl}}^2 m_{3/2}^2}$$

For a photino-like neutralino with $m_{\tilde{\chi}_1^0} = 750$ GeV and $m_{3/2} = 2 \times 10^{-13}$ GeV, the width is 6.6 GeV.

Experimental bound on gravitino mass from monojet signal



Search for new phenomena
in monojet plus missing
transverse momentum
(ATLAS-CONF-2012-147)

For degenerate gluino/squark masses ($m_{\tilde{g}} = 500 \text{ GeV}$):
 $m_{\tilde{G}} > 1 \cdot 10^{-13} \text{ GeV}$.