Gravitino productions at colliders

arXiv:1010.4255 [EPJC71(2011)], K.Hagiwara(KEK), KM, Y.Takaesu
arXiv:1101.1289 [appear in EPJC], KM, Y.Takaesu(KEK)

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Outlines

- **Gravitino**
  - What is a gravitino?
  - Mass of the gravitino
- **Productions**
  - HELAS and MadGraph/MadEvent with gravitinos/goldstinos
  - The gravitino-goldstino equivalence
- **at Colliders**
  - Collider signatures for a gravitino LSP with a gluino NLSP

Gravitinos

- spin-3/2 superpartners of gravitons in local supersymmetric extensions to the Standard Model (Supergravity).
- If SUSY breaks spontaneously, gravitinos absorb massless spin-1/2 goldstinos and become massive by the super-Higgs mechanism.

Mass of the gravitino

- related to the SUSY breaking scale as well as the Planck scale

$$m_{3/2} \sim (M_{\rm SUSY})^2/M_{\rm Pl}$$

- This implies that the gravitino can take a wide range of mass, depending on the SUSY breaking scale, from eV up to scales beyond TeV, and provide rich phenomenology in particle physics as well as in cosmology.

Collider phenomenology for a gravitino LSP

- The low-scale SUSY breaking can naturally happen in gauge-mediated SUSY breaking scenarios, where the gravitino is often the LSP and can play an important role even for collider signatures.

- The phenomenology depends so much on what the NLSP is.
  - In the minimal model of gauge mediation, the lightest neutralino and the lighter stau are often the NLSP.
  - A chargino, sneutrino, gluino, and squark can also be NLSP in, e.g., general gauge mediation models, split SUSY models, ...

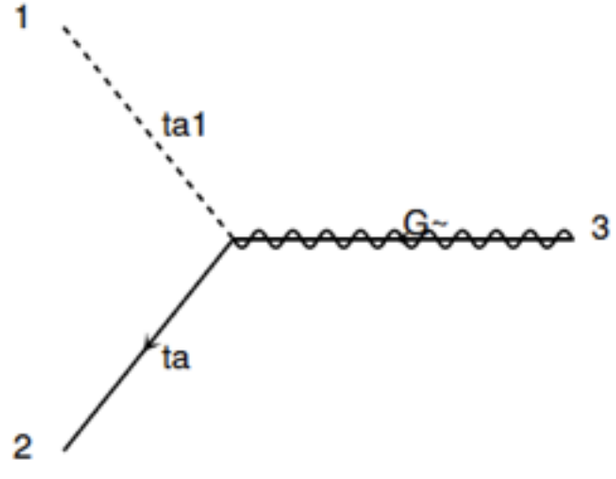
HELAS and MadGraph/MadEvent with gravitinos/goldstinos

- Although the gravitino can play an important role even in collider signatures when it is the LSP, there is few Monte Carlo event generators which can treat them.
- "HELAS and MadGraph with spin-3/2 particles (gravitinos)"
  K. Hagiwara (KEK), K. Mawatari (VUB), Y. Takaesu (KEK); EPJC71(2011) [arXiv:1010.4255]
- "HELAS and MadGraph with goldstinos"
  K. Mawatari (VUB), Y. Takaesu (KEK); appear in EPJC [arXiv:1101.1289]
  - We added new HELAS fortran subroutines for massive spin-3/2 gravitinos and goldstinos and their interactions, and implemented them into MadGraph/MadEvent (MG/ME) so that arbitrary amplitudes with external gravitinos/goldstinos can be generated automatically.
  - MG/ME v4 and v5 supports spin-0, 1/2, 1, and 2.
    [HELAS and MG/ME w/ spin-2 particles by Hagiwara, Kanzaki, Q.Li, KM, EPJC(2008)]

HELAS

- HELicity Amplitude Subroutines
  - by H. Murayama, I. Watanabe, K. Hagiwara (1992)
  - a set of FORTRAN77 subroutines which enable us to compute the helicity amplitudes of an arbitrary tree-level Feynman diagram with a simple sequence of CALL SUBROUTINE statements.

- e.g., stau l- > tau- + gravitino



$$i\mathcal{M}_{\sigma_1\sigma_2} = ig\,\bar{u}(p_1,\sigma_1)\,P_L\gamma^\mu\gamma^\nu\,\psi_\mu(p_2,\sigma_2)\,k_\nu$$

```
CALL SXXXXX(P1,                -1,  W1)
CALL OXXXXX(P2, MST1, HEL2, +1,  W2)
CALL IRXXXX(P3, MGRO, HEL3, -1,  W3)

CALL IROSXX(W3, W2, W1, GFRS,   AMP)
```

MadGraph/MadEvent

- A software that allows you to generate amplitudes and events for any process in any model.
  - MG by T. Stelzer and W.F. Long (1994)
  - ME by F. Maltoni and T. Stelzer (2003)
- Put your process, e.g., p p > go gro (proton+proton > gluino+gravitino)
  ./bin/newprocess
- MG automatically draws all possible Feynman diagrams and writes corresponding HELAS codes.
- Set your parameters, e.g., masses, couplings, collider energy, kinematical cuts, ...
  ./bin/generate_events
- ME gives you cross sections and distributions.

