Jets plus missing energy from light gravitino production at the LHC

Bettina Oexl

Vrije Universiteit Brussel and International Solvay Institutes

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P.de Aquino(VUB), F.Maltoni(UCL), K.Mawatari(VUB), BO

26.8.2013, SUSY 2013

Vrije
Universiteit
Brussel

New physics particles may show up as jet(s) plus missing energy

massive gravitons

weakly interacting massive particles

neutralino

gravitino

...

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massive gravitons

weakly interacting massive particles

neutralino

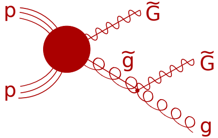
gravitino very light: $m_{3/2} = \mathcal{O}(10^{-13} - 10^{-12}\ \mathrm{GeV})$

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

...

For a light gravitino:
two processes contribute to jets + $\not{E}_T$

When the gravitino is very light,
direct production in association with
gluinos (squarks) becomes considerable.
At LO, we obtain monojet + $\not{E}_T$ signal.



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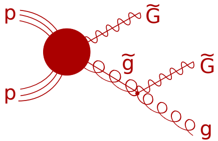
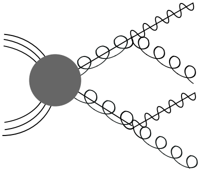
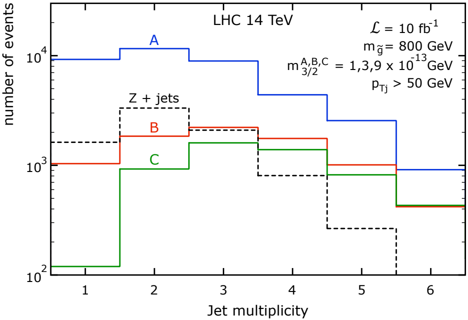


Taking into account additional jets from initial/final state radiation, this process leads to the same final state as gluino (squark) pair poduction, dijet + $\not{E}_T$.



We obtain bound on gravitino mass

We investigate the signature of the two processes for different gravitino masses.



Simple final state observables allow to extract information about gravitino mass when the gravitino is light enough.

The gravitino

The two contributing sub-processes

- Gluino-gravitino associated production
- Gluino-pair production
- Matrix element / parton shower merging

Jets plus $\not{E}_T$ signal and background

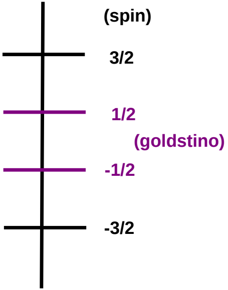
- Validation
- Background reduction
- Results

Spin 3/2 particles at colliders

The gravitino mass is directly related to the SUSY breaking scale

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

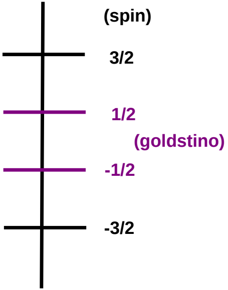
When SUSY breaks spontaneously, the gravitino becomes massive by absorbing the goldstino (super-Higgs mechanism).



The gravitino mass is directly related to the SUSY breaking scale

Interactions of the helicity 3/2 components are suppressed by the Planck scale.

Interactions of the helicity 1/2 components are suppressed by the SUSY breaking scale.



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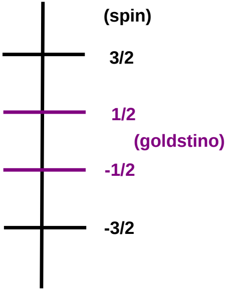
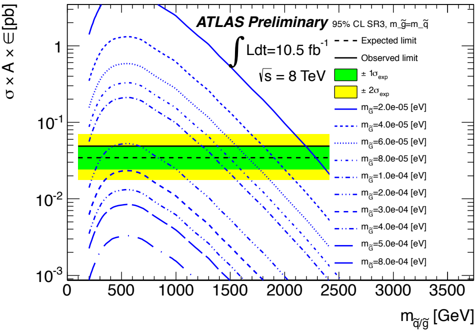


If the SUSY breaking scale is low, the gravitino interactions (goldstino interactions) can be important at colliders.

