Outline Introduccin Motivation Spinor Helicity Formalism Applications Gravitino Monophoton signal in LSP gravitino production Conclusions

GRAVITINO PHENOMENOLOGY WITH THE SPINOR HELICITY FORMALISM

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SILAFAE XI La Antigua, Guatemala

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SILAFAE XI

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Outline

- Introduction and Motivation,
- The Spinor Helicity Formalism,
- Application,
- Final Comments.

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tivation	

"Scattering experiments are crucial to understand the fundamental blocks in nature".

The Standard Model of elementary particles was developed largely because scattering experiments, (the discovery the gauge bosons W^{\pm} y Z^{0} and the gluons and quarks and more recently the Higgs bosons).

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Motivation

The principal physical observable in the scattering experiments

is the differential cross section (DCS) $\frac{d\sigma}{d\Omega}$.

Interpretation of DATA from scattering experiments is based mainly in the theoretical predictions of the cross section which are computed with QFT methods.

The DCS that connects theory with experiments is proportional to the modulus squared of the scattering amplitude

$$\frac{d\sigma}{d\Omega} \propto |\mathcal{A}|^2.$$

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Motivation	

There are several computer programs that undoubtedly help computing the scattering amplitudes (*MadGraph, Form, FeynRules, FeynCalc*, among others), most of them numerically. For example to analytically compute $\tilde{t} \rightarrow b W G$ (with the LSP 3/2-spin gravitino particle):

 $\tilde{t}_1 \rightarrow b + W + \tilde{\Psi}_u$



Figure 1. top diagram

Figure 2. sbotom diagram

 ${\bf Figure \ 3.} \ {\rm chargino \ diagram}$

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Lorenzo Diaz-Cruz & Bryan Larios-Lopez, EPJC (2016) 76:157.

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Considering just one channel and using Mathematica one obtain for the chargino $|\overline{M_{1\chi}}|^2$.

Tr83 + tr831 + mg (tr832 + tr833 + mg tr834)

$$\begin{split} & \frac{1}{1+q} - \frac{1}{q} \int_{0}^{1} \int_{0}^{1} (\log m_{1} + \log m_{1}^{2} + \log$$

 $\left\{P_{j} \, S_{j} + P_{j} \, S_{j}\right\} \left((\text{V12 } \sin(\beta) - \text{U12 } \cos(\beta)) \, (\text{U12 } \cos(\beta) + \text{V12 } \sin(\beta)) - r_{j} \, \Lambda_{ij} \right) (f_{ij})^{2} + \frac{1}{2} \left(\frac{1}{2} + \frac{1}{2} +$