The effective interaction Lagrangian relevant to the gravitino phenomenology

- The effective interaction Lagrangian:

$$\mathcal{L}_{\rm int} = -\frac{i}{\sqrt{2}\overline{M}_{\rm Pl}}\left[\bar{\psi}_\mu\gamma^\nu\gamma^\mu P_L f^i\left(D_\nu\phi_L^i\right)^* - \bar{f}^i P_R\gamma^\mu\gamma^\nu\psi_\mu\left(D_\nu\phi_L^i\right)\right]$$

$$-\frac{i}{8\overline{M}_{\rm Pl}}\bar{\psi}_\mu[\gamma^\nu,\gamma^\rho]\gamma^\mu\lambda^{(\alpha)a}F^{(\alpha)a}_{\nu\rho},$$

- The covariant derivative:

$$D_\mu = \partial_\mu + ig_s T_3^a A_\mu^a + igT_2^a W_\mu^a + ig'Y B_\mu$$

- The field-strength tensors for each gauge group:

$$F^{(3)a}_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g_s f_3^{abc} A^b_\mu A^c_\nu,$$

$$F^{(2)a}_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu - g f_2^{abc} W^b_\mu W^c_\nu,$$

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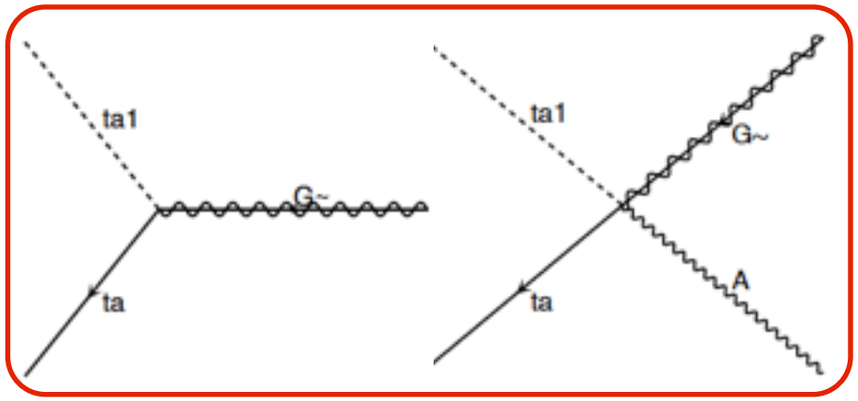

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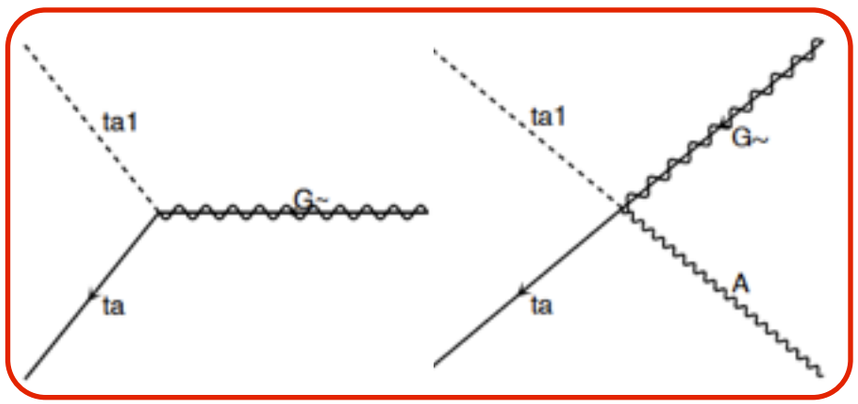

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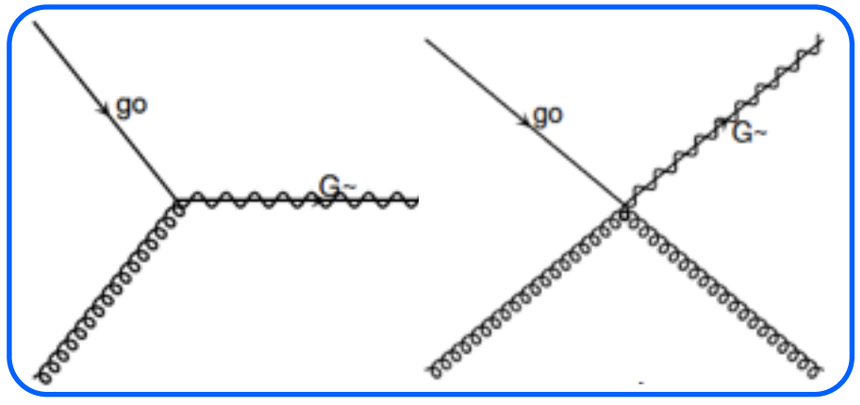

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The effective interaction Lagrangian for a goldstino

- In the high energy limit $E>>m_{3/2}$, the spin-3/2 gravitino field can be replaced by the spin-1/2 goldstino as

$$\psi_\mu \sim \sqrt{2/3}\,\partial_\mu \psi / m_{3/2}$$

- The effective interaction Lagrangian in non-derivative form:

$$\mathcal{L}_{\rm int} = \frac{i(m_{\phi^i}^2 - m_{f^i}^2)}{\sqrt{3}\,\overline{M}_{\rm Pl}\, m_{3/2}} \left[\bar{\psi} P_L f^i (\phi_L^i)^* - \bar{f}^i P_R \psi\, \phi_L^i\right]$$

$$- \frac{m_\lambda}{4\sqrt{6}\,\overline{M}_{\rm Pl}\, m_{3/2}} \bar{\psi}[\gamma^\mu, \gamma^\nu] \lambda^{(\alpha)a} F_{\mu\nu}^{(\alpha)a}$$

- The ψ-f-ϕ-A_μ vertex is absent.