The gravitino mass is $m_{3/2} \sim \frac{M_{\text{SUSY}}^2}{M_{\text{Pl}}}$.

Experimental bound on gravitino mass



Search for new phenomena in monojet plus missing transverse momentum

(ATLAS-CONF-2012-147)

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

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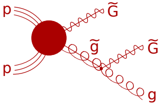
The setup

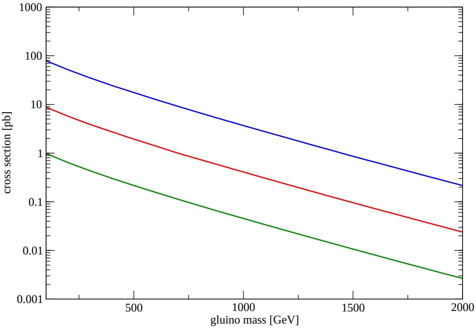
The gravitino is the LSP with $m_{3/2} \sim \mathcal{O}(10^{-13} - 10^{-12})$ GeV.

The gluino is the NLSP
and promptly decays into a gluon and a gravitino: $\tilde{g} \to g\tilde{G}$.

We assume R-parity conservation
and all other superparticles to be heavy.

Gluino-gravitino associated production strongly dependent on gravitino mass





$$\sigma(pp \to \tilde{g}\,\tilde{G}) \sim \frac{1}{(\overline{M}_{\rm Pl} m_{3/2})^2}$$

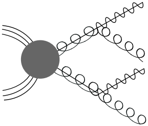
$m_{3/2} = 1 \cdot 10^{-13}\text{GeV}$

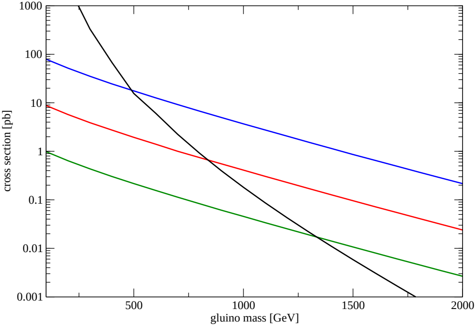
$m_{3/2} = 3 \cdot 10^{-13}\text{GeV}$

$m_{3/2} = 9 \cdot 10^{-13}\text{GeV}$

Associated production becomes relevant for very light gravitinos.

Gluino-pair production is independent of gravitino mass





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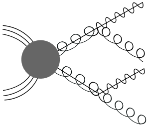

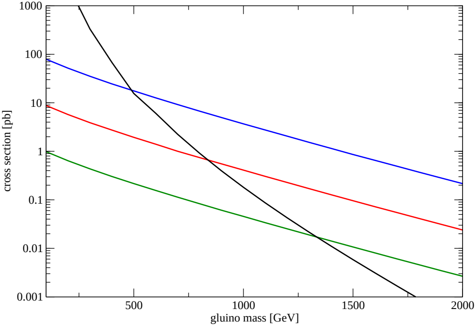

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Depending on the masses we expect dijet or monojet signal (LO).

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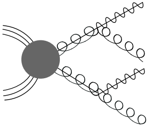

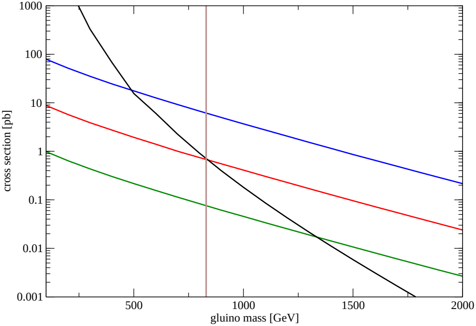

$m_{\tilde{g}} = 800$ GeV

$m_{3/2} = 1 \cdot 10^{-13}$GeV

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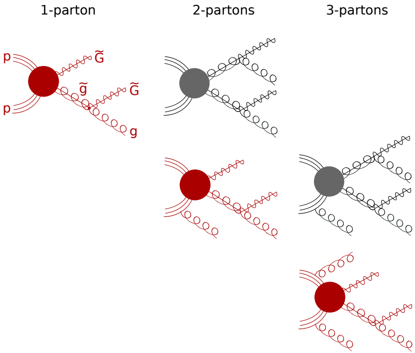
Depending on the masses we expect dijet or monojet signal (LO).

