# Gravitino phenomenology at the LHC

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# New phenomenology group at the VUB

- A 5-year GOA (Geconcentreerde Onderzoeksactie) project on "Supersymmetric Models and their signatures at the LHC"
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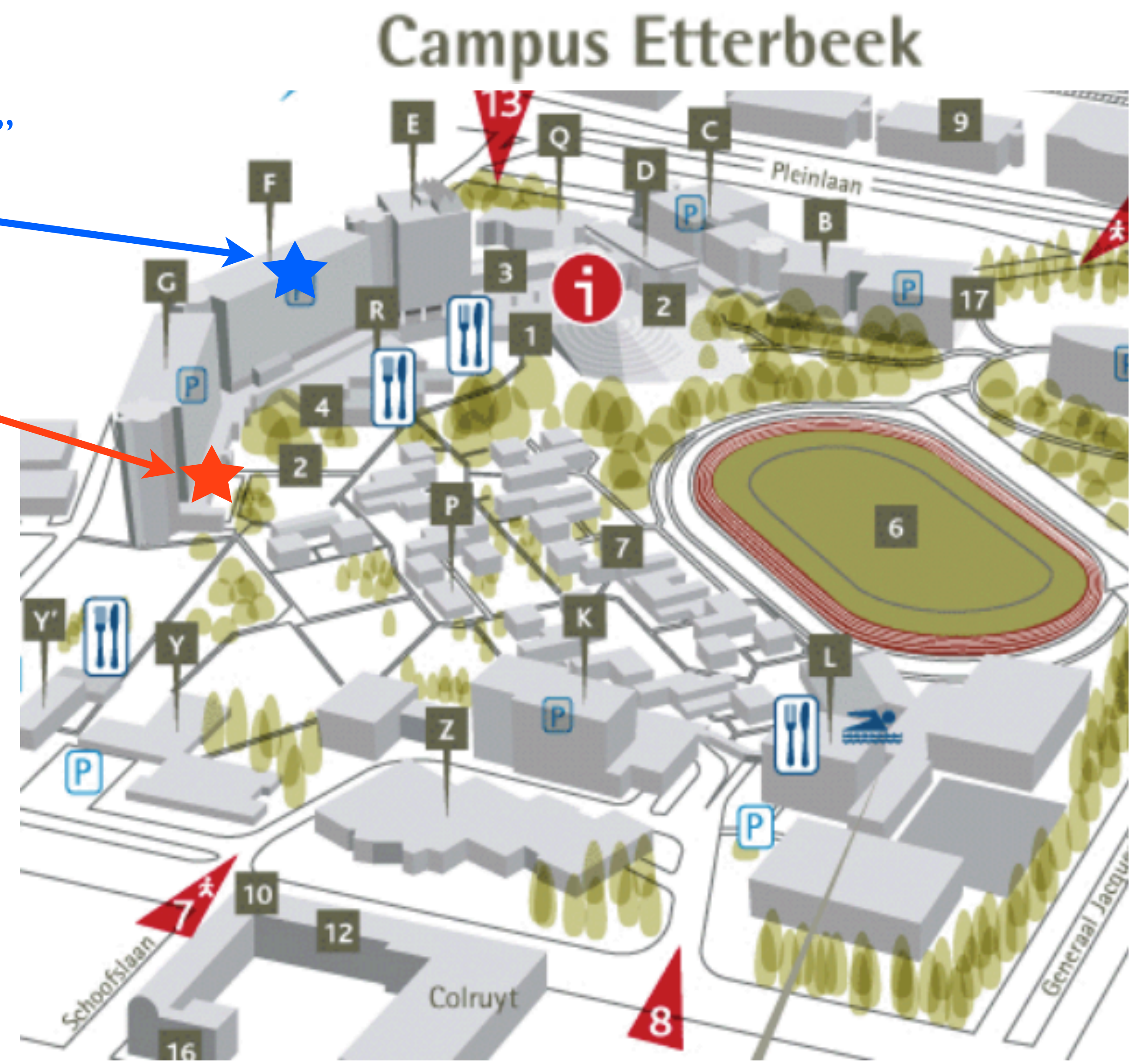
  - Catherine De Clercq, Jorgen D'Hondt (experiment) - G. 0th and 1st floor
- The main goal of the project is
  - to establish a complete chain from fundamental theory to experiment.
  - to use this chain to study possible signatures of SUSY models at the LHC.
- New phenomenology members since this fall
  - Kentarou Mawatari (from U. Heidelberg) -Project leader
  - Phillip Grajek (from KEK, Japan) -PD
  - Bettina Oexl (from U. Tuebingen) -PhD



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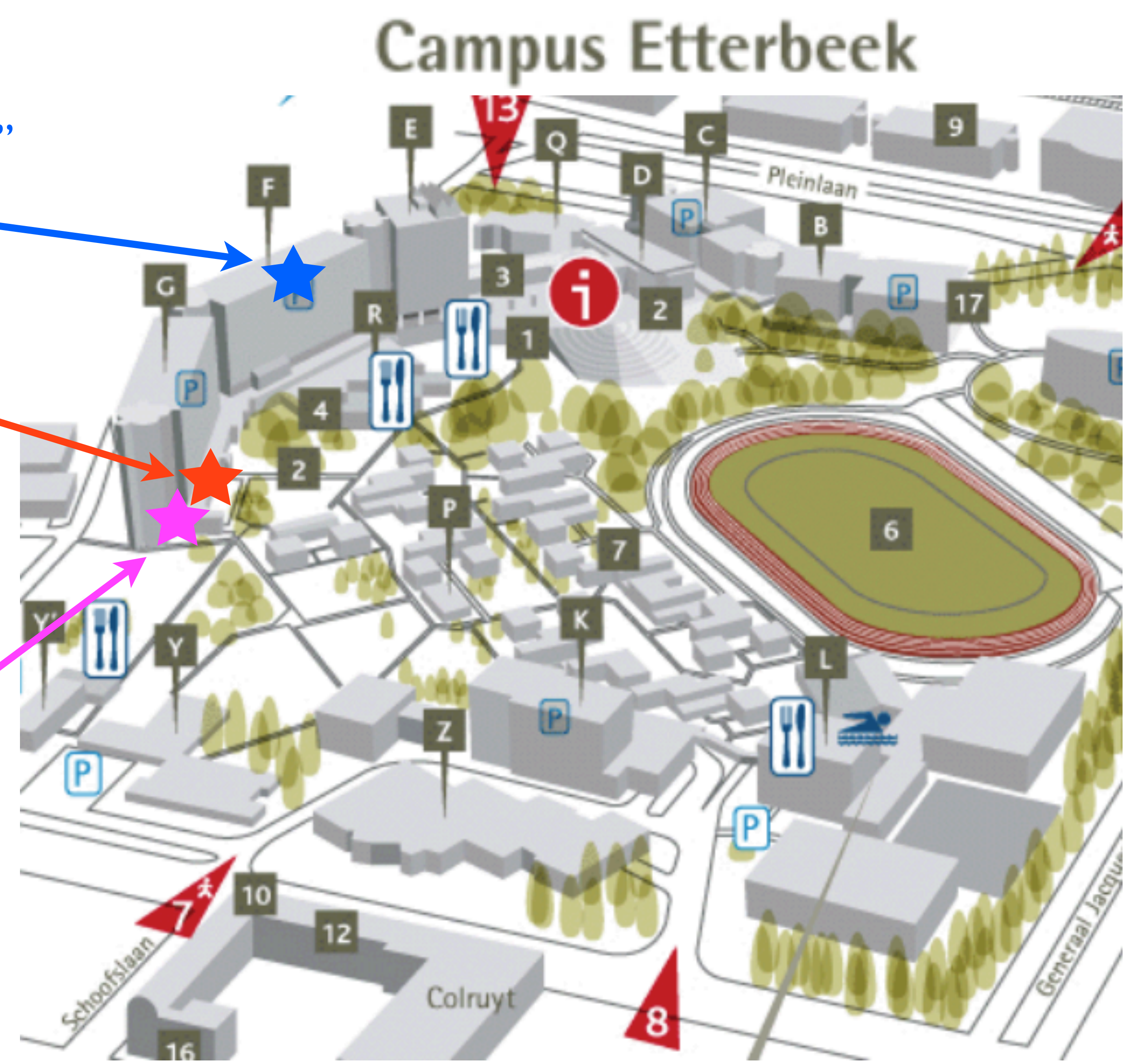

# Outlines

- **Gravitino**
  - What is a gravitino?
  - The effective Lagrangian
- **Phenomenology**
  - Helicity amplitude method
  - How can we simulate our models?
    -- MadGraph/MadEvent with gravitinos
- **At the LHC**
  - Collider signatures for the LSP gravitino

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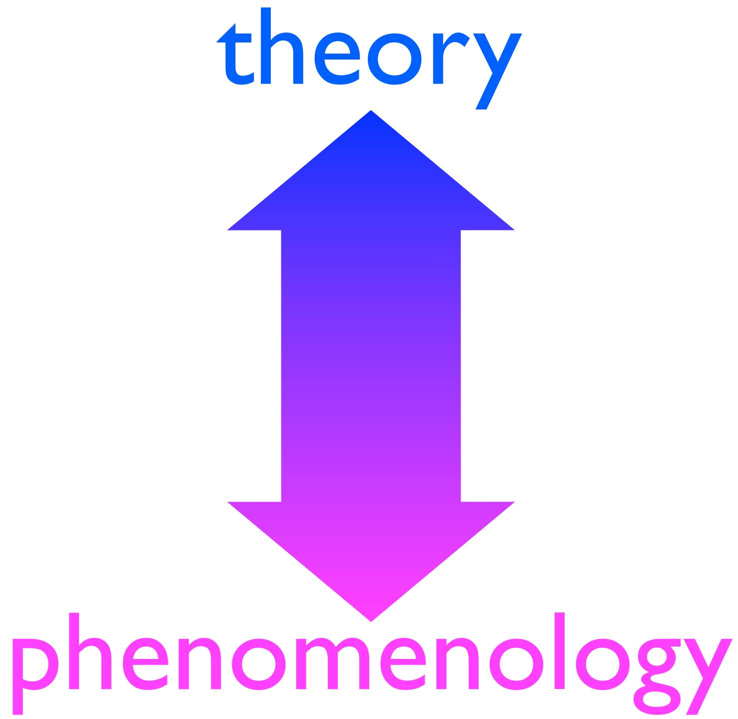

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# Gravitinos

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

# Massive gravitinos

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➡ spontaneously broken

(spin)

------ +1

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Higgs mechanism

*W, Z bosons*

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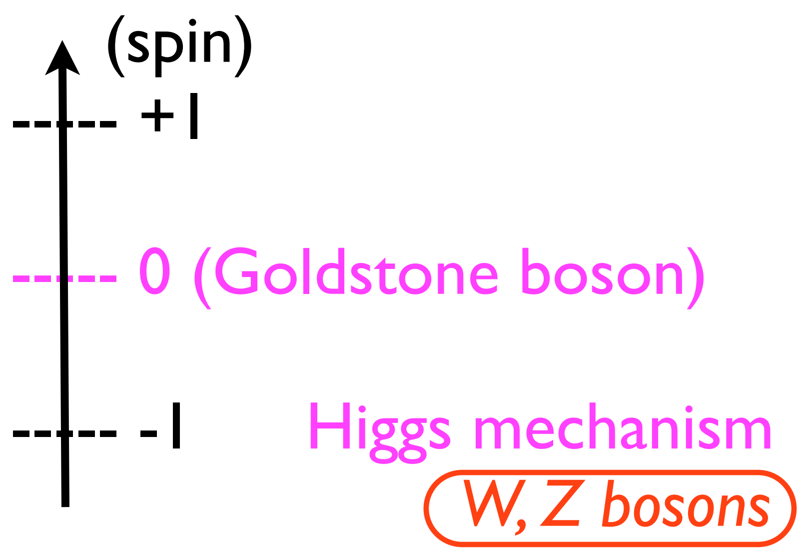


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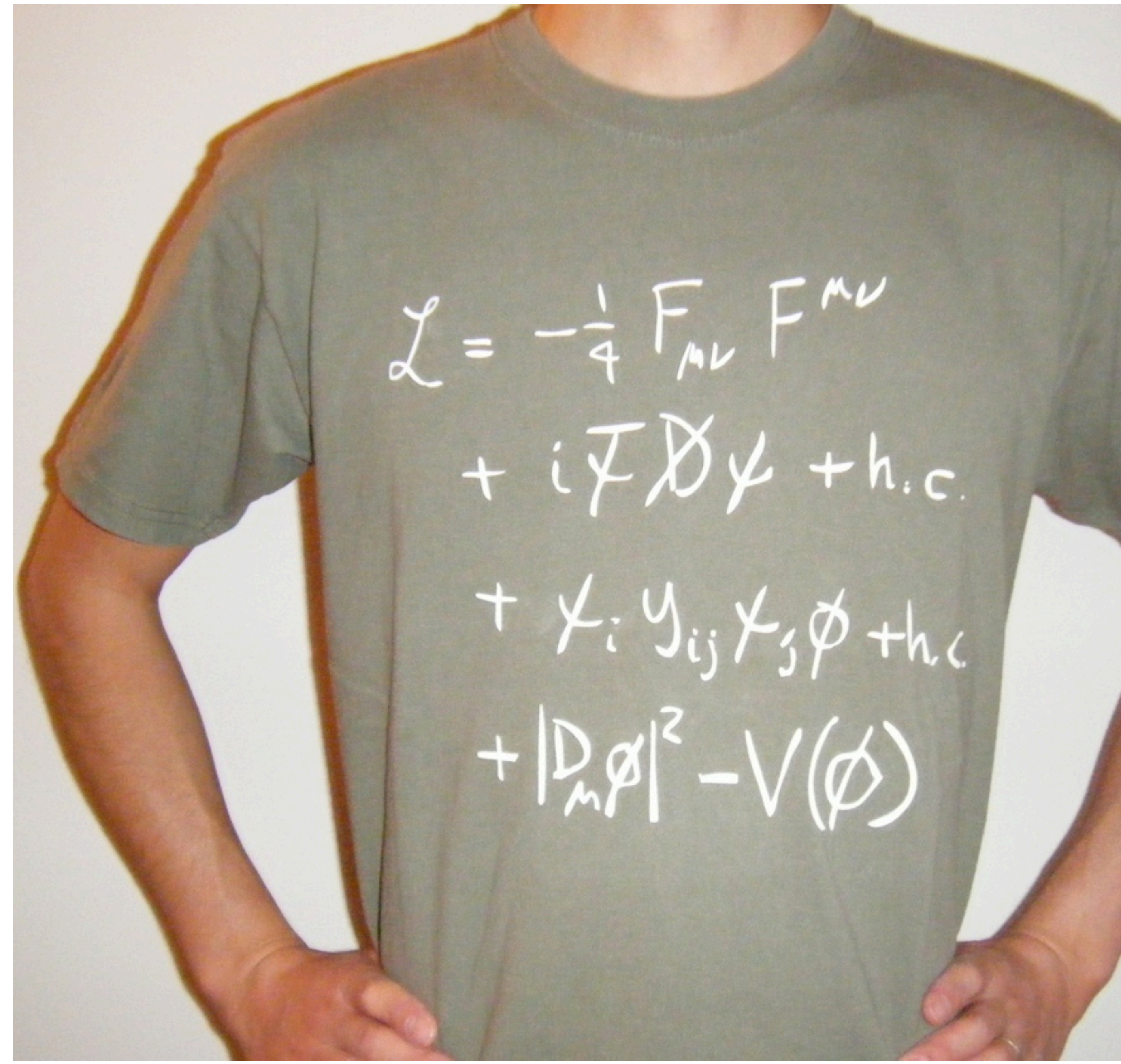