- The couplings are proportional to the mass splitting inside the supermultiplet.

- The couplings are inversely proportional to the SUSY-breaking scale through the gravitino mass

$$m_{3/2} = \langle F \rangle / \sqrt{3}\,\overline{M}_{\rm Pl}$$

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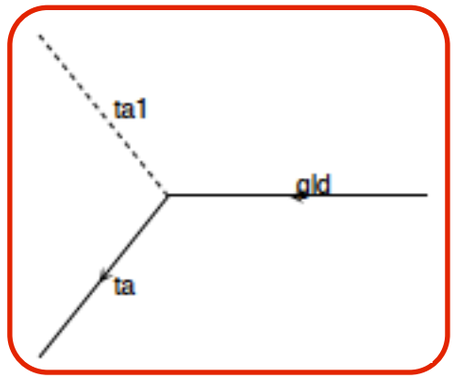

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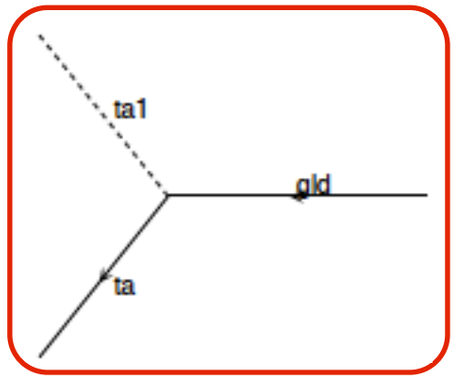

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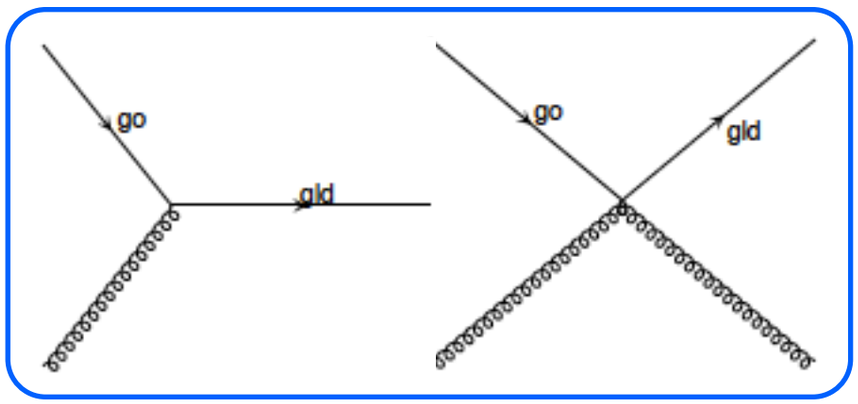

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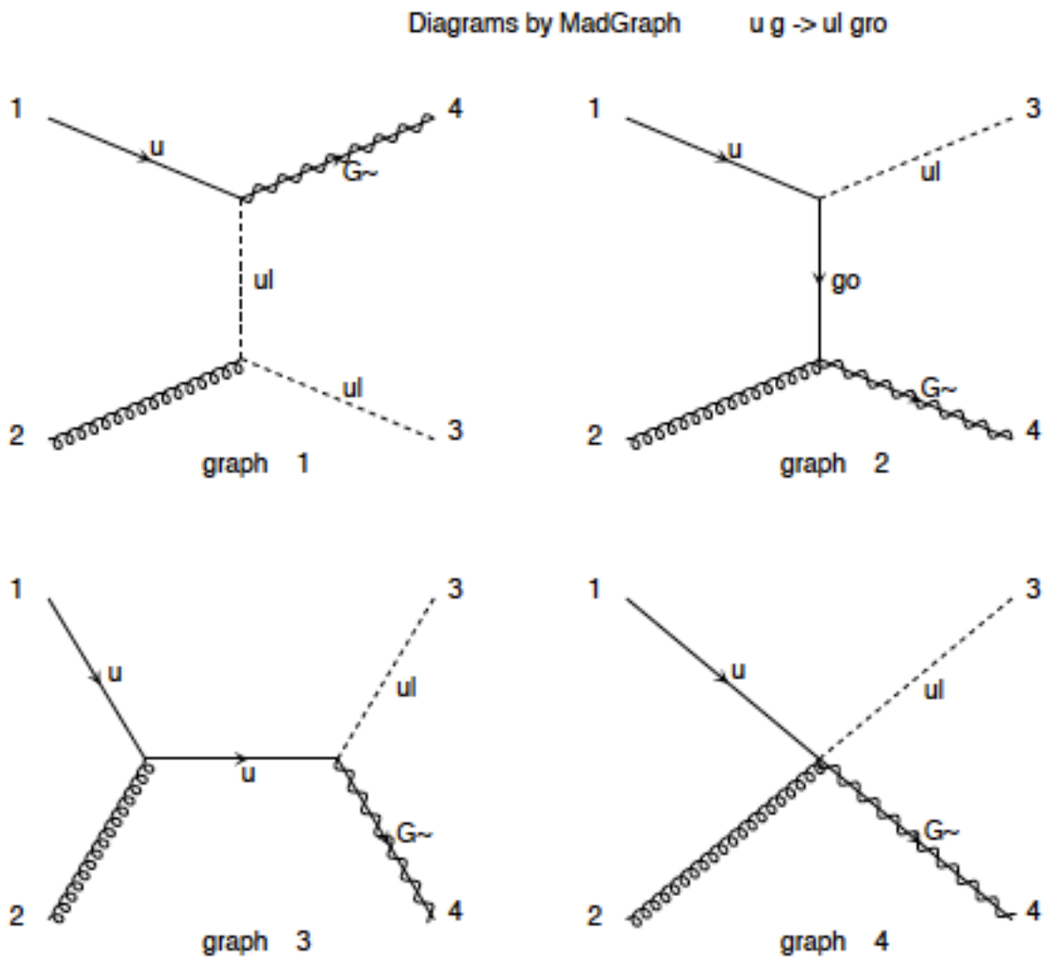
Checking our codes by the goldstino equivalence theorem