Matrix element / parton shower merging

For production processes with large partonic center-of-mass energy, initial and final state radiation becomes important.
We generate $pp \to \tilde{G}\tilde{G} + 1, 2, 3$ partons:



Matrix element / parton shower merging

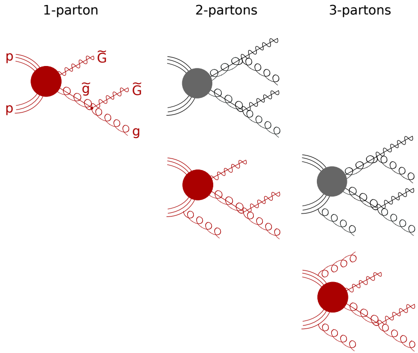
For production processes with large partonic center-of-mass energy, initial and final state radiation becomes important.
We generate $pp \to \tilde{G}\tilde{G} + 1, 2, 3$ partons:

Hard partons
are well described by a fixed order matrix element approach.

Soft/collinear partons
are well described by a parton shower.

The two approaches are **merged using the shower-k_T scheme**.

J.Alwall, S.deVisscher, F.Maltoni, JHEP 0902(2009)017



Shower-k_T-scheme

Based on event rejection:

Matrix element multi-parton events are generated (MadGraph) with a minimum separation between final state partons

$$d_{ij}^2 = \min(p_{T_i}^2, p_{T_j}^2)\,\Delta R_{ij}^2 > Q_{\mathrm{cut}}^2$$

and between final and initial state partons

$$d_{iB}^2 = p_{T_i}^2 > p_{T_{\mathrm{min}}}^2.$$

In our analysis, we use $Q_{cut} = 100$ GeV and $p_{T,min} = 50$ GeV.

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Events are then showered using the p_T-ordered shower (Pythia).

Shower-k_T-scheme

PYTHIA reports the scale $Q^{\mathrm{PS}}_{\mathrm{hardest}}$ of the hardest emission in the shower.

For lower parton-multiplicity samples an event is rejected if $Q^{\mathrm{PS}}_{\mathrm{hardest}} > Q_{\mathrm{cut}}$.

For the highest multiplicity sample an event is rejected if $Q^{\mathrm{PS}}_{\mathrm{hardest}}$ is bigger than the scale of the softest ME parton in the event.

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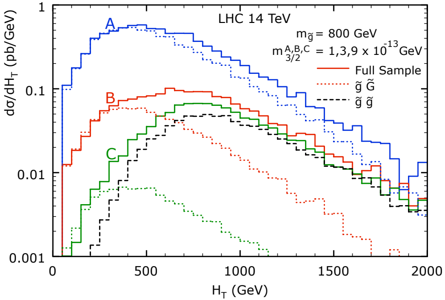
- **Results**

Spin 3/2 particles at colliders

We obtain distinguishable distributions for different gravitino masses

$pp \to \text{jets} + \not{E}_T$: We verified that the sum of the two contributing subprocesses reproduces the full inclusive result.



$$H_T = \sum_j p_T^j$$

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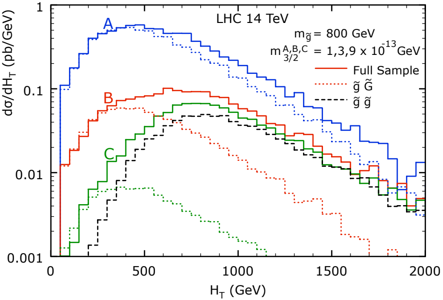

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Associated production scales with $\frac{1}{m_{\tilde{G}}^2}$ and has a peak around $\frac{m_{\tilde{g}}}{2}$ (energy of the gluon coming from the gluino decay in gluino rest frame).

