Gravitino production from WW scattering in the broken phase

$$W^a + W^b \longrightarrow \widetilde{W}^c + \widetilde{G}$$

$$W^+ + W^- \longrightarrow \widetilde{\chi}_i^0 + \widetilde{G}$$

(in other words, “About the mass as a source of Evil”)

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<0|Motivation: why do we study the gravitino?|0>

- <u>Cosmological interest in the gravitino has grown because...</u> -

- Supersymmetry (SUSY) is localized $\longrightarrow$ supergravity (SUGRA)

- The gravitino $\tilde{G}$ is the gauge field of local SUSY transformations, therefore of SUGRA theories. It is the supersymmetric partner of the graviton, with mass provided by the super-Higgs mechanism.

- In a number of scenarios (e.g. in gauge mediation), the gravitino is the <u>lightest supersymmetric particle</u> (LSP). If R-parity is conserved, we then have the immediate consequence that such a particle is a very attractive candidate for Dark Matter.

- If it is *not* the LSP (e.g. in gravity mediation), it may decay during the Big Bang Nucleosynthesis (BBN), causing EM or hadronic showers, which <u>disintegrate the primordial nuclei</u> (this is one of the aspects of the ”gravitino problem”).

<0| WW scattering: the basis of gauge eigenstates |0>

Within the particle content of the MSSM, one can consider gluon scattering into gluino and gravitino:

$$g^a(k) + g^b(k') \longrightarrow \tilde{g}^c(p') + \widetilde{G}(p)$$

which contributes to the thermal production of gravitinos in the early universe (M. Bolz, A. Brandenburg, W. Buchmueller, Nucl. Phys. B 606 (2001) 518).

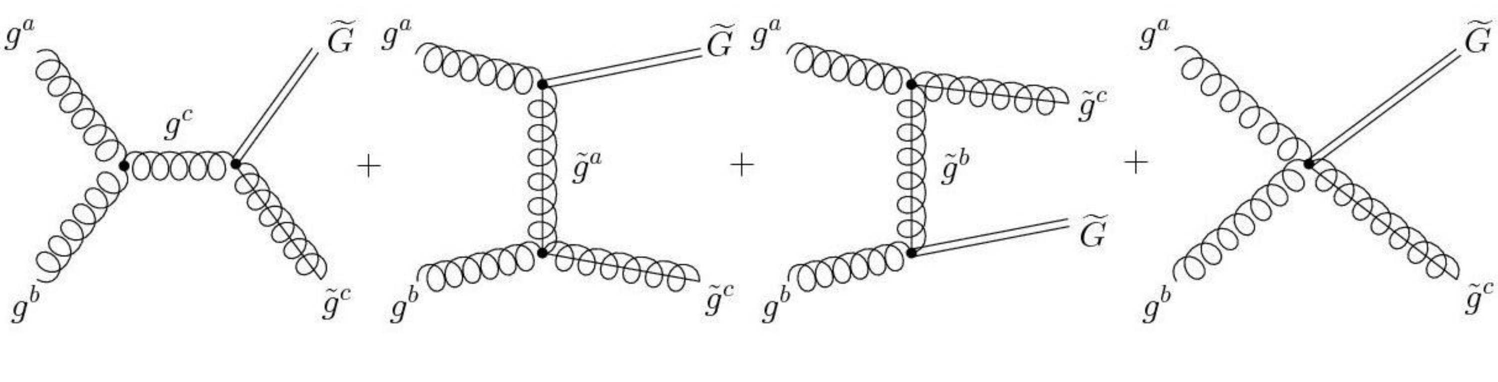


FIG. 1: The four diagrams which contribute to $g^a + g^b \longrightarrow \tilde{g}^c + \widetilde{G}$

As we will see in a moment, this process can be regarded as the *massless limit* of WW scattering in SUGRA in the broken phase.

<0| WW scattering: the basis of gauge eigenstates |0>

Let us now take into analysis the following Electroweak process in supergravity, with a wino and a gravitino in the final state:

$$W^a + W^b \longrightarrow \widetilde{W}^c + \widetilde{G}$$

The corresponding Feyman diagrams are analogous to those in the gluon scattering, since the couplings in supergravity are universal. Thus the amplitude is **formally the same** in both WW and gluon scattering.

The only difference is found in the kinematics and in the spin sums.