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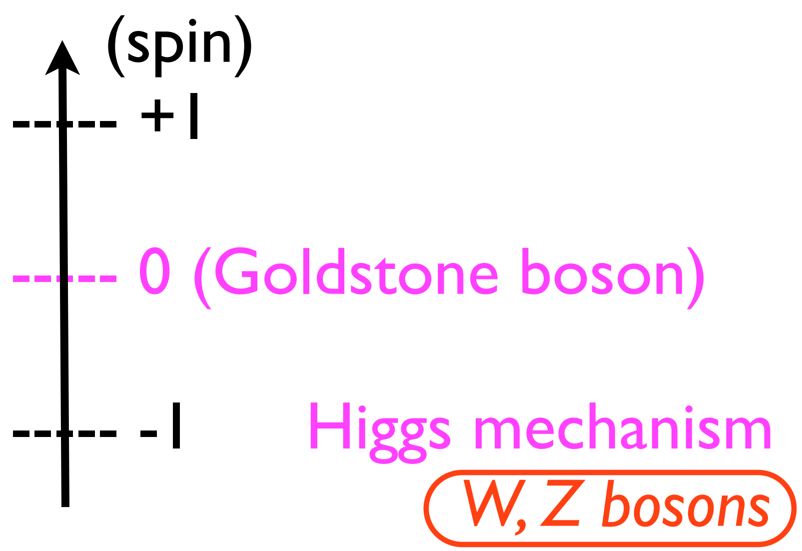


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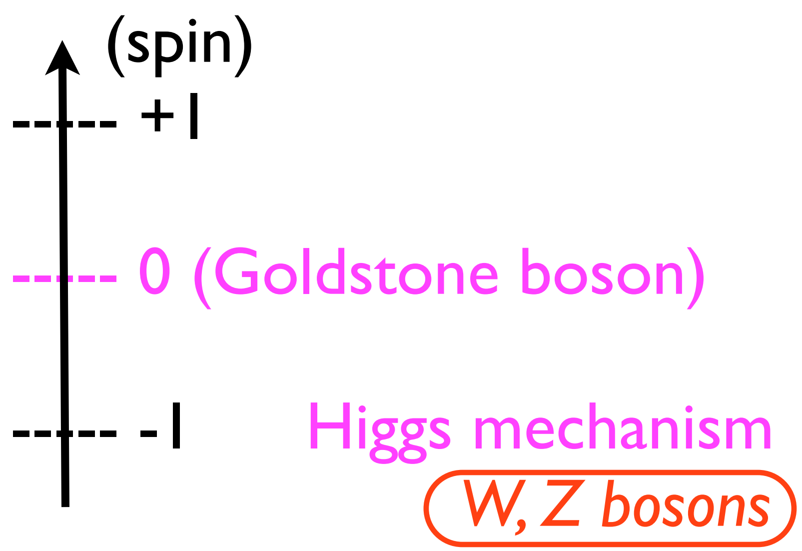


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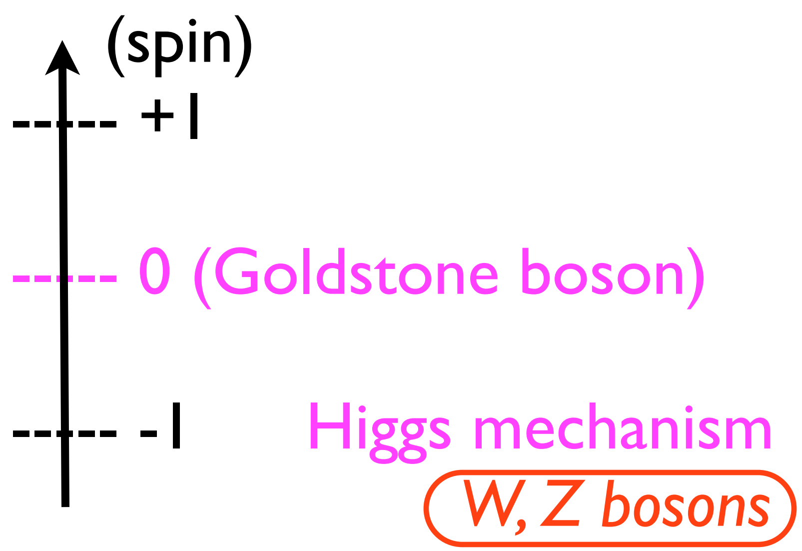


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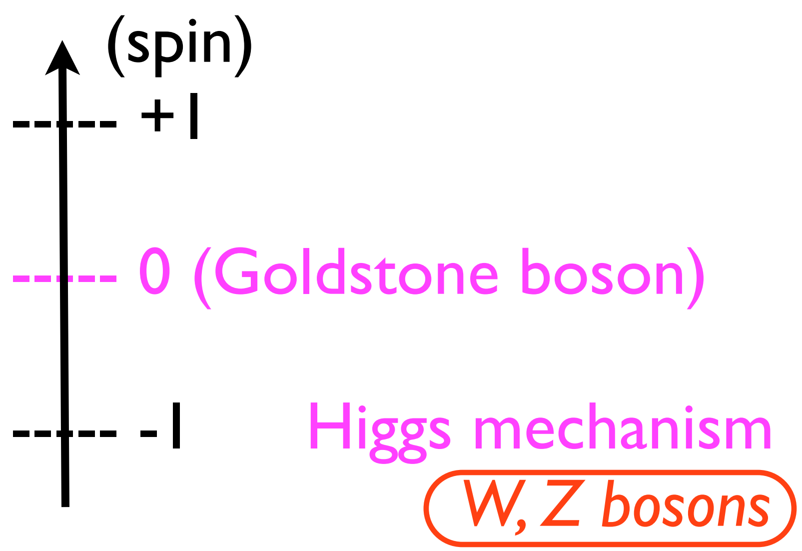


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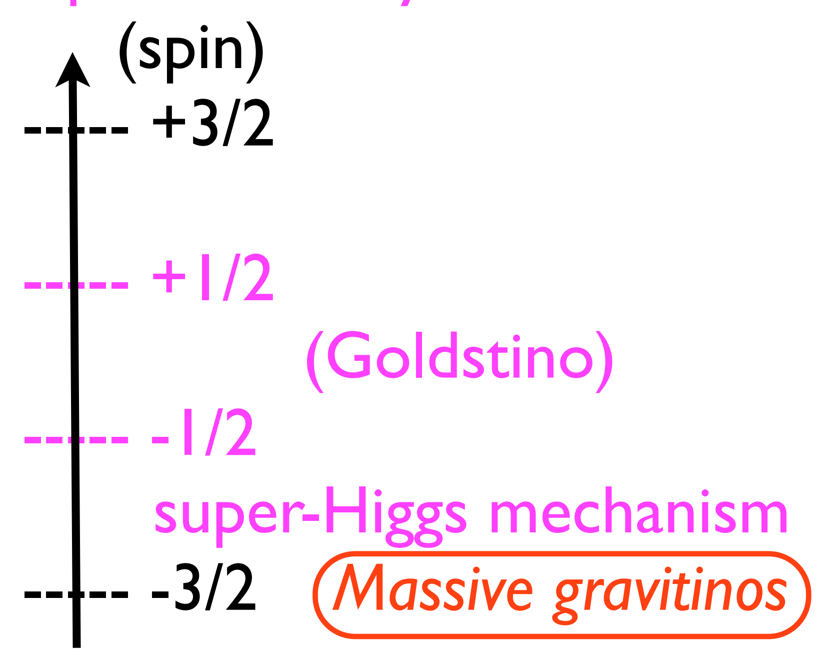


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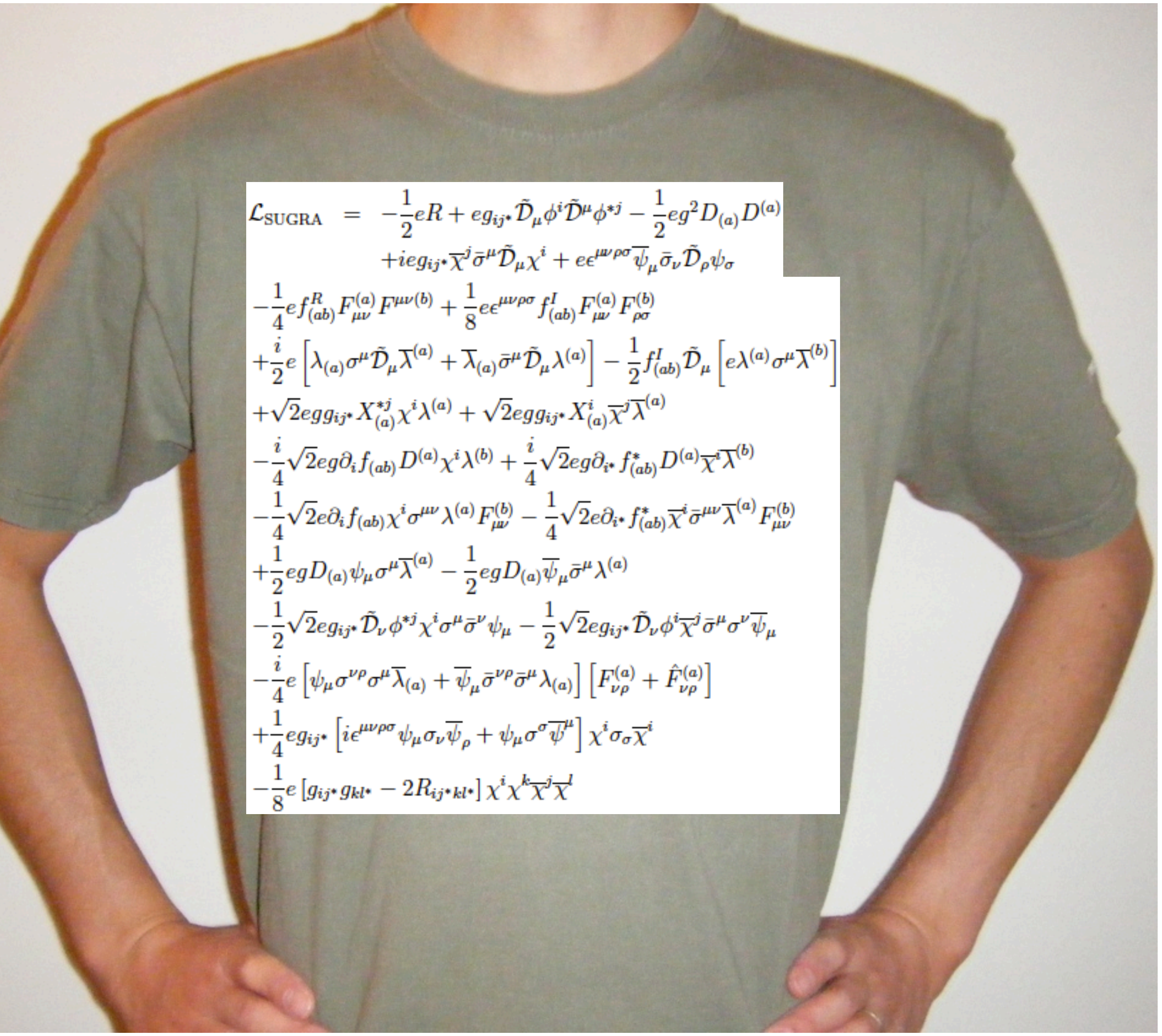


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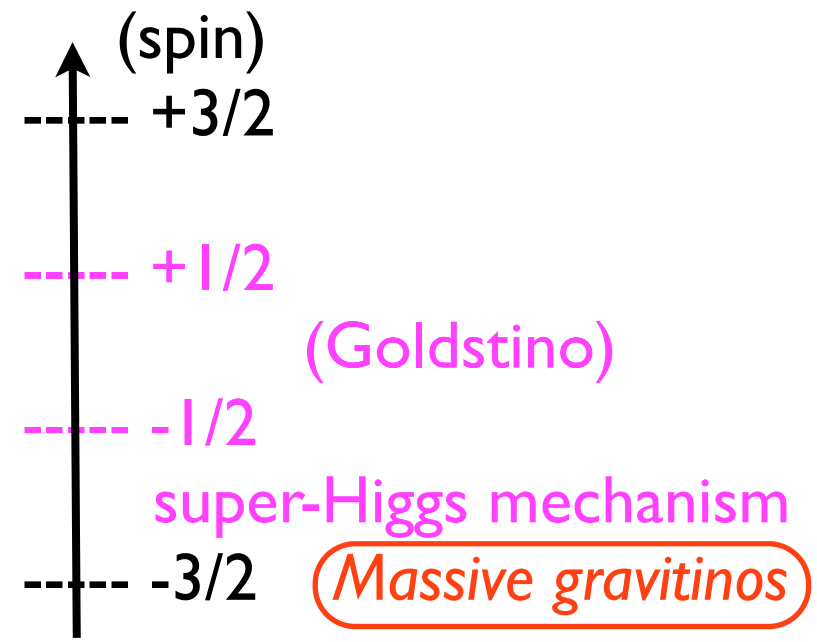