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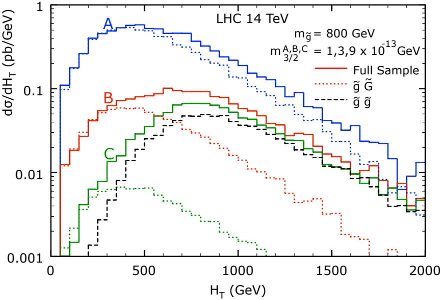
$pp \to$ jets $+ \not{E}_T$: We verified that the sum of the two contributing subprocesses reproduces the full inclusive result.



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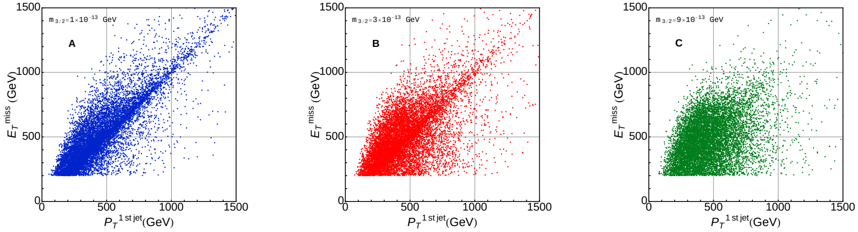
Gluino-pair production is independent of $m_{3/2}$ and has a peak around $m_{\tilde{g}}$ due to the two gluino decays.

Correlation between $p_T^{\text{1st jet}}$ and $\not{E}_T$

Scatter plots of the $pp \to \text{jets} + \not{E}_T$ signal differ for the three cases (minimal cut: $\not{E}_T > 200$ GeV).



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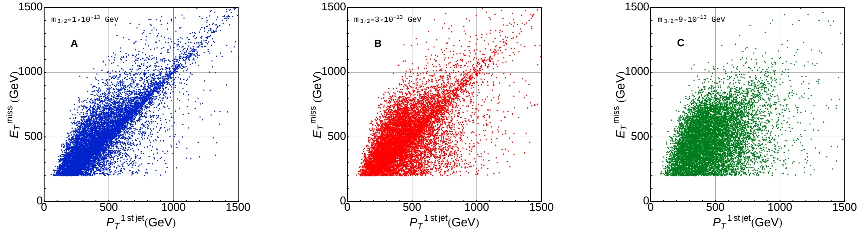


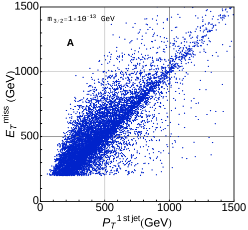
Associated production is dominant.
We find strong correlation $\not{E}_T \sim p_T^{\text{1st jet}}$ in high p_T region.

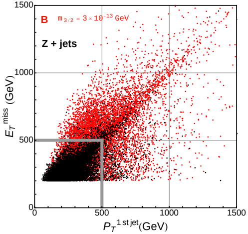
Intermediate case.

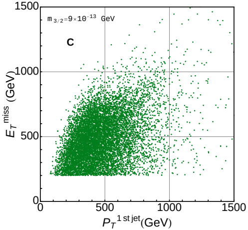
Gluino pair production is dominant.
No such a strong correlation is observed.

Background can be reduced efficiently

Scatter plots of the $pp \to \text{jets} + \not{E}_T$ signal differ for the three cases (minimal cut: $\not{E}_T > 200$ GeV).







The dominating background is $pp \to Z(\to \nu\bar{\nu}) +$ jets.