- MG/ME w/ gravitinos
  [arXiv:1010.4255]



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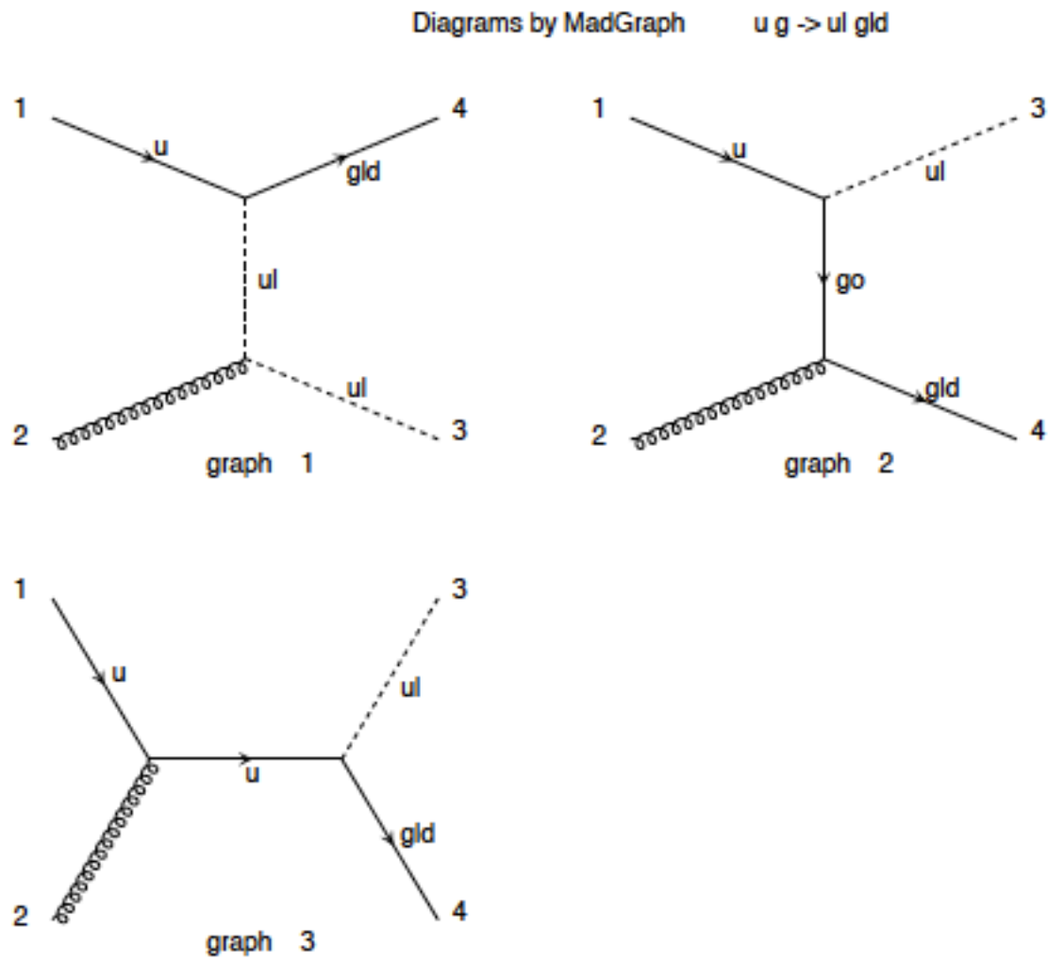
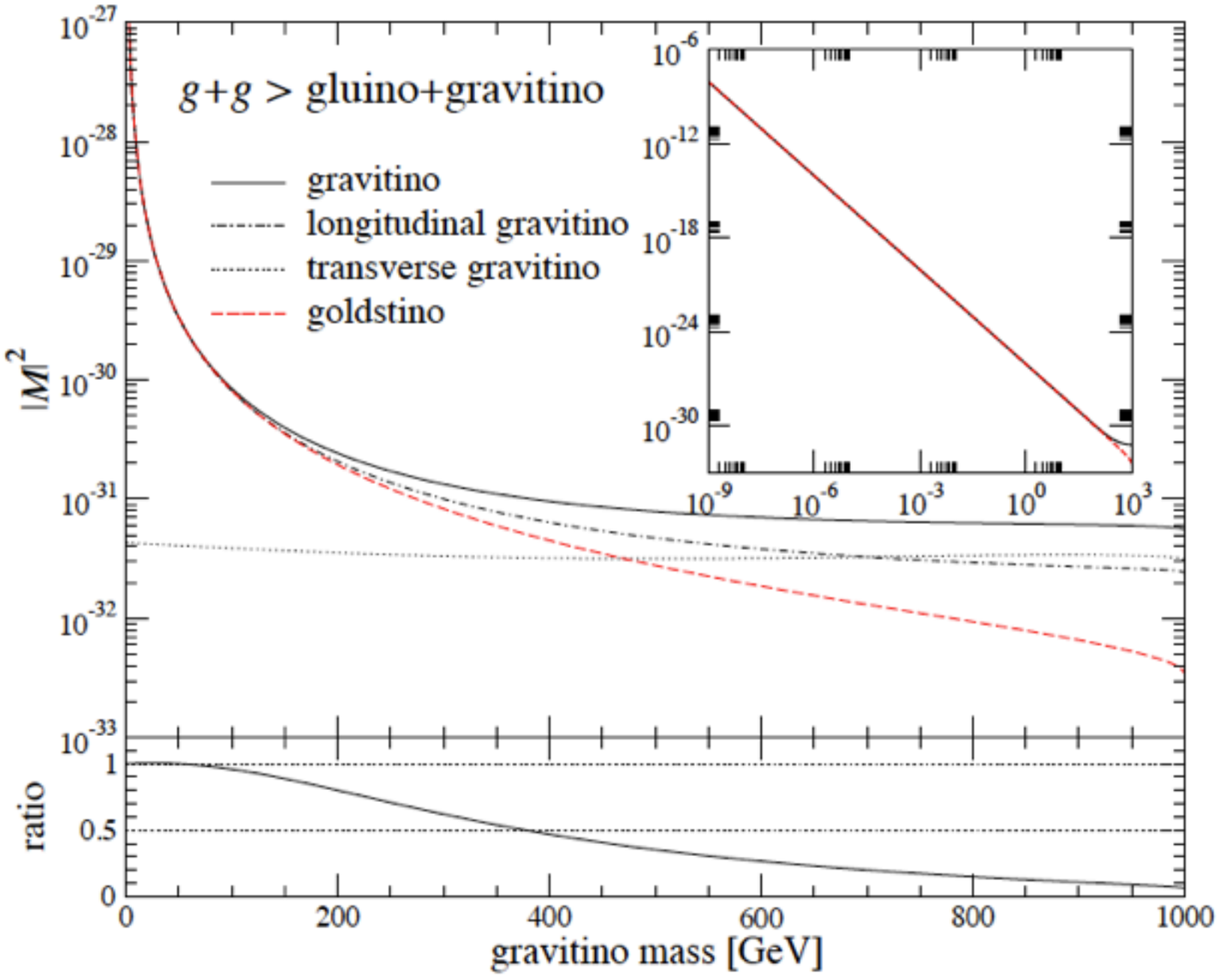