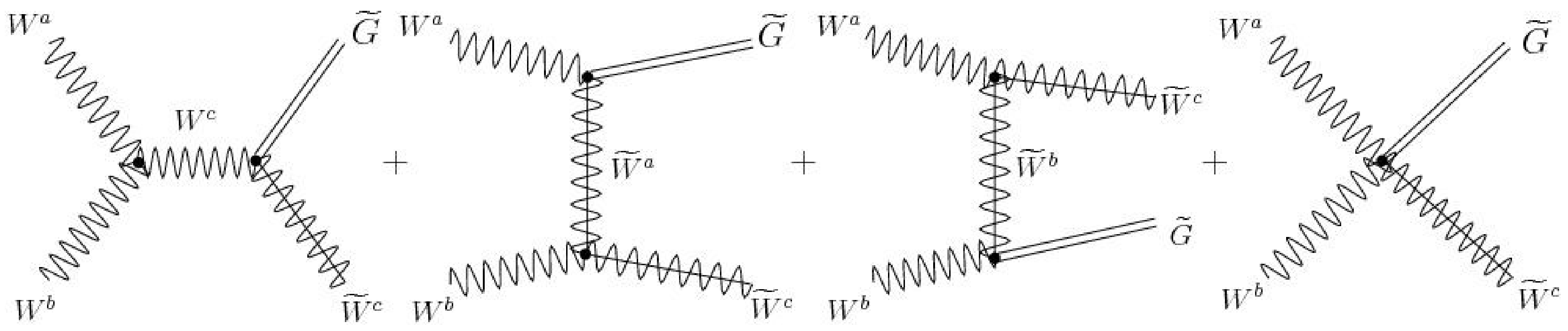


FIG. 2: The four diagrams which contribute to $W^a + W^b \longrightarrow \widetilde{W}^c + \widetilde{G}$

<0| WW scattering: the basis of gauge eigenstates |0>

- High energy limit (at energies which are well above the scale of Electroweak breaking, the W can be considered massless):

$$\sum_{spin} |\overline{\mathcal{M}}|^2 = \frac{1}{9}\sum_{spin} |\mathcal{M}|^2 = 4\frac{g^2|\epsilon^{abc}|^2}{9M_P^2}\left(1+\frac{m^2_{\widetilde{W}}}{3m^2_{\widetilde{G}}}\right)\left(s+2t+2\frac{t^2}{s}\right)$$

(J. Pradler and F. D. Steffen, Phys. Rev. D 75 (2007) 023509)

- Low energy limit (below the EW scale of 100 GeV, W is massive):

$$\sum_{spin} |\overline{\mathcal{M}}|^2 = 4\frac{g^2|\epsilon^{abc}|^2}{9M_P^2}\left[\left(1+\frac{m^2_{\widetilde{W}}}{3m^2_{\widetilde{G}}}\right)\left(s+2t+2\frac{t^2}{s}\right) - \frac{t(s+t)}{3m^2_{\widetilde{G}}} + \mathcal{O}\left(\frac{m_i^2}{m^2_{\widetilde{G}}}\right)f(s,t)\right]$$

Anomalous contribution to the cross section:

$$\left(\frac{d\sigma}{dt}\right)_{cm} \approx \frac{g^2|\epsilon^{abc}|^2}{64\pi M_P^2}\frac{(1-\cos^2\theta)}{3m^2_{\widetilde{G}}} \Longrightarrow \sigma_{tot} \approx \frac{s}{m^4}$$

<0| WW scattering: the basis of gauge eigenstates |0>

What happened?

By directly using the spin sums (1) and (2), we can separate the contributions of the Transverse and Longitudinal degrees of freedom of the gauge bosons, both in the high energy limit and in the broken phase:

Transverse (T) and longitudinal (L)	SUSY QCD	SUSY Weak Interaction
LL	$-2\frac{t(s+t)}{3m^2_{\tilde{G}}}$	$-\frac{t(s+t)}{3m^2_{\tilde{G}}}$
TL	$2\frac{t(s+t)}{3m^2_{\tilde{G}}}$	$\frac{t(s+t)}{3m^2_{\tilde{G}}}$
LT	$2\frac{t(s+t)}{3m^2_{\tilde{G}}}$	$\frac{t(s+t)}{3m^2_{\tilde{G}}}$
TT	$-2\frac{t(s+t)}{3m^2_{\tilde{G}}}$	$-2\frac{t(s+t)}{3m^2_{\tilde{G}}}$
Total contribution	0	$-\frac{t(s+t)}{3m^2_{\tilde{G}}}$