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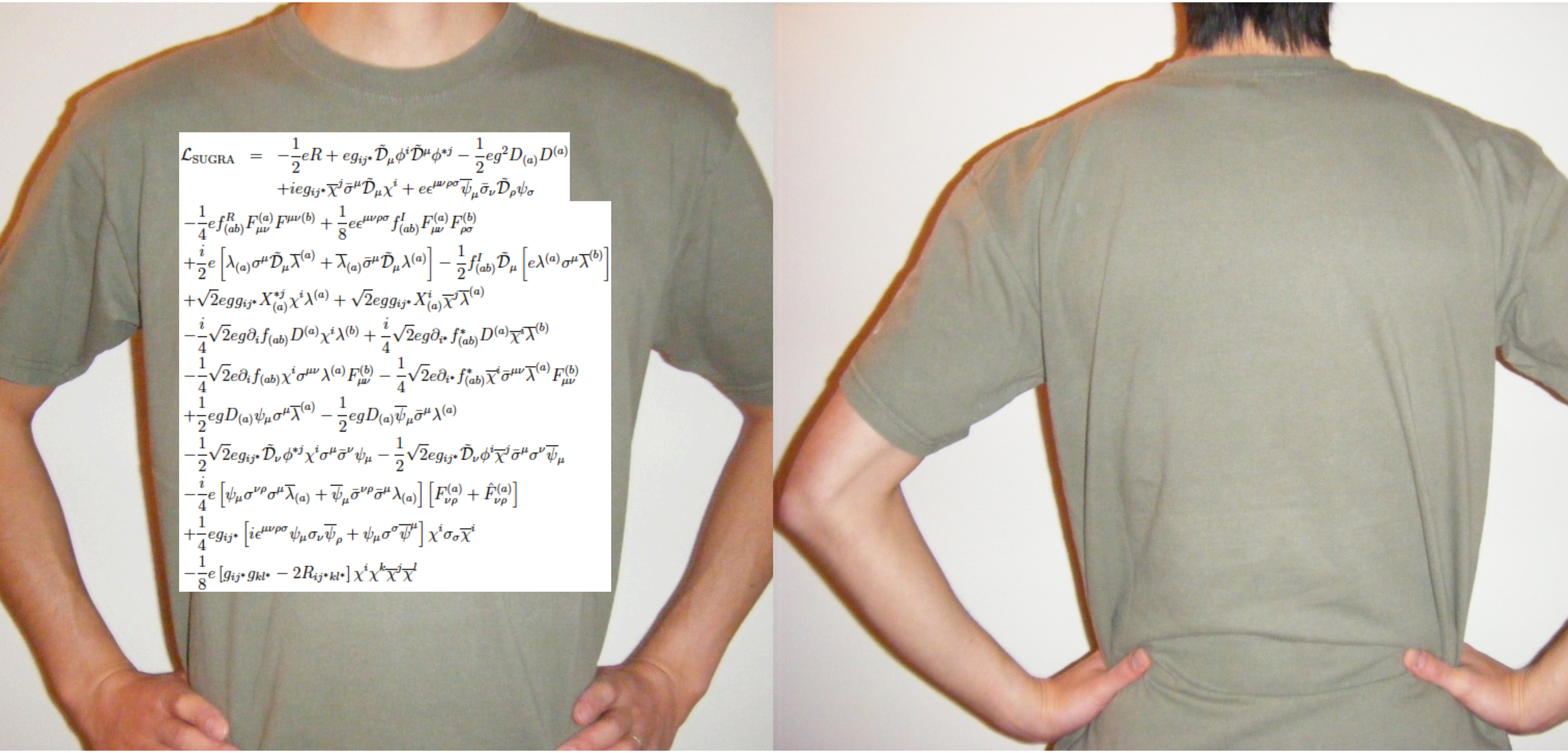
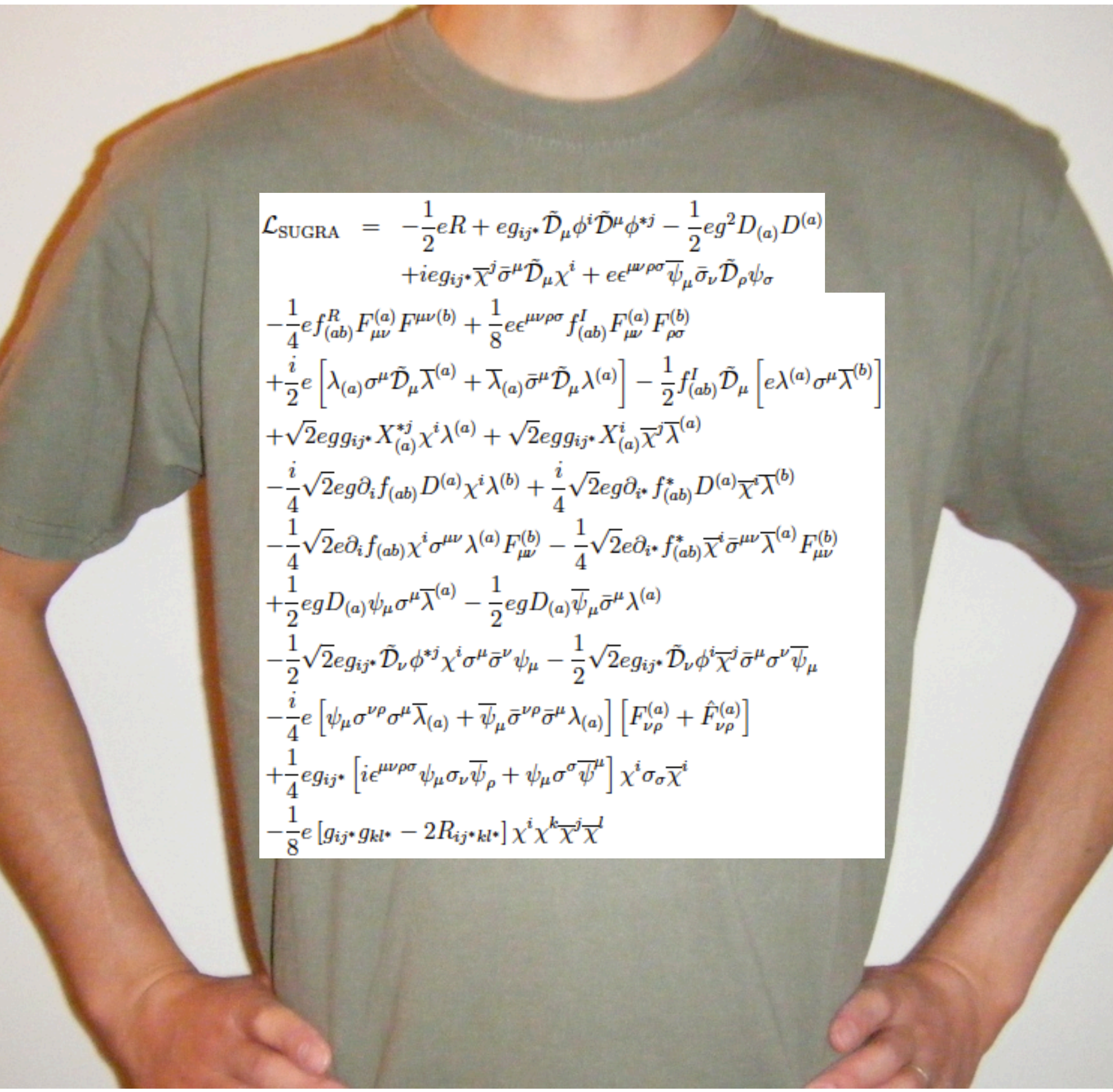
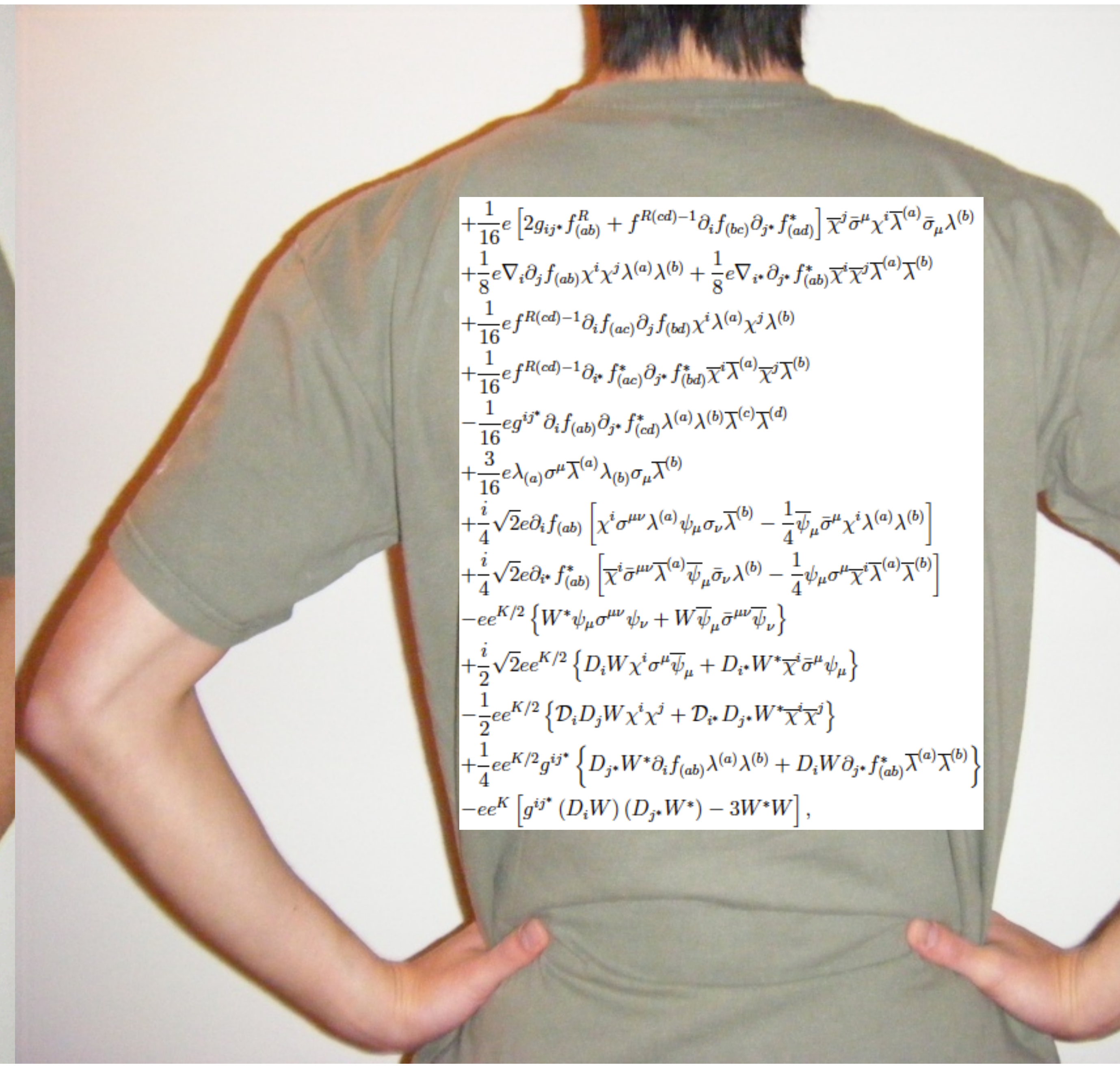


$$
\begin{aligned}
\mathcal{L}_{\rm SUGRA} \;=\; & -\frac{1}{2}eR + eg_{ij^*}\tilde{\mathcal{D}}_\mu\phi^i\tilde{\mathcal{D}}^\mu\phi^{*j} - \frac{1}{2}eg^2 D_{(a)}D^{(a)} \\
& + ieg_{ij^*}\overline{\chi}^j\bar{\sigma}^\mu\tilde{\mathcal{D}}_\mu\chi^i + e\epsilon^{\mu\nu\rho\sigma}\overline{\psi}_\mu\bar{\sigma}_\nu\tilde{\mathcal{D}}_\rho\psi_\sigma \\
& -\frac{1}{4}ef^R_{(ab)}F^{(a)}_{\mu\nu}F^{\mu\nu(b)} + \frac{1}{8}e\epsilon^{\mu\nu\rho\sigma}f^I_{(ab)}F^{(a)}_{\mu\nu}F^{(b)}_{\rho\sigma} \\
& +\frac{i}{2}e\left[\lambda_{(a)}\sigma^\mu\tilde{\mathcal{D}}_\mu\overline{\lambda}^{(a)} + \overline{\lambda}_{(a)}\bar{\sigma}^\mu\tilde{\mathcal{D}}_\mu\lambda^{(a)}\right] - \frac{1}{2}f^I_{(ab)}\tilde{\mathcal{D}}_\mu\left[e\lambda^{(a)}\sigma^\mu\overline{\lambda}^{(b)}\right] \\
& +\sqrt{2}egg_{ij^*}X^{*j}_{(a)}\chi^i\lambda^{(a)} + \sqrt{2}egg_{ij^*}X^i_{(a)}\overline{\chi}^j\overline{\lambda}^{(a)} \\
& -\frac{i}{4}\sqrt{2}eg\partial_i f_{(ab)}D^{(a)}\chi^i\lambda^{(b)} + \frac{i}{4}\sqrt{2}eg\partial_{i^*}f^*_{(ab)}D^{(a)}\overline{\chi}^i\overline{\lambda}^{(b)} \\
& -\frac{1}{4}\sqrt{2}e\partial_i f_{(ab)}\chi^i\sigma^{\mu\nu}\lambda^{(a)}F^{(b)}_{\mu\nu} - \frac{1}{4}\sqrt{2}e\partial_{i^*}f^*_{(ab)}\overline{\chi}^i\bar{\sigma}^{\mu\nu}\overline{\lambda}^{(a)}F^{(b)}_{\mu\nu} \\
& +\frac{1}{2}egD_{(a)}\psi_\mu\sigma^\mu\overline{\lambda}^{(a)} - \frac{1}{2}egD_{(a)}\overline{\psi}_\mu\bar{\sigma}^\mu\lambda^{(a)} \\
& -\frac{1}{2}\sqrt{2}eg_{ij^*}\tilde{\mathcal{D}}_\nu\phi^{*j}\chi^i\sigma^\mu\bar{\sigma}^\nu\psi_\mu - \frac{1}{2}\sqrt{2}eg_{ij^*}\tilde{\mathcal{D}}_\nu\phi^i\overline{\chi}^j\bar{\sigma}^\mu\sigma^\nu\overline{\psi}_\mu \\
& -\frac{i}{4}e\left[\psi_\mu\sigma^{\nu\rho}\sigma^\mu\overline{\lambda}_{(a)} + \overline{\psi}_\mu\bar{\sigma}^{\nu\rho}\bar{\sigma}^\mu\lambda_{(a)}\right]\left[F^{(a)}_{\nu\rho} + \hat{F}^{(a)}_{\nu\rho}\right] \\
& +\frac{1}{4}eg_{ij^*}\left[i\epsilon^{\mu\nu\rho\sigma}\psi_\mu\sigma_\nu\overline{\psi}_\rho + \psi_\mu\sigma^\sigma\overline{\psi}^\mu\right]\chi^i\sigma_\sigma\overline{\chi}^i \\
& -\frac{1}{8}e\left[g_{ij^*}g_{kl^*} - 2R_{ij^*kl^*}\right]\chi^i\chi^k\overline{\chi}^j\overline{\chi}^l
\end{aligned}
$$

# Massive gravitinos




* copied from T.Moroi, hep-ph/9503210.