The gravitino-goldstino equivalence



at $\sqrt{\hat{s}} = 2$ TeV and $\cos\hat{\theta} = 0.5$ as a function of the gravitino mass, where the squark and gluino masses are fixed at 1 TeV. The ratios of the squared matrix elements are also shown.

- In the region of the small gravitino mass, or in the high energy region, both amplitudes agree well each other.

- The longitudinal modes (or the goldstino) become dominant in the high energy region, while the contributions from the transverse modes do not depend on the energy.

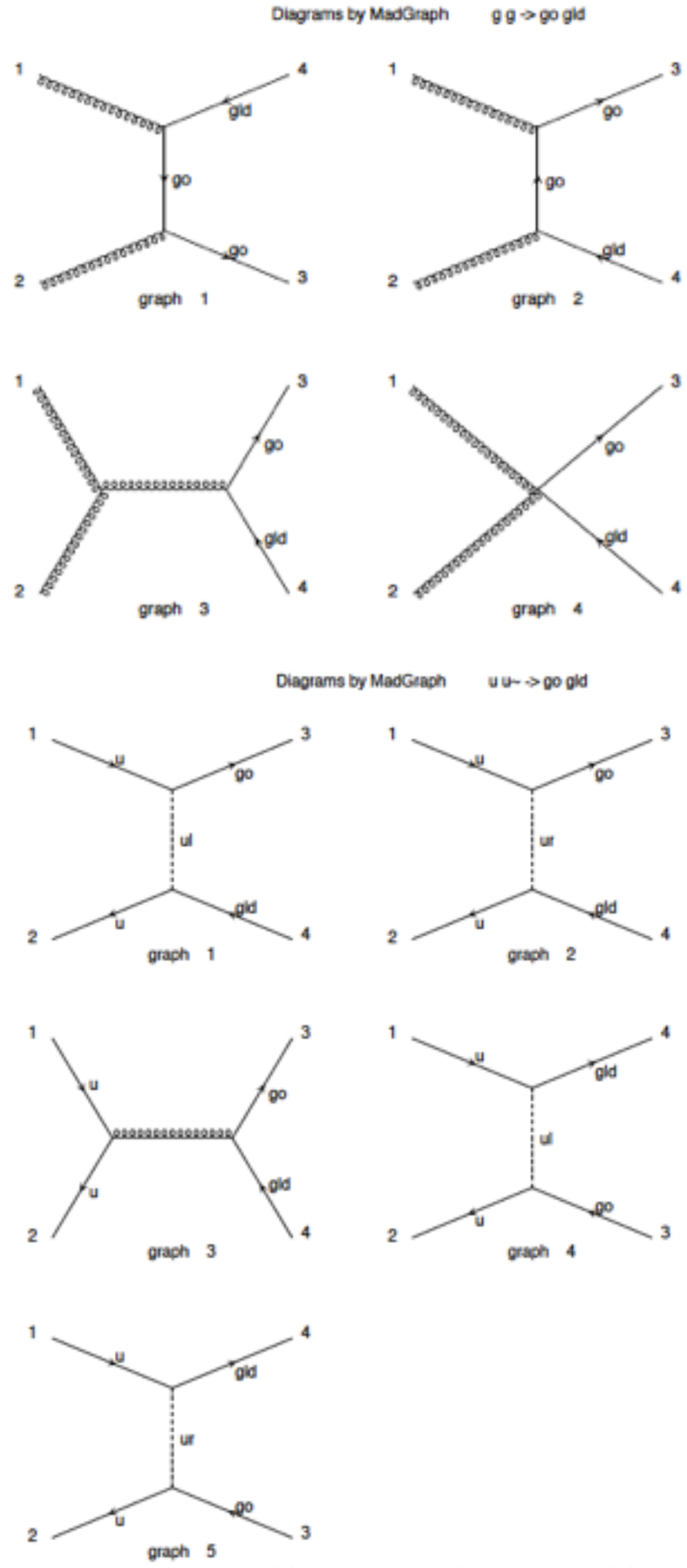
- The squared matrix elements are proportional to $(m_{3/2})^{-2}$.