Massless gauge boson:

$$\sum_r \epsilon_\alpha^{a(r)}(k)\epsilon_\nu^{l(r)*}(k) = -\left(\eta_{\alpha\nu} - \frac{k_\alpha \eta_\nu + k_\nu \eta_\alpha}{k\eta}\right)\delta^{al} := T + L \quad (1)$$

Massive gauge boson:

$$\sum_r \epsilon_\alpha^{a(r)}(k)\epsilon_\nu^{l(r)*}(k) = -\left(\eta_{\alpha\nu} - \frac{k_\alpha k_\nu}{m_W^2}\right)\delta^{al} := T + L \quad (2)$$

<0| WW scattering: the basis of gauge eigenstates |0>

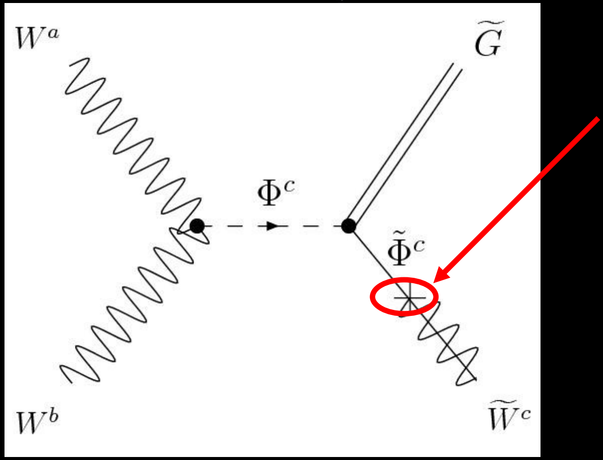
What is missing? Should we add the contribution of the Higgs?

The rise of a problem: the coupling terms between gravitino and supercurrent in the general Supergravity Lagrangian

$$\mathcal{L}_{\psi J} = -\frac{i}{\sqrt{2}M_{Pl}}\left(\widetilde{\mathcal{D}}_\nu \phi^{*j}\bar{\psi}_\nu \gamma^\mu \gamma^\nu \chi_L^j - \widetilde{D}_\nu \phi^j \bar{\chi}_R^j \gamma^\nu \gamma^\mu \psi_\nu\right) - \frac{i}{8M_{Pl}}\bar{\psi}_\mu \left[\gamma^\nu, \gamma^\rho\right] \gamma^\mu \lambda^{(a)} F_{\nu\rho}^{(a)},$$

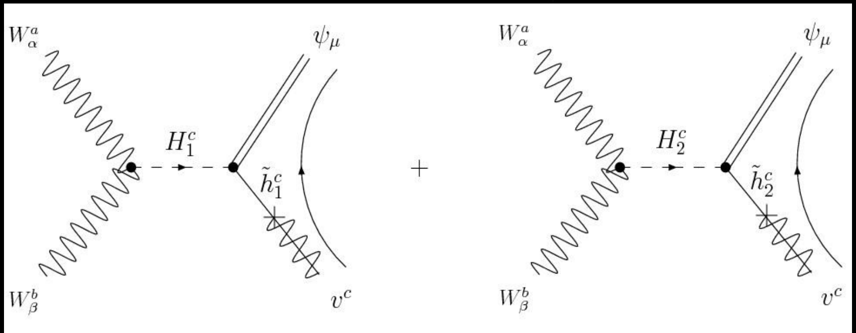
do not admit any scalar-gravitino-gaugino vertex.