Background can be reduced efficiently

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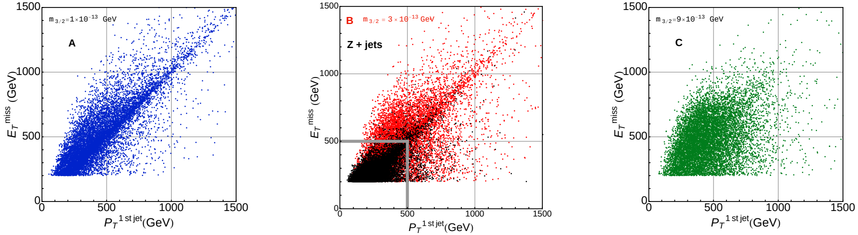
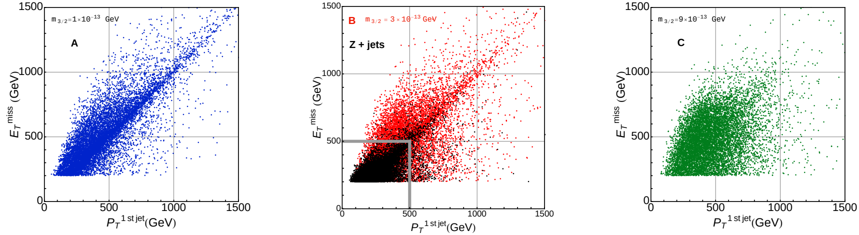


The dominating background is $pp \to Z(\to \nu\bar{\nu}) +$ jets.

We apply the cut $p_T^{\text{1st jet}} > 500$ GeV or $\not{E}_T > 500$ GeV.

Background can be reduced efficiently

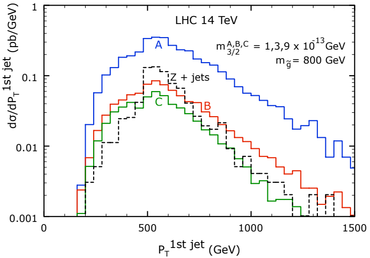
Scatter plots of the $pp \to \text{jets} + \not{E}_T$ signal differ for the three cases (minimal cut: $\not{E}_T > 200$ GeV).



σ (pb)	A	B	C	bkg
$\not{E}_T > 200$ GeV	7.50	1.53	0.90	19.4
$+\ p_T^{\text{1st jet}} > 500$ GeV or $\not{E}_T > 500$ GeV	3.81	0.85	0.55	0.81

Results: p_T distribution

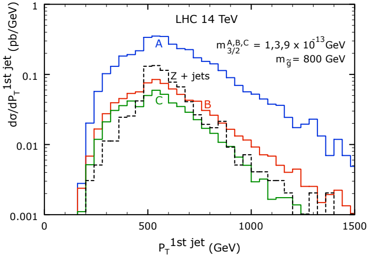
p_T of leading jet



Similar distributions because first hard jet comes from gluino decay in both subprocesses.
Signal dominates background in low p_T region for all three cases.

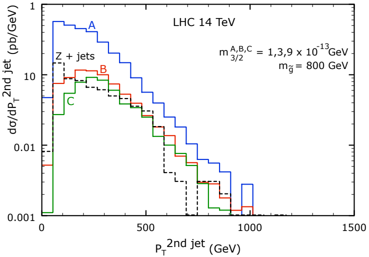
Results: p_T distribution

p_T of leading jet



Similar distributions because first hard jet comes from gluino decay in both subprocesses.
Signal dominates background in low p_T region for all three cases.

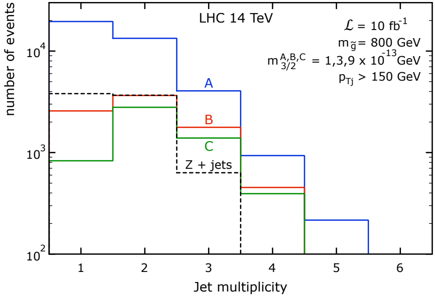
p_T of second jet



Two gluino decays lead to two hard gluon jets.
Second jet in associated production comes from QCD radiation and tends to be soft.

Simple observables provide information on gravitino and gluino mass

Jet multiplicity distribution



$m_{3/2} = 1 \cdot 10^{-13}\mathrm{GeV}$

$m_{3/2} = 3 \cdot 10^{-13}\mathrm{GeV}$

$m_{3/2} = 9 \cdot 10^{-13}\mathrm{GeV}$

When we count only hard jets, we recover LO expectations.