Gluino NLSP

- If gluinos are the NLSP and light enough, those productions can be explored in the early LHC data as well as in the Tevatron.
- Associated gravitino productions with a gluino (or a squark) lead to characteristic signals of monojet plus missing energy when a produced gluino (squark) promptly decays into a gluon (quark) and a LSP gravitino.

$$pp \to \tilde{g}\tilde{G} \to g\tilde{G}\tilde{G} \Rightarrow \text{jet} + \not{E}$$

* The associated productions for SPS7 and 8 studied by Klasen and Pignor (2007)



Associated gravitino productions with a gluino

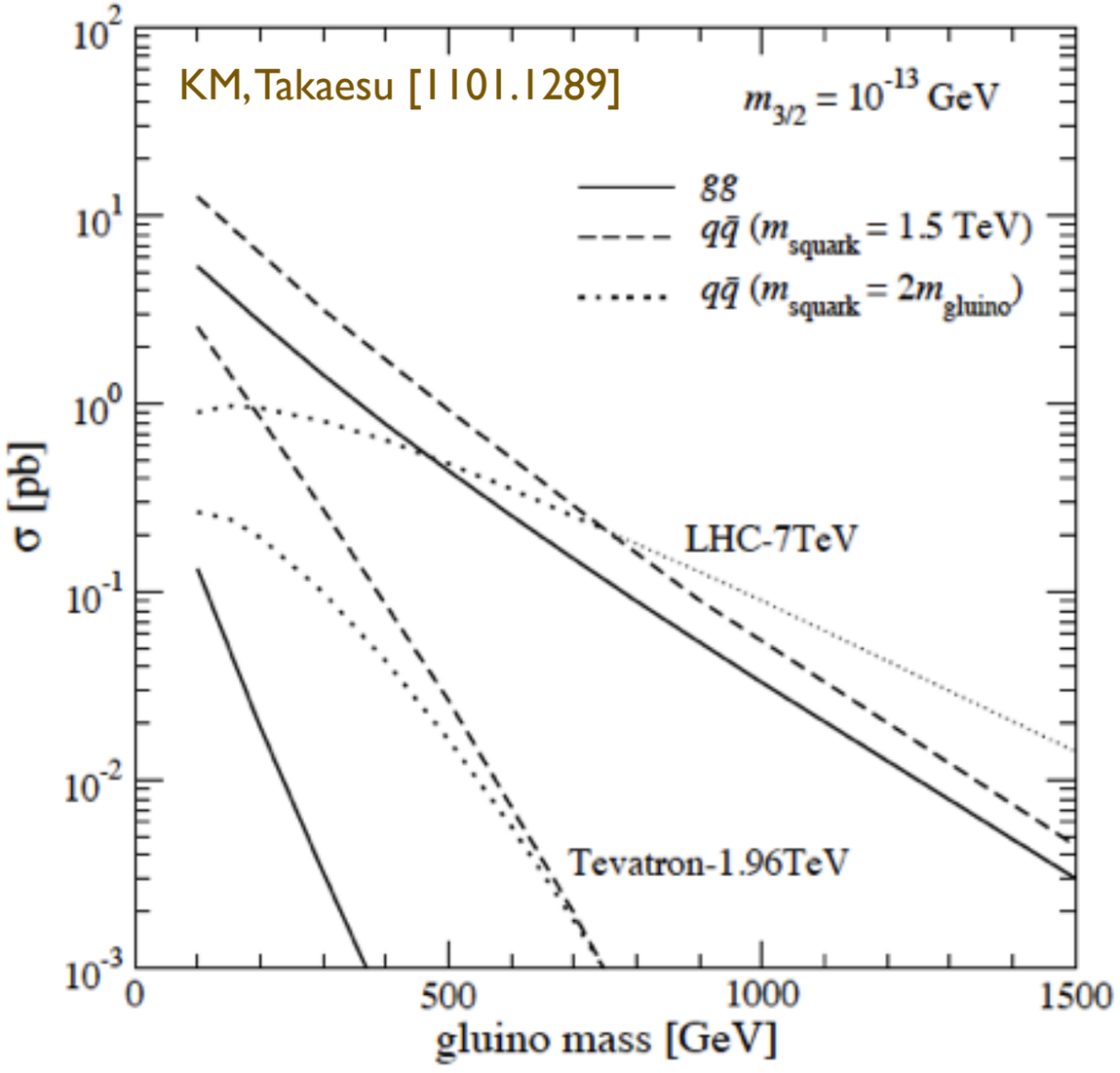


Fig. 3. Total cross sections of each subprocess of associated gravitino productions with a gluino, $p\bar{p}/pp \to \tilde{g}\tilde{G}$, at the Tevatron-1.96TeV/LHC-7TeV for $m_{3/2} = 10^{-13}$ GeV as a function of the gluino mass. The squark masses are fixed at 1.5 TeV (dashed) and $2m_{\tilde{g}}$ (dotted) for the $q\bar{q}$ subprocesses, where the cross section in the $\Gamma_{\tilde{q}\to q\tilde{G}} > m_{\tilde{q}}/2$ region is shown with a thin dotted line.

- The cross sections of all the subprocesses scale with $(m_{3/2})^{-2}$.

➡ The lighter gravitinos enhance the monojet signals, which can be interpreted as the direct lower bound for the gravitino mass.
(Note that the dijet signals produced through gluino-pair productions do not depend on the gravitino mass.)

- The t- and u- channel squark masses are quite sensitive to the cross section, and the heavier squark exchange increases the cross section because $g_{\tilde{G}q\tilde{q}} \propto m_{\tilde{q}}^2$.

➡ The cross section of the qqbar channel can be larger than that of the gg channel even for the LHC.