We must then use the method of **mass insertions:**

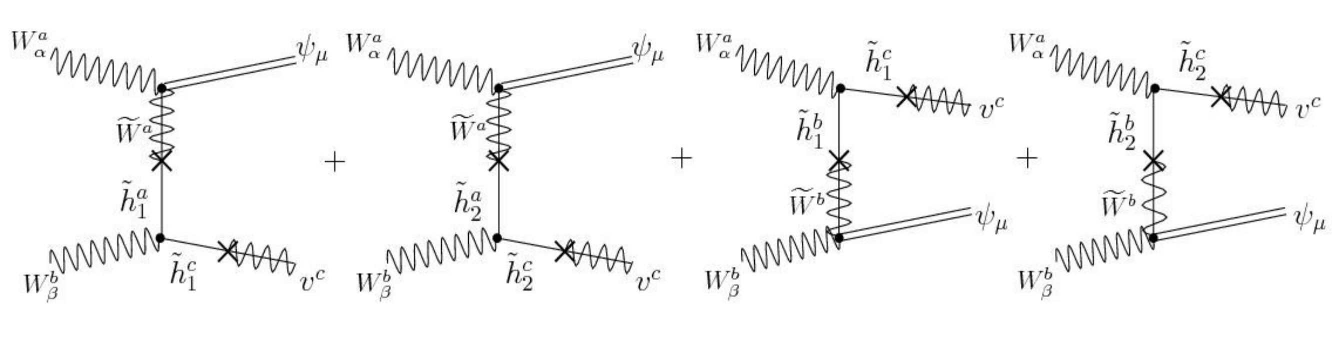


<0| WW scattering: the basis of gauge eigenstates |0>

New diagrams appear:

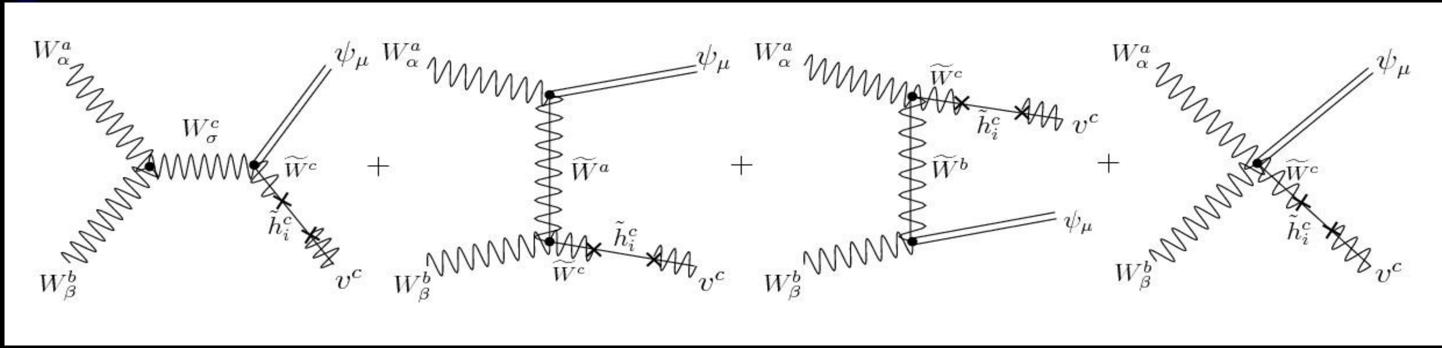


annihilation into Higgses: $M^{(H)}$



mixing of winos and higgsinos in the t and u channels: $M^{(1)}$

diagrams with two mass insertions in the external leg: $M^{(2)}$



<0| WW scattering: the basis of gauge eigenstates |0>

Consequently, the total amplitude has the following expression:

$$\mathcal{M}(W^a + W^b \longrightarrow \widetilde{W}^c + \widetilde{G}) = M^{(0)} + M^{(1)} + M^{(H)} + M^{(2)}$$

where the original amplitude, with no mass insertions, has been labeled with $M^{(0)}$

Result:

$$|\mathcal{M}|^2 \approx \frac{1}{4}\left(\frac{s^3}{3m_{\widetilde{W}}^2 m_{\widetilde{G}}^2} - \frac{s^2}{3m_{\widetilde{W}}^2}\right) - \frac{3s^2+16st+16t^2}{12m_{\widetilde{G}}^2} - \left(\frac{m_W^2}{m_{\widetilde{W}}^2}\right)\frac{s^2+6st+6t^2}{3m_{\widetilde{G}}^2} + - 4\left(\frac{m_W^4}{m_{\widetilde{W}}^4}\right)\frac{t(s+t)}{3m_{\widetilde{G}}^2}$$

The Higgses contribute to the original anomaly and provide with new divergences.

It has been shown that there is no cancellation of the anomalies found in the scattering of massive W bosons, neither by including the Higgs and considering higher orders in a perturbation theory developed around a mass parameter. Within the MSSM, there is no other suitable particle.