# 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.

# The effective interaction Lagrangian relevant to the gravitino phenomenology

- The effective interaction Lagrangian:

$$\mathcal{L}_{\rm int} = -\frac{i}{\sqrt{2}\,\overline{M}_{\rm Pl}}\left[\bar{\psi}_\mu \gamma^\nu \gamma^\mu P_{R/L} f^i \,(D_\nu \phi^i_{R/L})^* - \bar{f}^i P_{L/R} \gamma^\mu \gamma^\nu \psi_\mu \,(D_\nu \phi^i_{R/L})\right] - \frac{i}{8\overline{M}_{\rm Pl}} \bar{\psi}_\mu [\gamma^\nu, \gamma^\rho] \gamma^\mu \lambda^{(\alpha)a} F^{(\alpha)a}_{\nu\rho},$$

  - The covariant derivative:

$$D_\mu = \partial_\mu + i g_s T^a_3 A^a_\mu + i g T^a_2 W^a_\mu + i g' Y B_\mu$$

  - The field-strength tensors for each gauge group:

$$F^{(3)a}_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g_s f^{abc}_3 A^b_\mu A^c_\nu,$$
$$F^{(2)a}_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu - g f^{abc}_2 W^b_\mu W^c_\nu,$$
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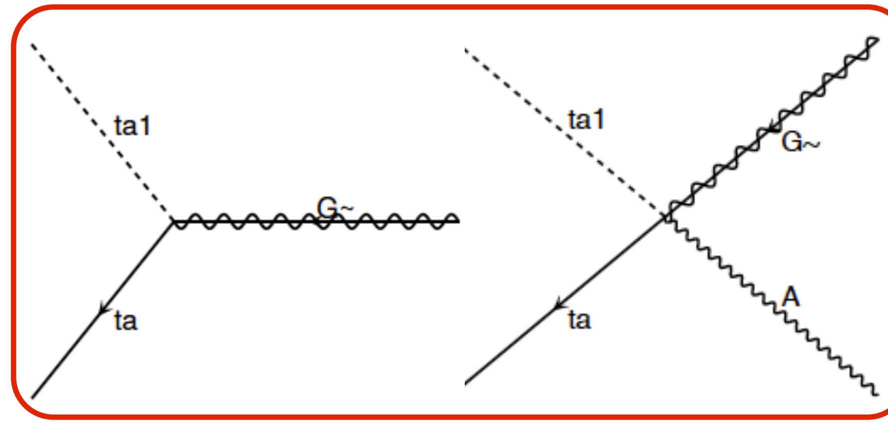


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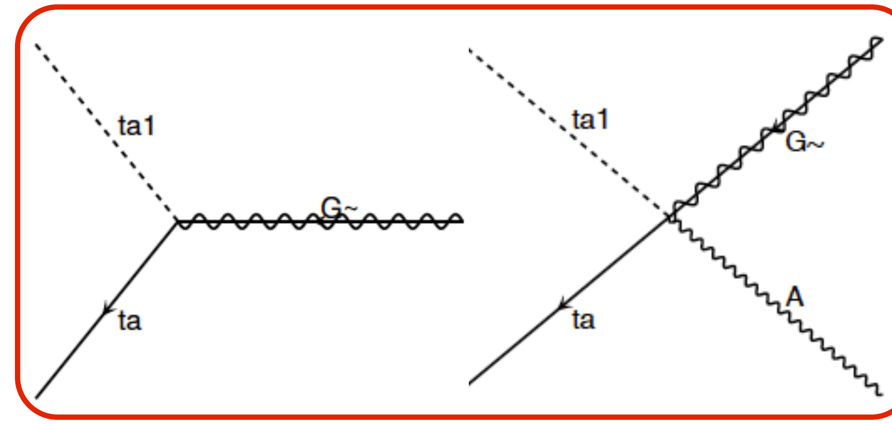


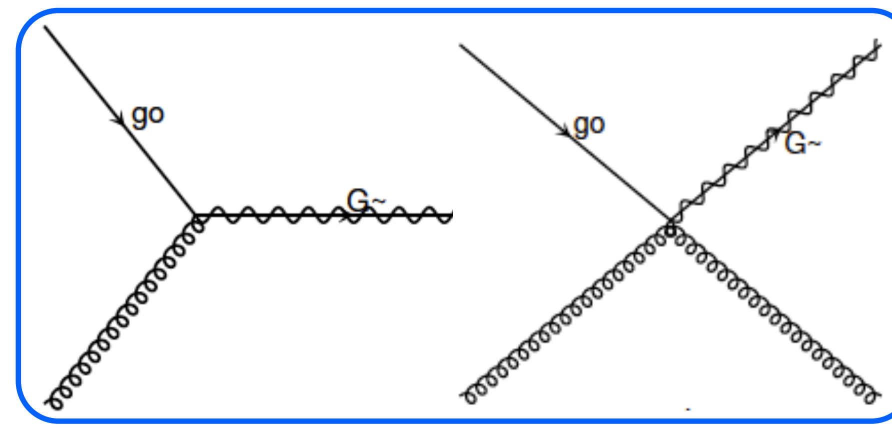


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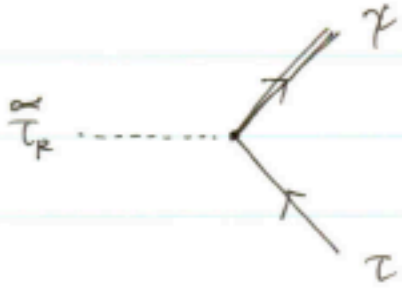
# Pheno calculations

- pick up Lagrangian
- derive Feynman rules
- draw possible Feynman diagrams
- write corresponding amplitudes
- calculate the amplitudes (or amplitude^2)
- get (differential) cross section, decay rate

• $\tilde{\tau}_R \to \tau + \psi_{3/2}$




$$\begin{cases} k^\mu = M(1,0,0,0) \\ p_1^\mu = \frac{M}{2}\beta(1, \sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta) \\ p_2^\mu = \frac{M}{2}\left(1+\frac{m^2}{M^2}, -\beta\sin\theta\cos\phi, -\beta\sin\theta\sin\phi, -\beta\cos\theta\right) \end{cases}$$

$$\beta = 1-\frac{m^2}{M^2}, \quad E_2+|\vec{p}_2| = M, \quad E_2-|\vec{p}_2| = \frac{m^2}{M}$$

$$\mathcal{M}_{\sigma_1\sigma_2} = g\,\bar{\psi}_\mu(p_2,\sigma_2)\gamma^\nu\gamma^\mu P_R u(p_1,\sigma_1) k_\nu \qquad \left(g = \frac{1}{\sqrt{2}M_{pl}}\right)$$

$$= gM\,\bar{\psi}_\mu(p_2,\sigma_2)\underbrace{\gamma^0\gamma^\mu P_R}\, u(p_1,\sigma_1)$$

$$= \begin{pmatrix} 0 & \sigma^\mu \\ \bar{\sigma}^\mu & 0 \end{pmatrix}\begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} 0 & \sigma^\mu \\ 0 & 0 \end{pmatrix}$$

$$J^\mu_{\sigma_1\sigma_2'} = u^\dagger(p_2,\sigma_2')\begin{pmatrix} 0 & \sigma^\mu \\ 0 & 0 \end{pmatrix} u(p_1,\sigma_1)$$

• $$J^\mu_{-+} = -\sqrt{M\beta}\sqrt{\frac{m^2}{M}}\left(\sin\frac{\theta}{2}, -\cos\frac{\theta}{2}e^{-i\phi}\right)\left[\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}\right]\begin{pmatrix} \cos\frac{\theta}{2} \\ \sin\frac{\theta}{2}e^{i\phi} \end{pmatrix}$$

$$= -\sqrt{\beta}m\left[0, \sin^2\frac{\theta}{2}e^{i\phi}-\cos^2\frac{\theta}{2}e^{-i\phi}, -i\left(\sin^2\frac{\theta}{2}e^{i\phi}+\cos^2\frac{\theta}{2}e^{-i\phi}\right), 2\sin\frac{\theta}{2}\cos\frac{\theta}{2}\right]$$

$$= -\sqrt{\beta}m\left[0, -\cos\theta\cos\phi+i\sin\phi, -\cos\theta\sin\phi-i\cos\phi, \sin\theta\right]$$

• $$J^\mu_{--} = -\sqrt{M\beta}\sqrt{M}\left(\cos\frac{\theta}{2}e^{i\phi}, \sin\frac{\theta}{2}\right)\sigma^\mu\begin{pmatrix} \cos\frac{\theta}{2} \\ \sin\frac{\theta}{2}e^{i\phi} \end{pmatrix}$$

$$= -\sqrt{\beta}M\left[e^{i\phi}, \sin\frac{\theta}{2}\cos\frac{\theta}{2}\left(e^{2i\phi}+1\right), -i\sin\frac{\theta}{2}\cos\frac{\theta}{2}\left(e^{2i\phi}-1\right), e^{i\phi}\left(\cos^2\frac{\theta}{2}-\sin^2\frac{\theta}{2}\right)\right]$$

$$= -\sqrt{\beta}M e^{i\phi}\left[1, \sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta\right]$$

DATE 2008. 2. 22 No. $\tilde{\tau}$-2

$p \to p_2$ i.e. $\phi \to \phi + \pi$ $\therefore e^{i\phi} \to -e^{i\phi}$

$$\cdot\ \psi^\mu(p, -\tfrac{1}{2}) = \sqrt{\tfrac{2}{3}}\, \varepsilon^\mu(p,0)\, u(p,-)\, e^{i\phi} + \sqrt{\tfrac{1}{3}}\, \varepsilon^\mu(p,-)\, u(p,+)$$

$$\therefore \mathcal{M}_{\sigma_1\sigma_2} = gM \left[ -\sqrt{\tfrac{2}{3}}\, \varepsilon^*_\mu(p_2,0)\, J^\mu_{--}\, e^{-i\phi} + \sqrt{\tfrac{1}{3}}\, \varepsilon^*_\mu(p_2,-)\, J^\mu_{-+} \right]$$

$\sigma_1\sigma_2 = --$

$$\varepsilon^*(p_2,0)\cdot J_{--} = -\sqrt{\beta}\, M\, e^{+i\phi} \frac{E_2}{m} \left[ \frac{|\vec{p}_2|}{E_2} + 1 \right]$$
$$= -\sqrt{\beta} M e^{i\phi} \frac{1}{m} \cdot M$$
$$= -\sqrt{\beta} \frac{M^2}{m} e^{i\phi}$$

$$\varepsilon^*(p_2,-)\cdot J_{-+} = +\sqrt{\beta}\, m \frac{1}{\sqrt{2}} \Big[ (\cos\theta\cos\phi + i\sin\phi)(-\cos\theta\cos\phi + i\sin\phi)$$
$$+ (\cos\theta\sin\phi - i\cos\phi)(-\cos\theta\sin\phi - i\cos\phi)$$
$$- \sin^2\theta \Big]$$
$$= -\frac{\sqrt{\beta}}{\sqrt{2}} m \left[ \cos^2\theta\cos^2\phi + \sin^2\phi + \cos^2\theta\sin^2\phi + \cos^2\phi + \sin^2\theta \right]$$
$$= -\sqrt{2\beta}\, m$$

$$\therefore \mathcal{M}_{--} = gM \left[ +\sqrt{\tfrac{2}{3}} \sqrt{\beta} \frac{M^2}{m} - \sqrt{\tfrac{2}{3}} \sqrt{\beta}\, m \right]$$
$$= +\sqrt{\tfrac{2}{3}} \sqrt{\beta} \frac{M}{m} g (M^2 \pm m^2)$$

$$|\mathcal{M}_{--}|^2 = \frac{2}{3} \beta g^2 \frac{M^2}{m^2} (M^2 \pm m^2)^2$$

$$\therefore \Gamma = \frac{1}{2M} |\mathcal{M}|^2 d\Phi_2$$
$$= \frac{1}{2M} \frac{\beta}{8\pi} \frac{2}{3} \beta \frac{1}{2M_{pl}^2} \frac{M^2}{m^2} (M^2 \pm m^2)^2$$
$$= \frac{M^5}{48\pi M_{pl}^2 m^2} \left(1 - \frac{m^2}{M^2}\right)^2 \left(1 \pm \frac{m^2}{M^2}\right)^2$$
$$= \frac{M^5}{48\pi M_{pl}^2 m^2} \left(1 - \frac{m^2}{M^2}\right)^4$$

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$$\varepsilon^*(p_2,-)\cdot J_{-+} = +\sqrt{\beta}\, m \frac{1}{\sqrt{2}} \Big[ (\cos\theta\cos\phi + i\sin\phi)(-\cos\theta\cos\phi + i\sin\phi) + (\cos\theta\sin\phi - i\cos\phi)(-\cos\theta\sin\phi - i\cos\phi) - \sin^2\theta \Big]$$

$$= -\frac{\sqrt{\beta}}{\sqrt{2}}\, m \left[ \cos^2\theta\cos^2\phi + \sin^2\phi + \cos^2\theta\sin^2\phi + \cos^2\phi + \sin^2\theta \right] = -\sqrt{2\beta}\, m$$

$$\therefore \mathcal{M}_{--} = g M \left[ +\sqrt{\tfrac{2}{3}} \sqrt{\beta}\, \frac{M^2}{m} - \sqrt{\tfrac{2}{3}} \sqrt{\beta}\, m \right] = +\sqrt{\tfrac{2}{3}} \sqrt{\beta}\, \frac{M}{m}\, g (M^2 \pm m^2)$$

$$|\mathcal{M}_{--}|^2 = \frac{2}{3} \beta g^2 \frac{M^2}{m^2} (M^2 \pm m^2)^2$$

$$\therefore \Gamma = \frac{1}{2M} |\mathcal{M}|^2 d\Phi_2 = \frac{1}{2M} \frac{\beta}{8\pi} \frac{2}{3} \beta \frac{1}{2 M_{pl}^2} \frac{M^2}{m^2} (M^2 \pm m^2)^2 = \frac{M^5}{48\pi M_{pl}^2 m^2} \left(1 - \frac{m^2}{M^2}\right)^2 \left(1 \pm \frac{m^2}{M^2}\right)^2 = \frac{M^5}{48\pi M_{pl}^2 m^2} \left(1 - \frac{m^2}{M^2}\right)^4$$

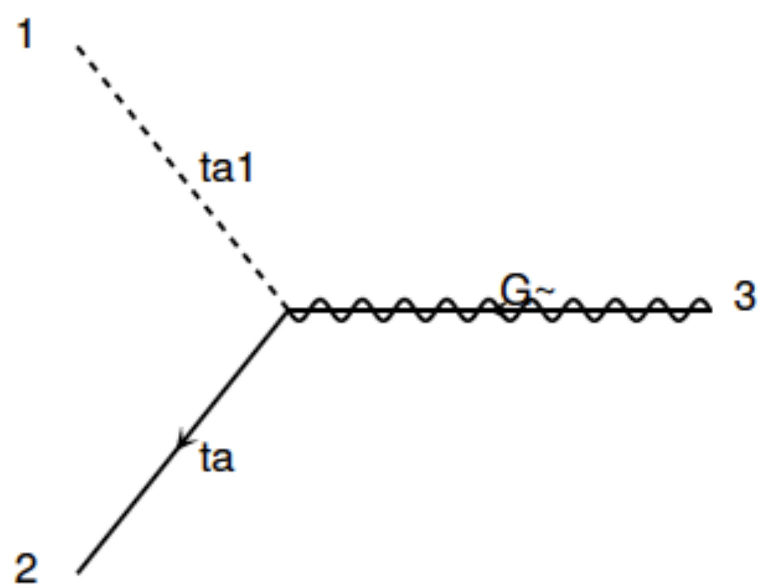
➡ Reliable tools to generate amplitudes and to calculate them automatically are needed!