Associated gravitino productions with a squark

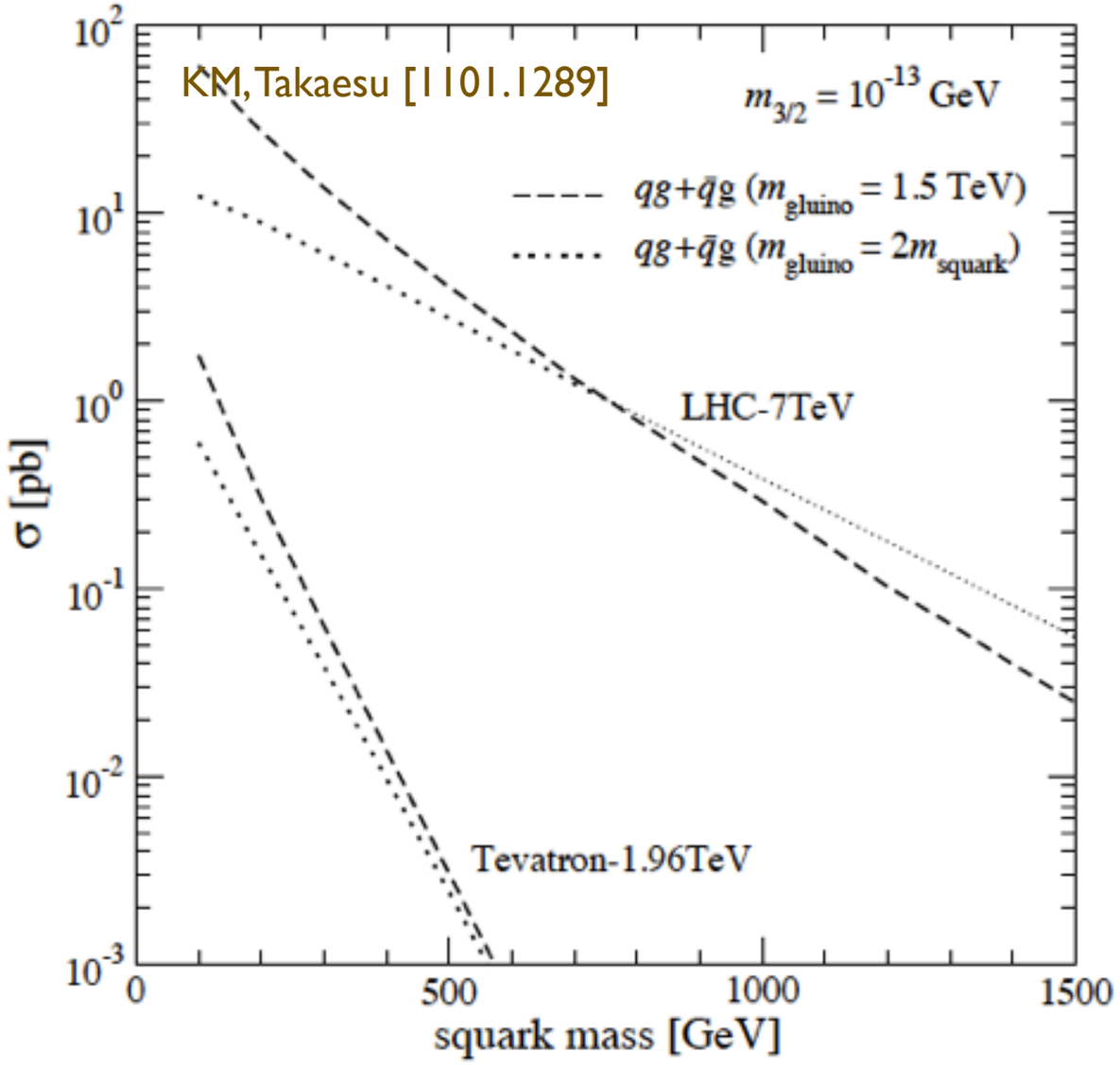
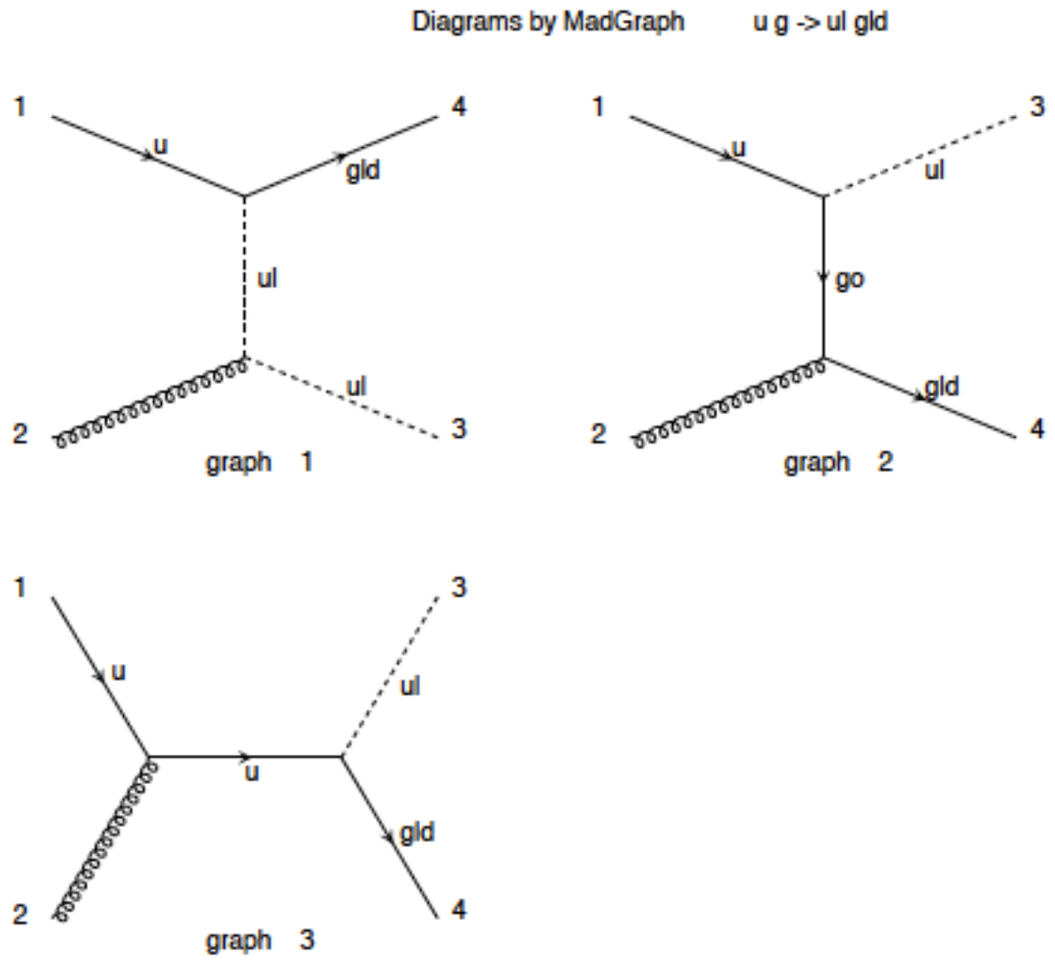


Fig. 4. Total cross sections of associated gravitino productions with a squark, $p\bar{p}/pp \to \tilde{q}\tilde{G}$, at the Tevatron-1.96TeV/LHC-7TeV for $m_{3/2} = 10^{-13}$ GeV as a function of the squark mass. The gluino masses are fixed at 1.5 TeV (dashed) and $2m_{\tilde{q}}$ (dotted), where the cross section in the $\Gamma_{\tilde{g}\to g\tilde{G}} > m_{\tilde{g}}/2$ region is shown with a thin dotted line.



- Similar to the gluino productions, the heavy gluino increases the cross section.

Summary

- Gravitinos can provide rich phenomenology in particle physics as well as in cosmology, and especially play an important role in collider signatures when it is the LSP. The phenomenology really depends on what is the NLSP.
- We (Hagiwara, KM, Takaesu [1010.4255], KM, Takaesu [1101.1289])
  - added new HELAS fortran subroutines to calculate helicity amplitudes with massive gravitinos/goldstinos.
  - coded them in such a way that arbitrary amplitudes with external gravitinos/goldstinos can be generated automatically by MadGraph.
    (Our implementation was officially supported by MG/MEv4.5, and will be available in MG5 soon.)
  - tested our codes carefully by using the goldstino equivalence theorem as well as the gauge invariance.
- We just started to enjoy "gravitino phenomenology at the LHC" !