<0| WW scattering: the basis of mass eigenstates |0>

$$W^+ + W^- \longrightarrow \widetilde{\chi}_i^0 + \widetilde{G}$$

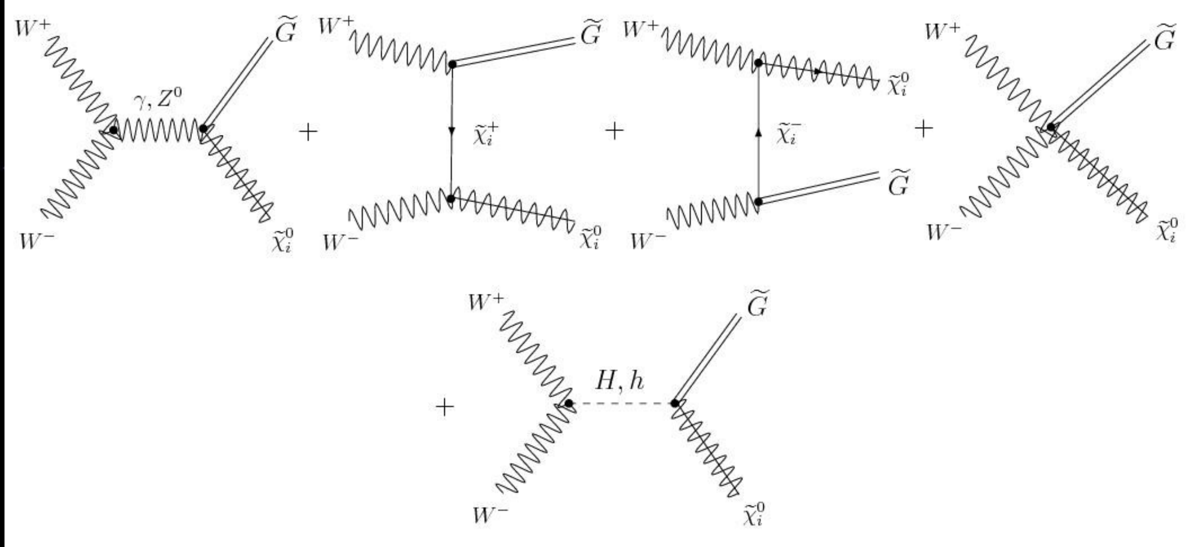


FIG. 8: The WW scattering in the basis of mass eigenstates

Result:

same anomalies as before.

Moreover, **new terms** emerge.

$$\sum_{spin}|\mathcal{M}|^2 = 4\frac{g^2}{M_P^2}|N_{\widetilde{W}i}|^2\left[\frac{1}{3m_W^2}(s+t)^2 - \left(\frac{m^2_{\widetilde{\chi}^0_i}}{3m_W^2}\right)\frac{t(s+t)}{3m^2_{\widetilde{G}}} - \frac{t(s+t)}{3m^2_{\widetilde{G}}}\right]$$

$$\sum_{spin}(M_H M_u^* + M_u M_H^*) = \frac{g^2}{M_P^2}\left[N'_{\tilde{h}i}\sin(\beta-\alpha) + N'_{\tilde{H}i}\cos(\beta-\alpha)\right] V^*_{j\widetilde{\chi}^+} O^{R*}_{ij}\left[-\frac{2}{3m^2_{\widetilde{G}}}\left(\frac{m_{\widetilde{\chi}^0_i}}{m_W}\right) st\right]$$

Conclusions and perspectives

- We have calculated WW scattering in Supergravity (SUGRA), namely:

$$W^a + W^b \longrightarrow \widetilde{W}^c + \widetilde{G} \qquad W^+ + W^- \longrightarrow \widetilde{\chi}_i^0 + \widetilde{G}$$

- It turns out that, in the squared amplitude, unitarity is preserved at any scale only if the W bosons are considered massless. In they are massive, new terms, the so-called "anomalies" which would violate unitarity, are generated.

- The result holds in both the bases of gauge and mass eigenstates, due to the non vanishing mass of the W boson, which affects the longitudinal modes of the Ws and their couplings with the gravitino. Moreover, in the MSSM the Higgs bosons do not cure the problem, but contribute with new divergences.

- We may need to understand this result more deeply, first of all from a formal point of view, as it is unexpected in the context of SUGRA theories and may provide with interesting theoretical issues.

- From a more phenomenological perspective, this production channel of gravitinos can be observed as a secondary reaction at the LHC (through e.g. gluon-fusion), with the related implications in the context of Cosmology.

→ Work in Progress!

Thank you very much