Simple observables provide information on gravitino and gluino mass

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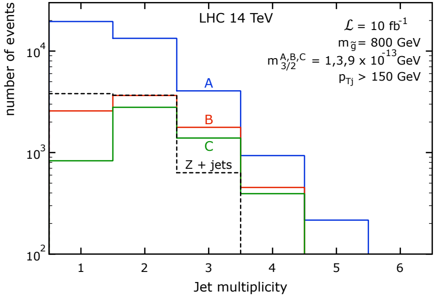

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When we count only hard jets, we recover LO expectations.

The distributions are sensitive to the gravitino mass when it is light enough.

Once gluino pair production dominates, no information about gravitino mass can be extracted.

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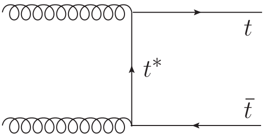
Spin 3/2 particles might give interesting signatures

When $E \gg m_{\tilde{G}}$, the gravitino can be replaced by the spin 1/2 goldstino (goldstino equivalence theorem).

When $E \sim m_{\tilde{G}}$, the theorem does not apply and we have to use full spin 3/2 formalism.

Other spin 3/2 particles than the gravitino are proposed: excited tops (compositeness models).



W.J.Stirling, E.Vryonidou
JHEP 1201 (2012) 055

Spin 3/2 particles can be simulated!

We implemented and validated the support for interactions of spin 3/2 particles.

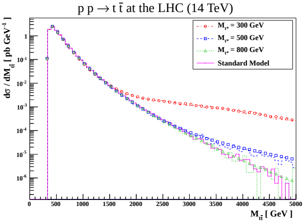
'Simulating spin-3/2 particles at colliders'

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

arXiv:1308.1668 [hep-ph]

A full chain of tools is available to study spin 3/2 particles:

FEYNRULES http://feynrules.irmp.ucl.ac.be/,
MADGRAPH https://launchpad.net/madgraph5,
CALCHEP http://theory.sinp.msu.ru/ pukhov/calchep.html.



Summary

We studied a jets $+\not{E}_T$ signature at the LHC in a scenario where
the gravitino is very light and the gluino is the NLSP
which promptly decays into a gluon and a gravitino.

The LHC may be able to explore the parameter space around our
benchmark points and hence
provide information on the gluino as well as the gravitino mass,
yielding information on the SUSY breaking scale.

Spin 3/2 particles can be simulated at colliders.

Goldstino gravitino equivalence theorem

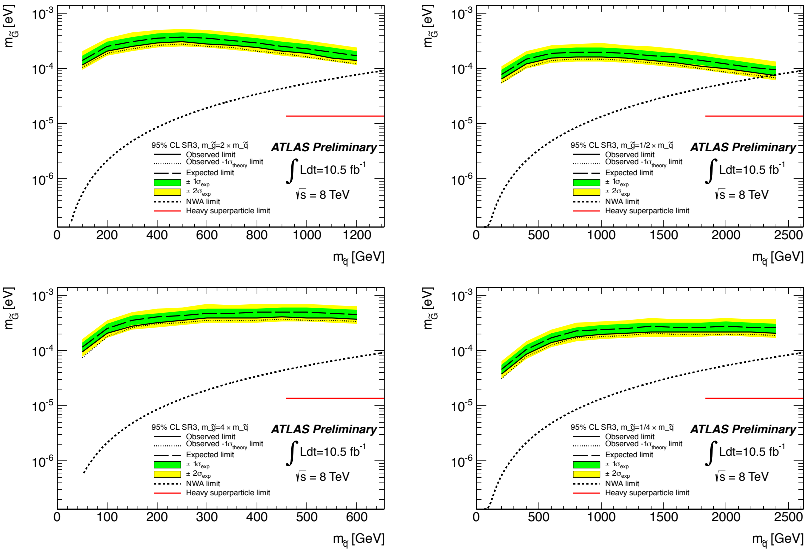
Replace the spin-3/2 gravitino field by the spin-1/2 goldstino field as $\psi_\mu \sim \sqrt{2/3}\,\partial_\mu \psi / m_{3/2}$.