# MadGraph/MadEvent with gravitinos

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

# HELAS

- HELicity Amplitude Subroutines (in Fortran77)
  - by H. Murayama, I. Watanabe, K. Hagiwara (1992)
- e.g., stau1- > tau- + gravitino




```
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

- MG by T. Stelzer and W.F. Long (1994)
- ME by F. Maltoni and T. Stelzer (2003)

- Put your process, e.g., e+e- > n1n1 > a gro a gro
  *./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.

# Sample results: neutralino NLSP

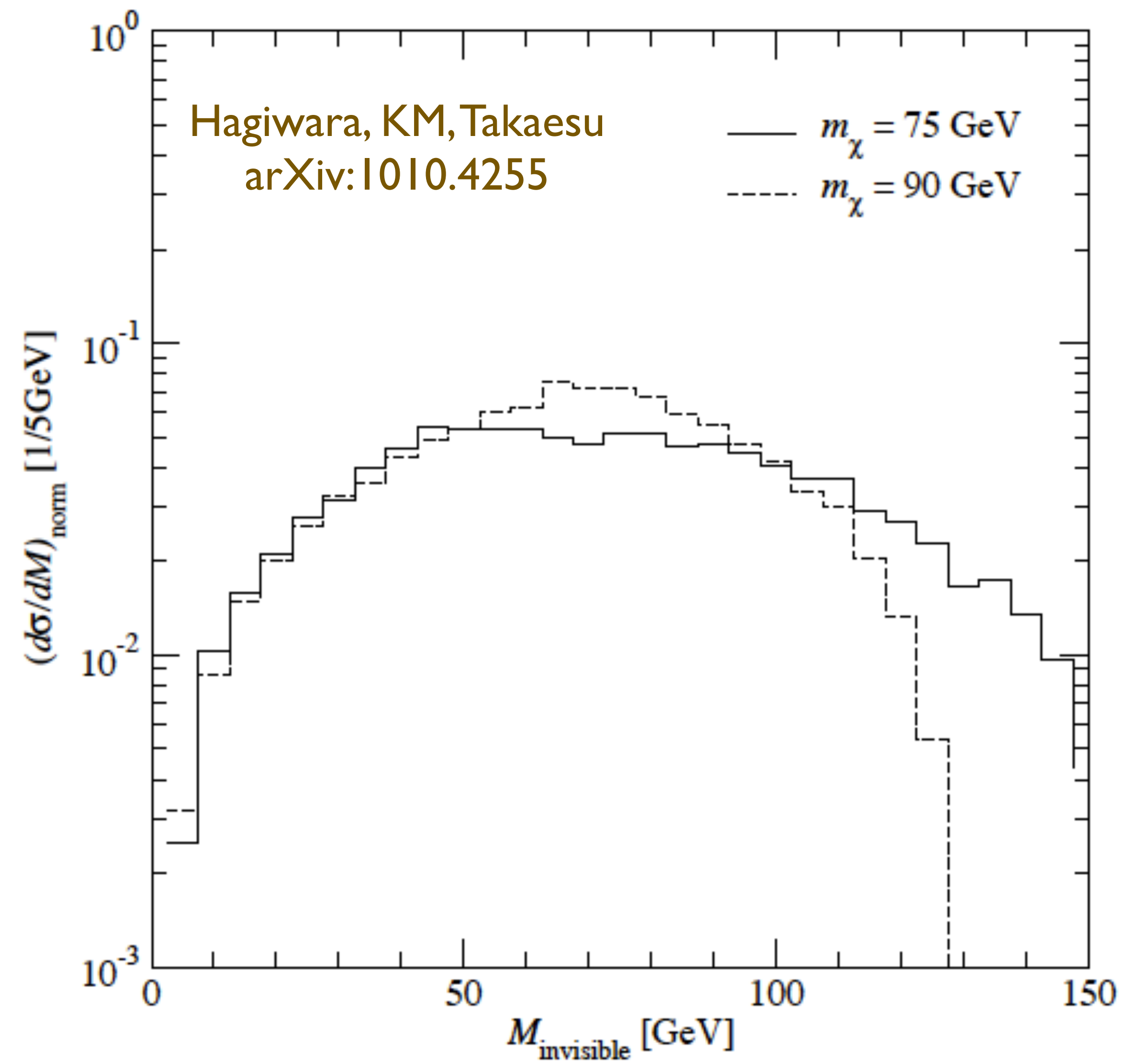



Fig. 4. Missing invariant mass distributions for $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 \to \gamma\gamma\tilde{G}\tilde{G}$ at $\sqrt{s} = 190$ GeV. The cases for the neutralino mass $m_\chi = 75$ and 90 GeV are shown as a solid and dashed line, respectively, with the normalized cross section after kinematical cuts of (121).

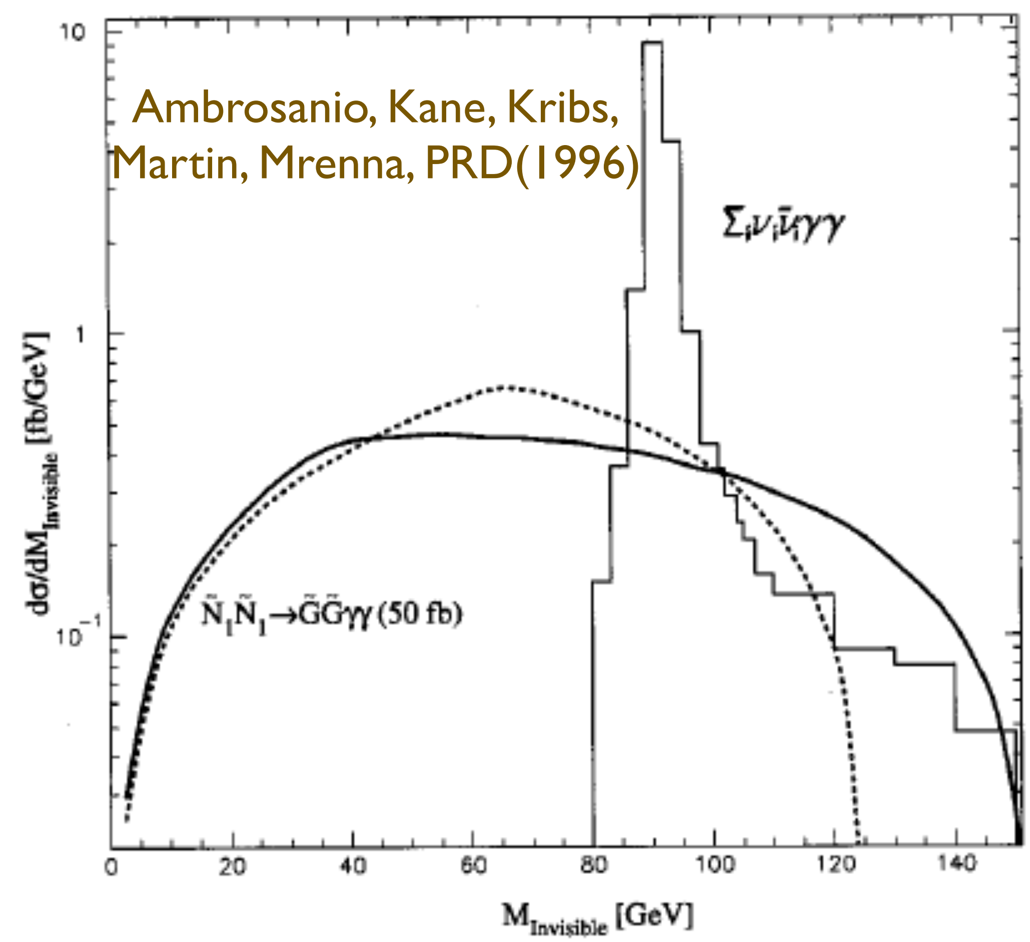
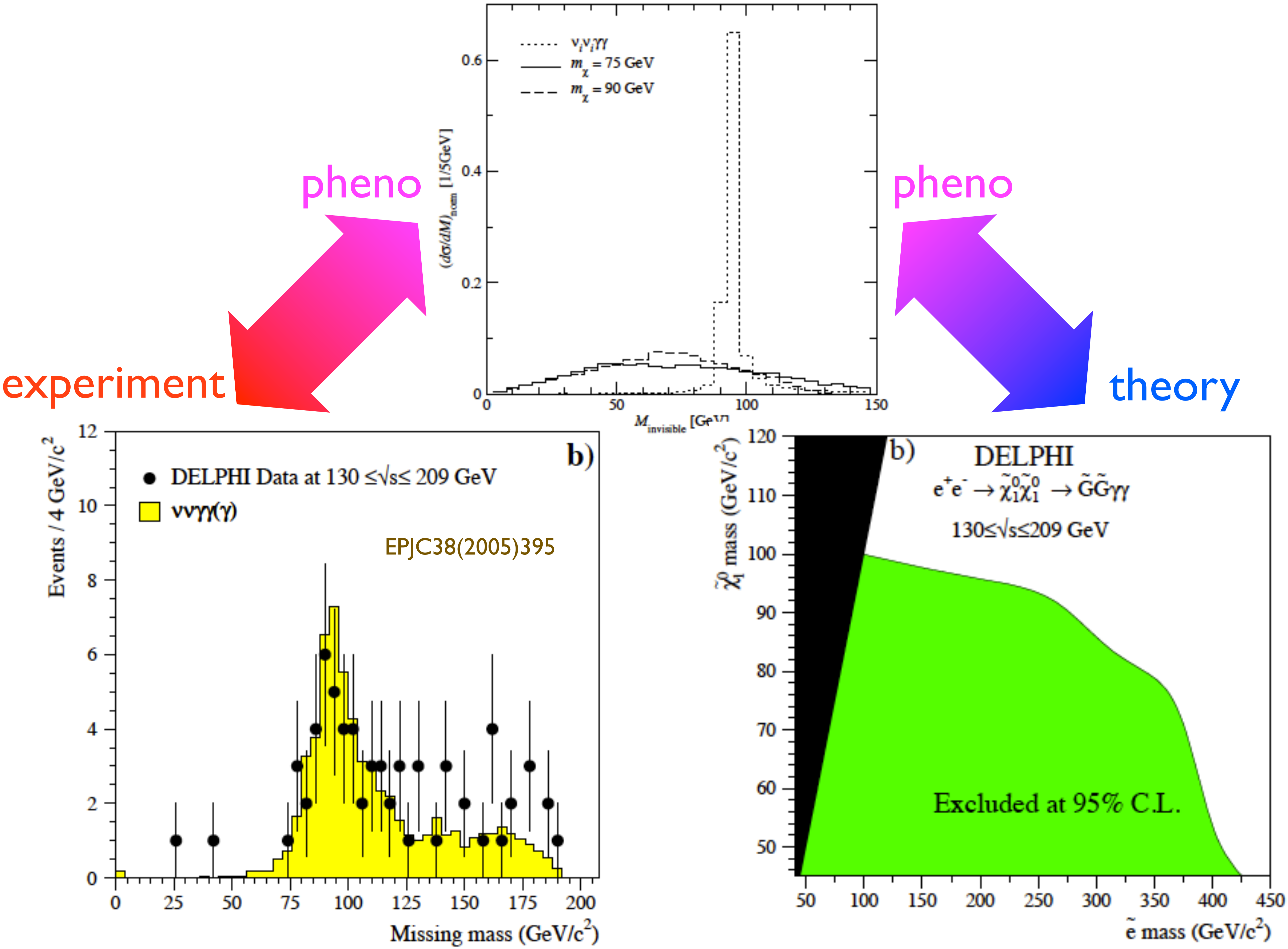



FIG. 16. Distribution of the missing invariant mass in $\gamma\gamma E$ events at LEP with $\sqrt{s} = 190$ GeV. Angular and photon energy cuts have been applied as described in the text. The lighter solid line is the remaining total background (56 fb) for all three neutrino species. The signals for $m_{\tilde{N}_1} = 75$ and 90 GeV are the solid and dashed lines, respectively, with an arbitrary choice of 50 fb for the signal before cuts in each case.


pheno
pheno
experiment
theory
(dσ/dM)norm [1/5GeV]
Minvisible [GeV]
mχ = 75 GeV
mχ = 90 GeV
Events / 4 GeV/c2
DELPHI Data at 130 ≤√s≤ 209 GeV
ννγγ(γ)
EPJC38(2005)395
Missing mass (GeV/c2)
b)
DELPHI
130≤√s≤209 GeV
Excluded at 95% C.L.
mass (GeV/c2)
ẽ mass (GeV/c2)

# Sample results: stau NLSP

Buchmuller, Hamaguchi, Ratz, Yanagida, PLB(2004)