The effective interaction Lagrangian in non-derivative form is

$$\begin{aligned}\mathcal{L}_{\mathrm{int}} = &\pm \frac{i m^2_{\phi^i_{L/R}}}{\sqrt{3}\,\overline{M}_{\mathrm{Pl}}\,m_{3/2}} \left[\bar{\psi} P_{L/R} f^i (\phi^i_{L/R})^* - \bar{f}^i P_{R/L} \psi\, \phi^i_{L/R}\right] \\ &- \frac{m_\lambda}{4\sqrt{6}\,\overline{M}_{\mathrm{Pl}}\,m_{3/2}} \bar{\psi}[\gamma^\mu, \gamma^\nu] \lambda^a F^a_{\mu\nu}.\end{aligned}$$

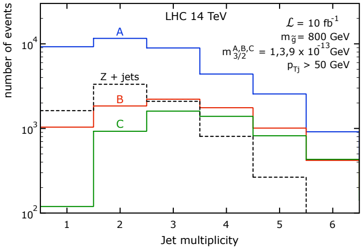
The gluino decay width is given by $\Gamma(\tilde{g} \to g\,\tilde{G}) = \frac{m^5_{\tilde{g}}}{48\pi \overline{M}^2_{\mathrm{Pl}} m^2_{3/2}}$.
For $m_{\tilde{g}} = 800\text{GeV}$ and $m_{3/2} = 3 \cdot 10^{-13}\text{GeV}$ the width is 4.1GeV.

ATLAS limits on light gravitinos

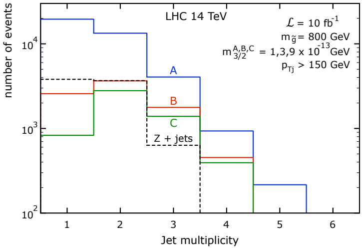


Jet multiplicity distribution depends on minimal p_T of all jets

$P_{Tj} > 50$ GeV



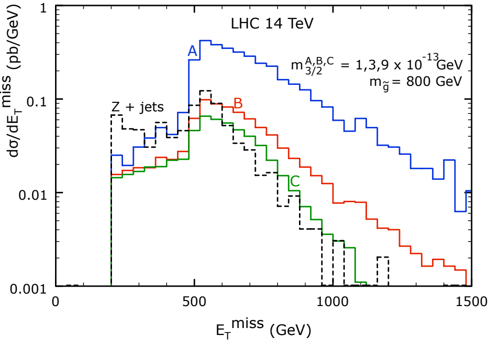
$P_{Tj} > 150$ GeV



Lighter gravitino leads to a peak at lower jet multiplicities than heavier gravitino.

When counting only very hard jets, we recover leading order expectations: associated production tends to produce mono-jet events, gluino-pair production gives di-jet events.

Missing transverse energy

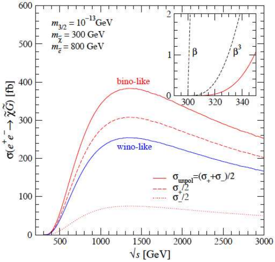


Lighter gravitino results in higher $\not{E}_T$ events,
because a gravitino is directly produced in association with a gluino and hence can have a higher p_T than the ones resulting from gluino decays.

Light gravitinos at linear colliders

Associated production of light gravitinos
in e^+e^- and $e^-\gamma$ collisions

K. Mawatari, BO, Y. Takaesu
Eur.Phys.J. C71 (2011) 1783



$e^+e^- \to \tilde{\chi}^0_1\tilde{G} \to \gamma\tilde{G}\tilde{G}$ and $e^-\gamma \to \tilde{e}\tilde{G} \to e^-\tilde{G}\tilde{G}$

Higgs mechanism

SU(2) x U(1) gauge symmetry spontaneously broken

$m_W \sim v$

$$\epsilon_0^\mu(p) = \frac{1}{m_W} \begin{pmatrix} |\vec{p}| \\ E \sin\theta \cos\phi \\ E \sin\theta \sin\phi \\ E \cos\theta \end{pmatrix}$$

Super-Higgs mechanism

Supersymmetry spontaneously broken

$m_{3/2} \sim \sqrt{F}$