- Radiative stau decays to study the spin-3/2 nature of the gravitino

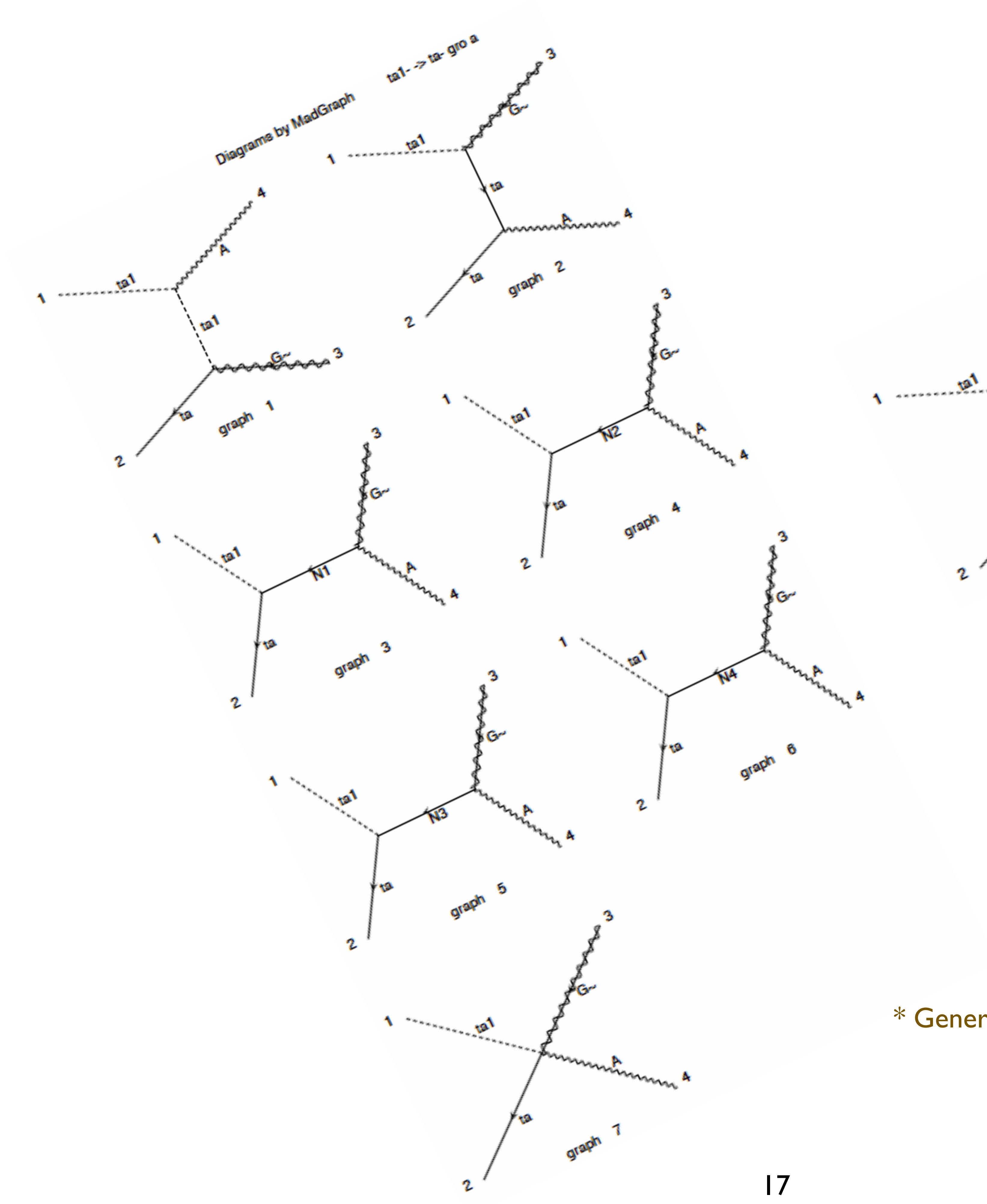
$$\tilde{\tau}_R^- \to \tau^- \, \tilde{G} \, \gamma \quad \text{vs.} \quad \tilde{\tau}_R^- \to \tau^- \, \tilde{\chi}_1^0 \, \gamma$$

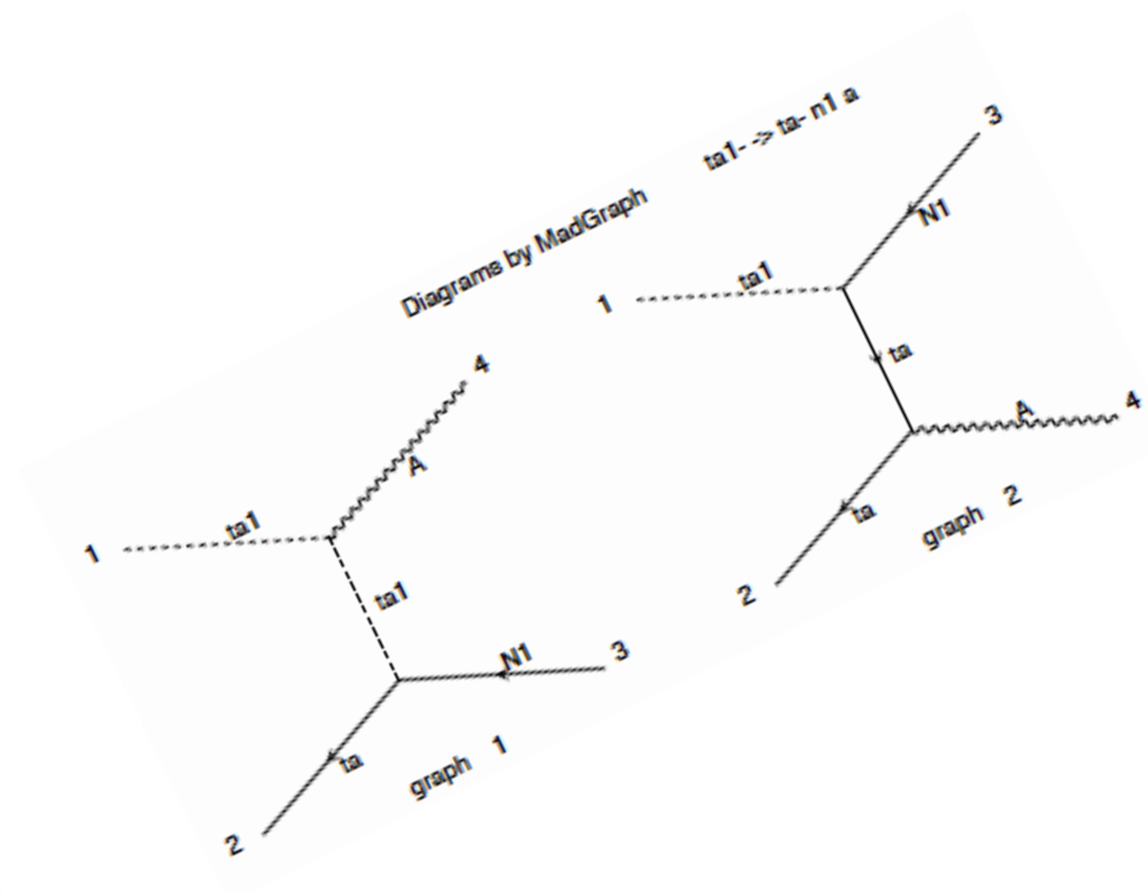
- Photon polarization by means of Stokes parameters

$$\frac{d\rho_{\lambda\lambda'}}{dE_\gamma \, d\cos\theta} = \frac{1}{2}\left(1 + \sum_{i=1}^{3} P_i \sigma_i\right)_{\lambda\lambda'} \cdot \frac{d\Gamma_{\rm sum}}{dE_\gamma \, d\cos\theta}$$

- The photon density matrix

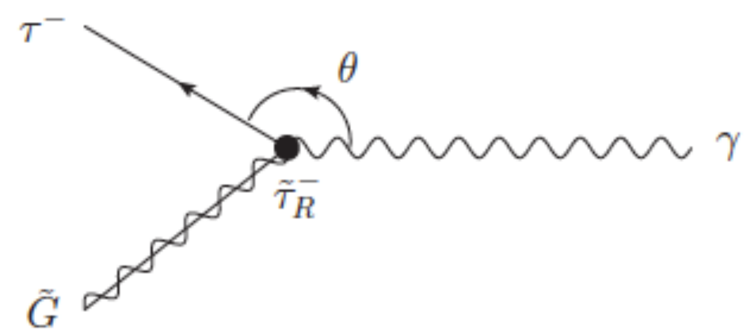
$$d\rho_{\lambda\lambda'} = \frac{1}{2m_{\tilde{\tau}}} \sum \mathcal{M}_\lambda \mathcal{M}^*_{\lambda'} \, d\Phi_3$$




* Generated by MG/ME with gravitinos.

# spin-3/2 vs. spin-1/2



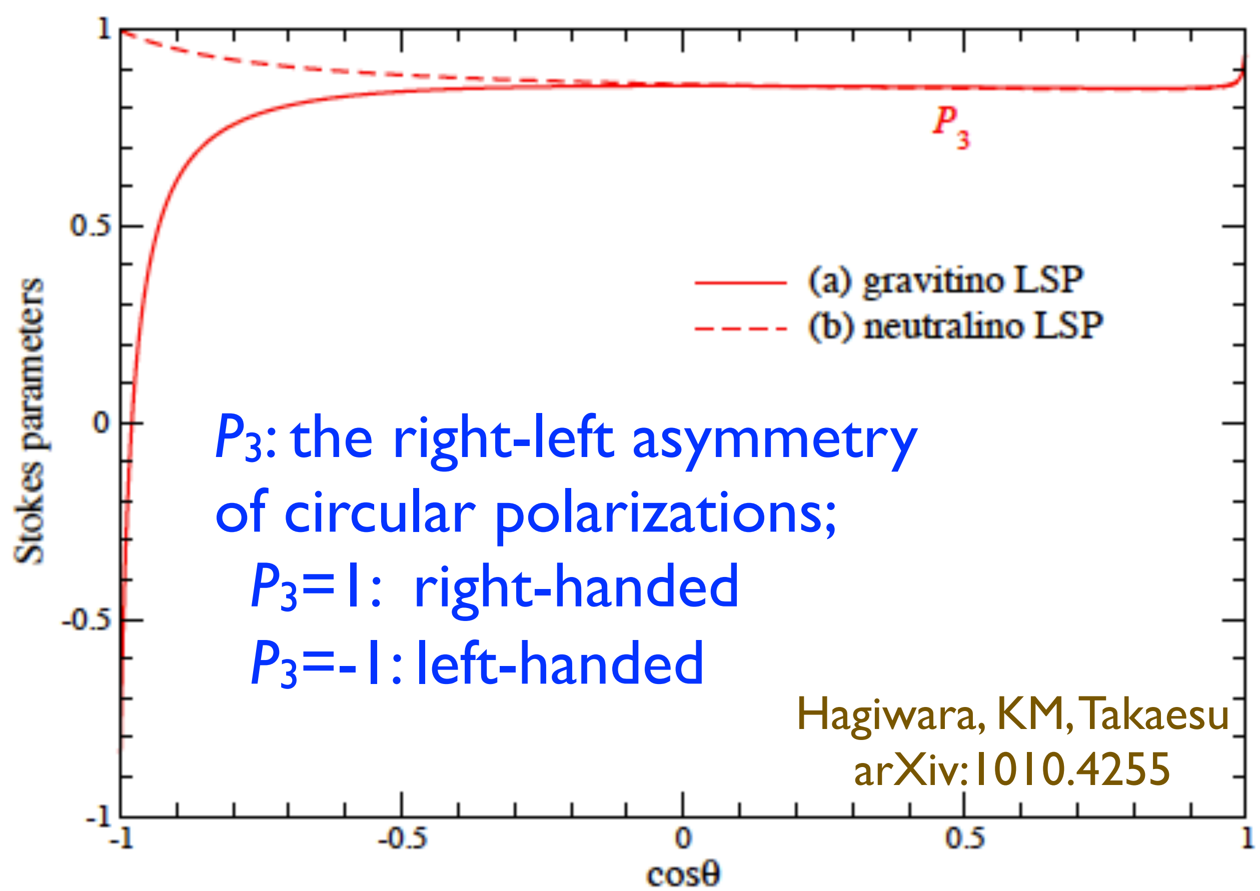
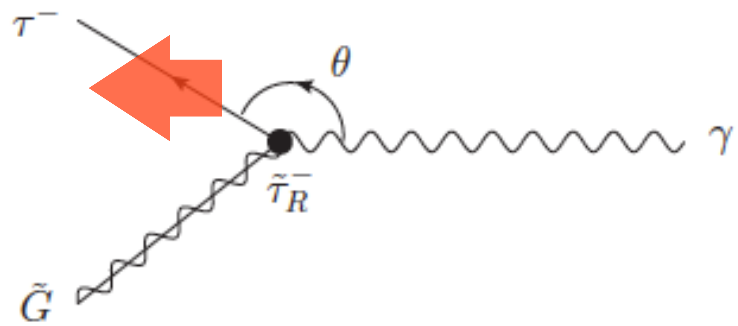




**Fig. 3.** Angular dependence of the Stokes parameters of the radiated photon for the $\tilde{\tau}$ decay process, $\tilde{\tau}_R \to \tau \tilde{G} \gamma$ (a) and $\tilde{\tau}_R \to \tau \tilde{\chi}_1^0 \gamma$ (b), where $\theta$ is the decay angle between the photon and the tau-lepton. We set $m_{\tilde{\tau}} = 150$ GeV, $m_{\rm LSP} = 75$ GeV and $E_\gamma = 40$ GeV.

- cosθ>0: the photon bremsstrahlung is dominant, and only 1/2 helicities of the gravitino are allowed.
- cosθ<0: the neutralino propagating amplitudes and the 4-point interaction amplitude become important.
- cosθ~-1: The left-handed photon is only allowed for spin-3/2 LSP, i.e. gravitino.

# spin-3/2 vs. spin-1/2



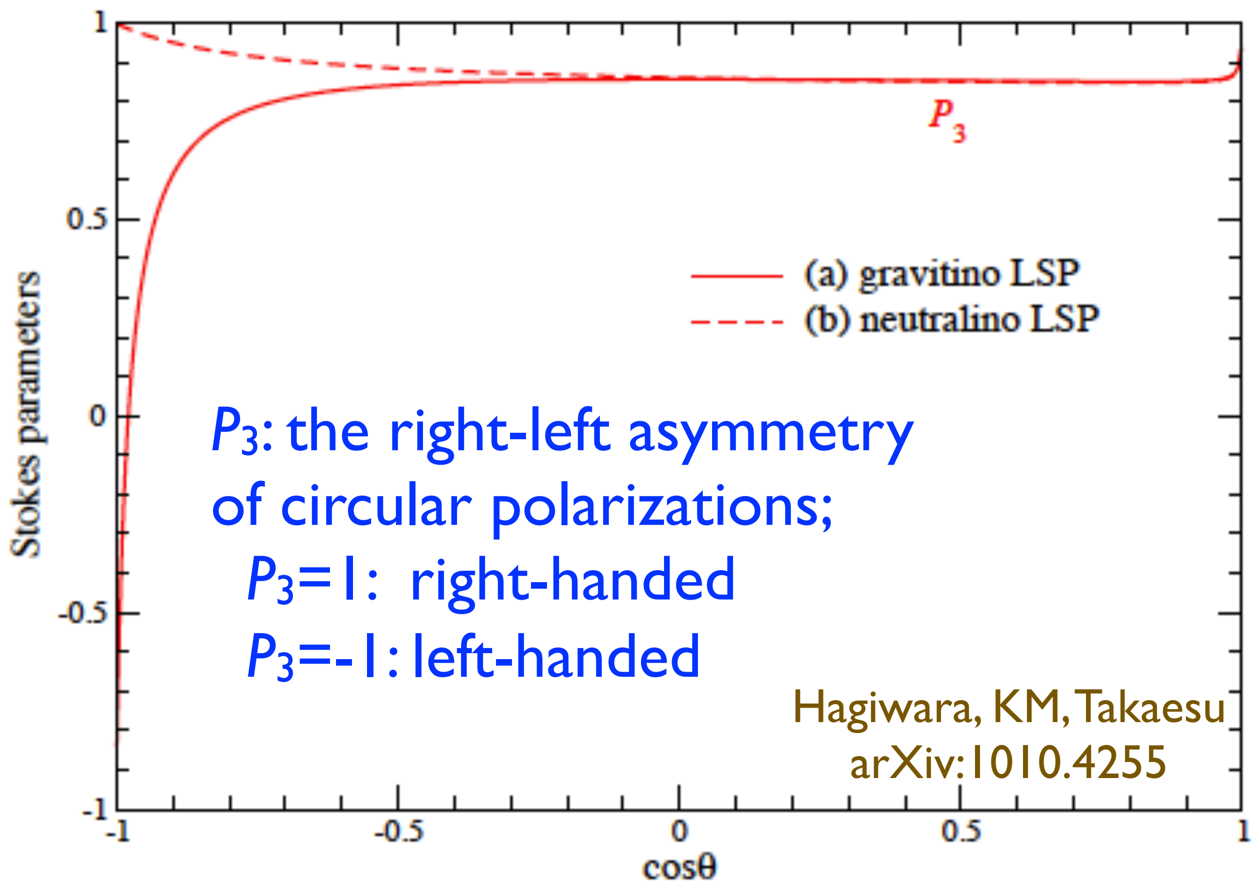




**Fig. 3.** Angular dependence of the Stokes parameters of the radiated photon for the $\tilde{\tau}$ decay process, $\tilde{\tau}_R \to \tau\tilde{G}\gamma$ (a) and $\tilde{\tau}_R \to \tau\tilde{\chi}_1^0\gamma$ (b), where $\theta$ is the decay angle between the photon and the tau-lepton. We set $m_{\tilde{\tau}} = 150$ GeV, $m_{\rm LSP} = 75$ GeV and $E_\gamma = 40$ GeV.

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- cosθ~-1: The left-handed photon is only allowed for spin-3/2 LSP, i.e. gravitino.

# spin-3/2 vs. spin-1/2

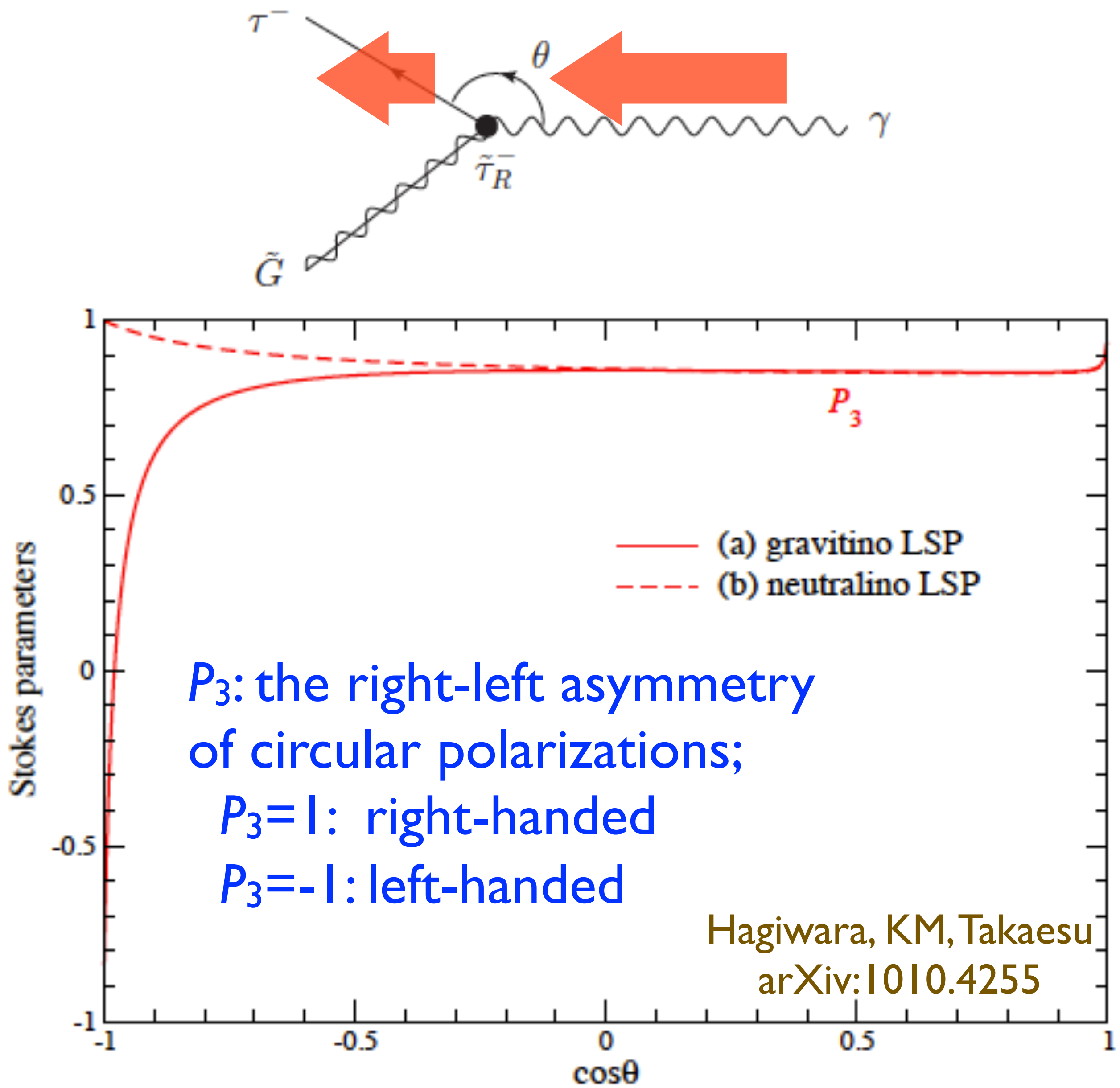


**Fig. 3.** Angular dependence of the Stokes parameters of the radiated photon for the $\tilde{\tau}$ decay process, $\tilde{\tau}_R \to \tau \tilde{G} \gamma$ (a) and $\tilde{\tau}_R \to \tau \tilde{\chi}_1^0 \gamma$ (b), where $\theta$ is the decay angle between the photon and the tau-lepton. We set $m_{\tilde{\tau}} = 150$ GeV, $m_{\rm LSP} = 75$ GeV and $E_\gamma = 40$ GeV.

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# spin-3/2 vs. spin-1/2

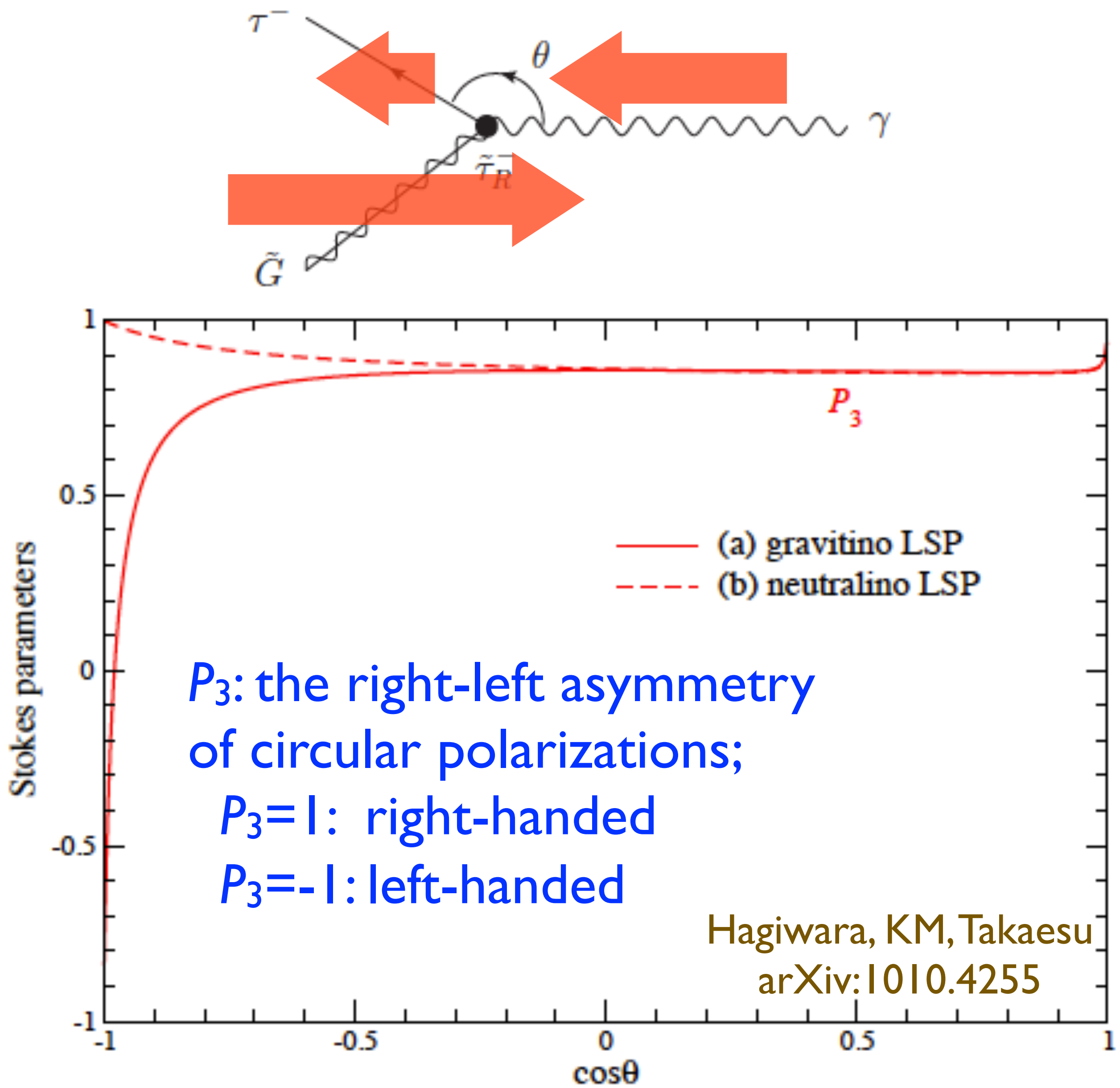



Fig. 3. Angular dependence of the Stokes parameters of the radiated photon for the $\tilde{\tau}$ decay process, $\tilde{\tau}_R \to \tau\tilde{G}\gamma$ (a) and $\tilde{\tau}_R \to \tau\tilde{\chi}^0_1\gamma$ (b), where $\theta$ is the decay angle between the photon and the tau-lepton. We set $m_{\tilde{\tau}} = 150$ GeV, $m_{\rm LSP} = 75$ GeV and $E_\gamma = 40$ GeV.

- cosθ>0: the photon bremsstrahlung is dominant, and only 1/2 helicities of the gravitino are allowed.
- cosθ<0: the neutralino propagating amplitudes and the 4-point interaction amplitude become important.
- cosθ~-1: The left-handed photon is only allowed for spin-3/2 LSP, i.e. gravitino.

# 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.
- We (K.Hagiwara, KM, Y.Takaesu, arXiv:1010.4255)
  - added new HELAS fortran subroutines to calculate helicity amplitudes with massive gravitinos.
  - coded them in such a way that arbitrary amplitudes with external gravitinos can be generated automatically by MadGraph. (The code is available at http://madgraph.kek.jp/KEK/.)
  - presented sample numerical results for the neutralino NLSP and the stau NLSP scenarios.

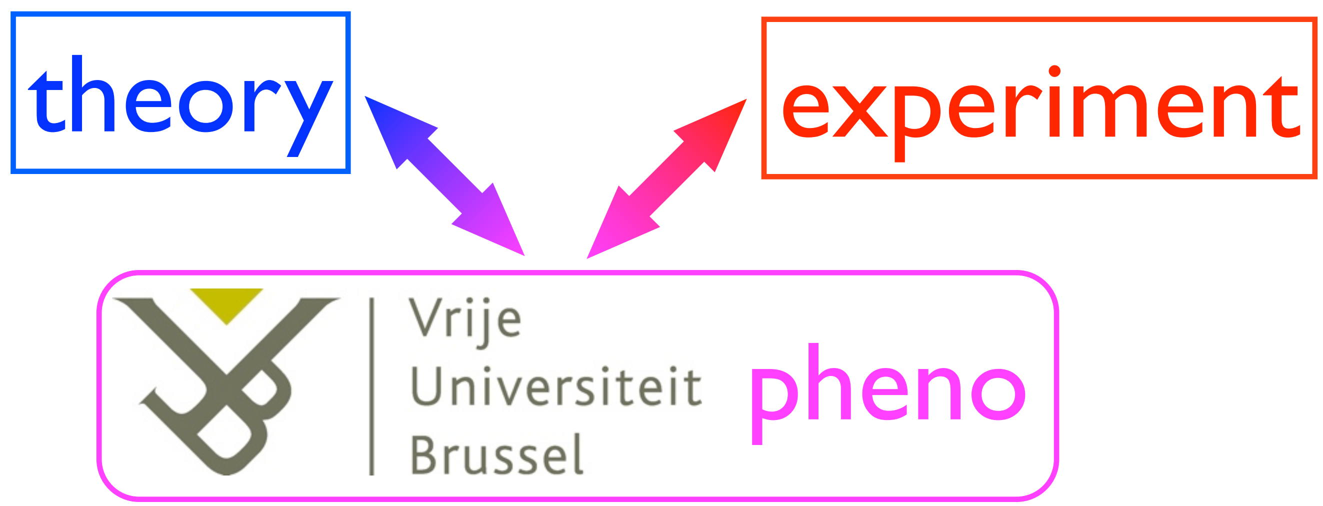
# Future plans

- add new HELAS fortran subroutines for goldstinos.
- test the goldstino-gravitino equivalence in the high energy limit.
- collaborate with theorists and experimentalists, by using MadGraph/MadEvent with gravitinos.
- enjoy "gravitino phenomenology at the LHC" !

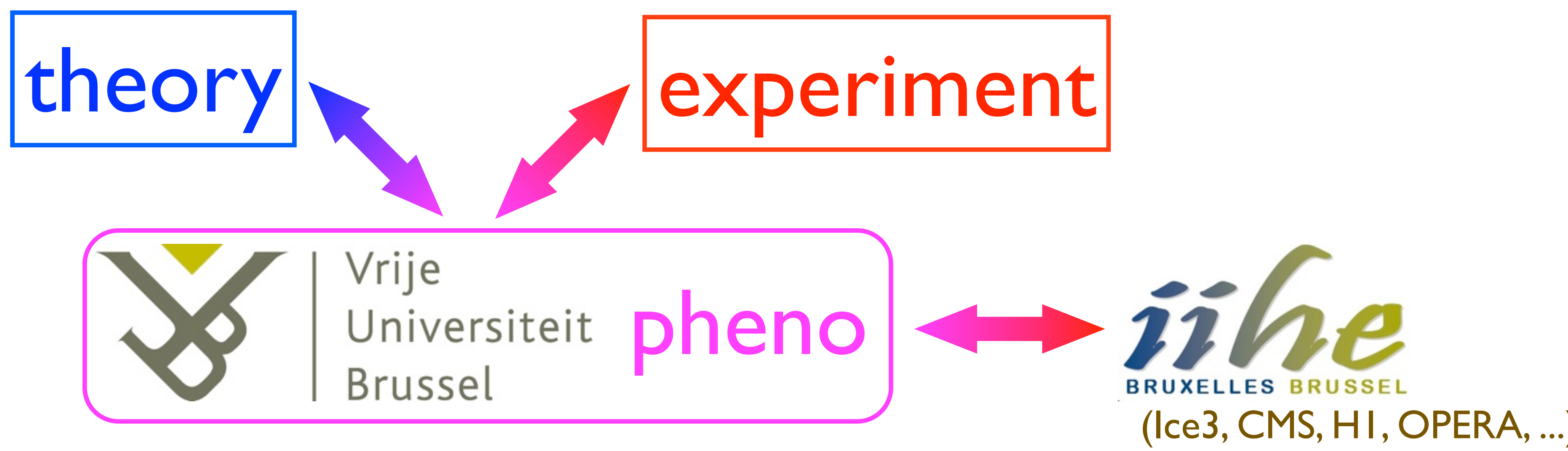
# Interactions of the VUB pheno group

Vrije
Universiteit
Brussel
pheno

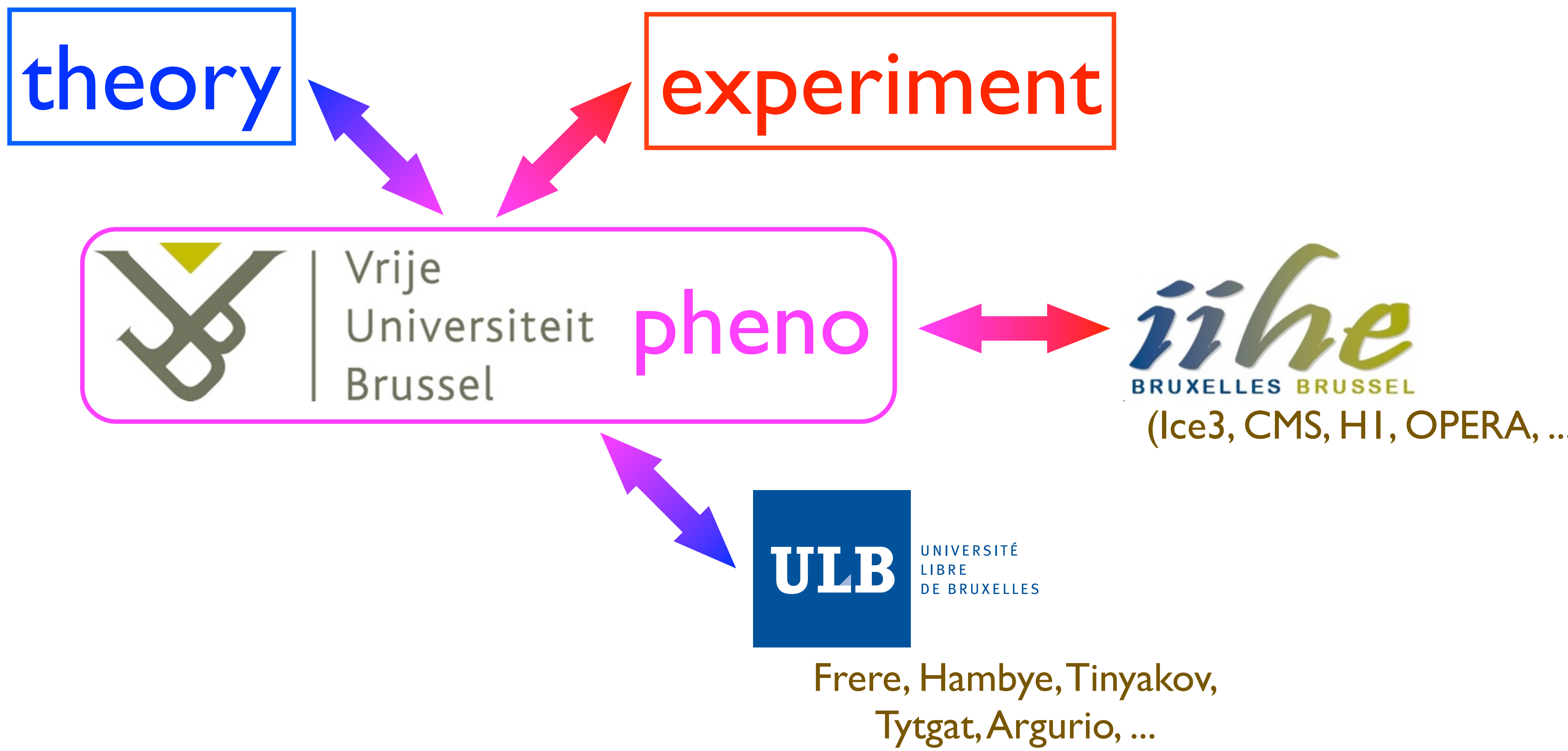
# Interactions of the VUB pheno group



# Interactions of the VUB pheno group



# Interactions of the VUB pheno group



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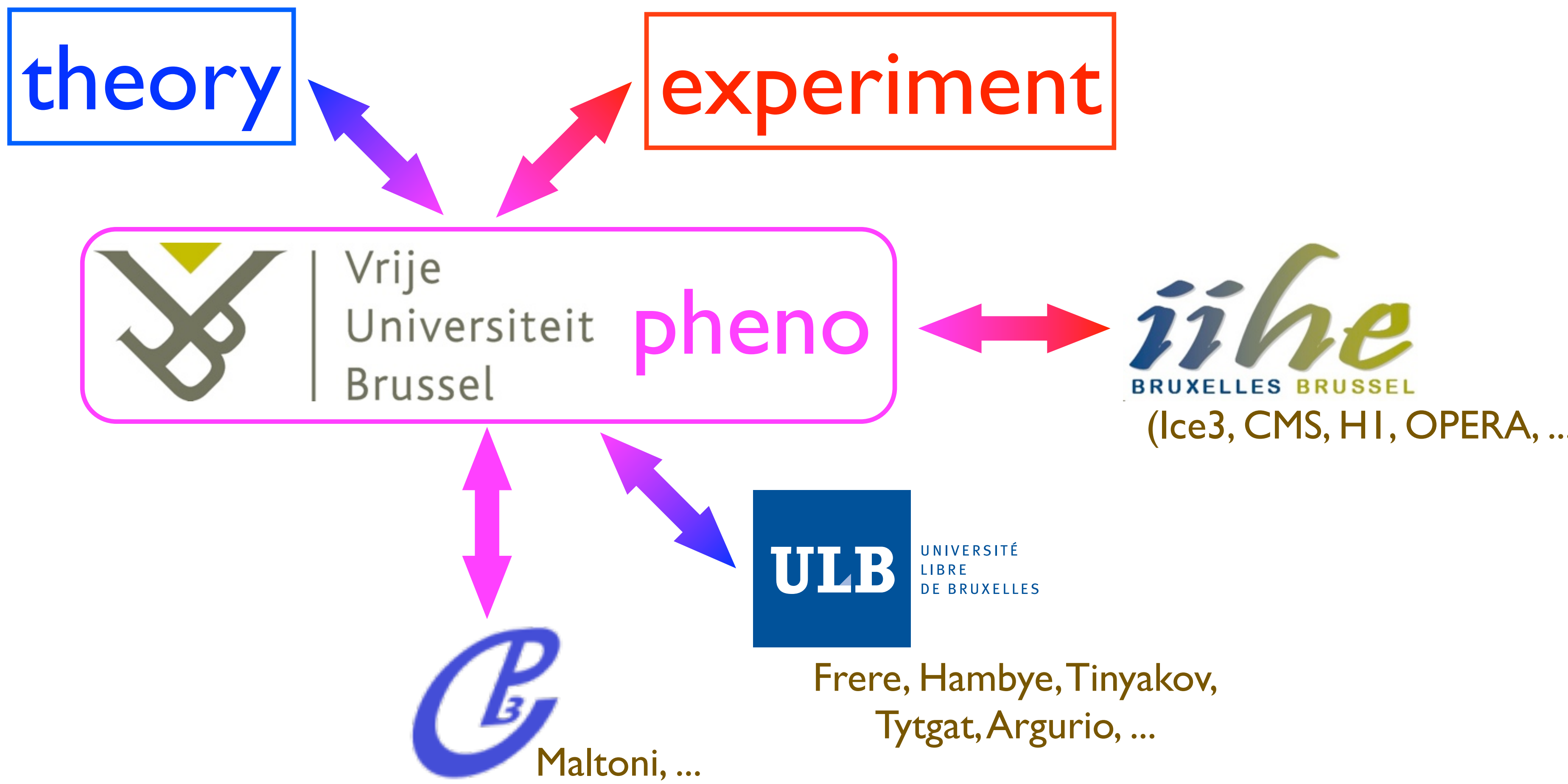
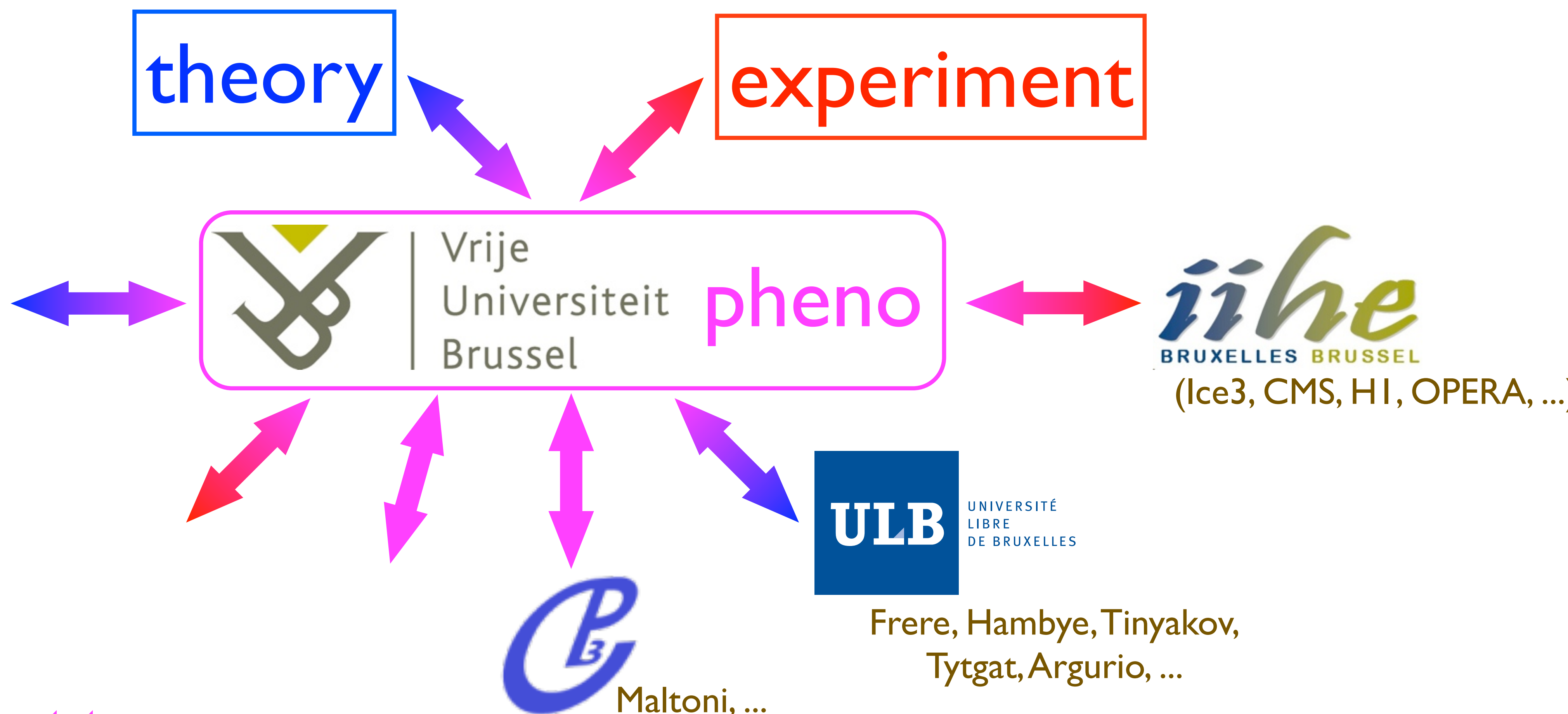


# Interactions of the VUB pheno group




- Contact to
  - http://we.vub.ac.be/dntk/onderzoek/GOAindex.htm
  - pheno@vub.ac.be

# back-up

# Wavefunction of a spin-3/2 particle

- Rarita-Schwinger wavefunction
- expressed by using the vector boson wavefunctions and the spinor wavefunctions:

$$
\begin{aligned}
\psi_u^\mu(p,+3/2) &= \epsilon^\mu(p,+)\,u(p,+), \\
\psi_u^\mu(p,+1/2) &= \sqrt{\frac{2}{3}}\,\epsilon^\mu(p,0)\,u(p,+) \\
&\quad + \sqrt{\frac{1}{3}}\,\epsilon^\mu(p,+)\,u(p,-)\,e^{i\phi}, \\
\psi_u^\mu(p,-1/2) &= \sqrt{\frac{1}{3}}\,\epsilon^\mu(p,-)\,u(p,+) \\
&\quad + \sqrt{\frac{2}{3}}\,\epsilon^\mu(p,0)\,u(p,-)\,e^{i\phi}, \\
\psi_u^\mu(p,-3/2) &= \epsilon^\mu(p,-)\,u(p,-)\,e^{i\phi},
\end{aligned}
$$