 $(P_1, S_1 + P_1, S_2)$ [(V12 sin(β) - U32 cos(β)) (U32 cos(β) + V12 sin(β)) - v_1, S_2 [((f_2)² + $\frac{1}{1-2}q_0 l^2 \left[(|U|2\cos(\beta) + V|2\sin(\beta)|^2 - (V|2\sin(\beta) - U|2\cos(\beta))^2 \right] (P, P_1 + S, S_1) - \frac{1}{1-2}q_0 l^2 \left[(|P_1|P_1 + S, S_1| - U|2\cos(\beta))^2 \right] (P, P_1 + S, S_1) - \frac{1}{1-2}q_0 l^2 \left[(|P_1|P_1 + S, S_1| - U|2\cos(\beta))^2 \right] (P, P_1 + S, S_1) - \frac{1}{1-2}q_0 l^2 \left[(|P_1|P_1 + S, S_1| - U|2\cos(\beta))^2 \right] (P, P_1 + S, S_1) - \frac{1}{1-2}q_0 l^2 \left[(|P_1|P_1 + S, S_1| - U|2\cos(\beta))^2 \right] (P, P_1 + S, S_1) - \frac{1}{1-2}q_0 l^2 \left[(|P_1|P_1 + S, S_1| - U|2\cos(\beta))^2 \right] (P, P_1 + S, S_1) - \frac{1}{1-2}q_0 l^2 \left[(|P_1|P_1 + S, S_1| - U|2\cos(\beta))^2 \right] (P, P_1 + S, S_1) - \frac{1}{1-2}q_0 l^2 \left[(|P_1|P_1 + S, S_1| - U|2\cos(\beta))^2 \right] (P, P_1 + S, S_1) - \frac{1}{1-2}q_0 l^2 \left[(|P_1|P_1 + S, S_1| - U|2\cos(\beta))^2 \right] (P, P_1 + S, S_1) - \frac{1}{1-2}q_0 l^2 \left[(|P_1|P_1 + S, S_1| - U|2\cos(\beta))^2 \right] (P, P_1 + S, S_1) - \frac{1}{1-2}q_0 l^2 \left[(|P_1|P_1 + S, S_1| - U|2\cos(\beta))^2 \right] (P, P_1 + S, S_1) - \frac{1}{1-2}q_0 l^2 \left[(|P_1|P_1 + S, S_1| - U|2\cos(\beta))^2 \right] (P, P_1 + S, S_1) - \frac{1}{1-2}q_0 l^2 \left[(|P_1|P_1 + S, S_1| - U|2\cos(\beta))^2 \right] (P, P_1 + S, S_1) - \frac{1}{1-2}q_0 l^2 \left[(|P_1|P_1 + S, S_1| - U|2\cos(\beta))^2 \right] (P, P_1 + S, S_1) - \frac{1}{1-2}q_0 l^2 \left[(|P_1|P_1 + S, S_1| - U|2\cos(\beta))^2 \right] (P, P_1 + S, S_1) - \frac{1}{1-2}q_0 l^2 \left[(|P_1|P_1 + S, S_1| - U|2\cos(\beta))^2 \right] (P, P_1 + S, S_1) - \frac{1}{1-2}q_0 l^2 \left[(|P_1|P_1 + S, S_1| - U|2\cos(\beta))^2 \right] (P, P_1 + S, S_1) - \frac{1}{1-2}q_0 l^2 \left[(|P_1|P_1 + S, S_1| - U|2\cos(\beta))^2 \right] (P, P_1 + S, S_1) - \frac{1}{1-2}q_0 l^2 \left[(|P_1|P_1 + S, S_1| - U|2\cos(\beta))^2 \right] (P, P_1 + S, S_1) - \frac{1}{1-2}q_0 l^2 \left[(|P_1|P_1 + S, S_1| - U|2\cos(\beta))^2 \right] (P, P_1 + S, S_1) - \frac{1}{1-2}q_0 l^2 \left[(|P_1|P_1 + S, S_1| - U|2\cos(\beta))^2 \right] (P, P_1 + S, S_1) - \frac{1}{1-2}q_0 l^2 \left[(|P_1|P_1 + S, S_1| - U|2\cos(\beta))^2 \right] (P, P_1 + S, S_1) - \frac{1}{1-2}q_0 l^2 \left[(|P_1|P_1 + S, S_1| - U|2\cos(\beta)) \right] (P, P_1 + S, S_1) - \frac{1}{1-2}q_0 l^2 \left[(|P_1|P_1 + S, S_1| - U|2\cos(\beta)) \right] (P, P_1 + S, S_1) - \frac{1}{1-2}q_0 l^2 \left[(|P_1|P_1 + S, S_1| - U|2\cos(\beta)) \right] (P, P_1 + S, S_1) - \frac{1}{1-2}q_0 l^2 \left[(|P_1|P_1 + S, S_1| - U|2\cos(\beta)) \right] (P, P_1 + S, S_1) - \frac{1}{1-2}q_0 l^2 \left[(|P_1|P_1 + S, S_1| - U|2\cos(\beta)) \right] (P, P_1$ $(P_1,S_1+P_1,S_1)\left[(\text{Vi2}\sin(\beta)-\text{Ui2}\cos(\beta))(\text{Ui2}\cos(\beta)+\text{Vi2}\sin(\beta))-\nu_1,S_2\right]\left[(f_1)^2\right]$ $\frac{1}{3 \log_2 m_1^2} 2 f_2 q_1^{-2} \left(\right) (132 \cos(\beta) + V12 \sin(\beta))^2 - (V12 \sin(\beta) - 132 \cos(\beta))^2 \right) \left(\rho, P_1 + \delta, S_1 \right) - \left(12 \log(\beta) + 12 \log(\beta) \right) \left(\rho, P_1 + \delta, S_1 \right) + \left(12 \log(\beta) + 12 \log(\beta) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) + \left(12 \log(\beta) + 12 \log(\beta) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) + \left(12 \log(\beta) + 12 \log(\beta) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \right) \left(12 \log(\beta) + 12 \log(\beta) \right) \left$ $(P_1,S_1+P_1S_2)\left[(\text{Vi2}\sin(\beta)-\text{U3}2\cos(\beta))(\text{U3}2\cos(\beta)+\text{Vi2}\sin(\beta))-\nu_1S_2\right]((f_1)^2-\nu_2S_2)\left[((f_1)^2-(f_1)^2+(f_2)^2+$ $\frac{30}{2} \left[\left[(U_1^2 \cos(\beta) + V_1^2 \sin(\beta))^2 - (V_1^2 \sin(\beta) - U_2^2 \cos(\beta))^2 \right] (P, P_1 + S, S_1) \right]$ $(P_1,S_1+P_1S_2)\left[(\text{Vi2}\sin(\beta)-\text{U3}2\cos(\beta))(\text{U3}2\cos(\beta)+\text{Vi2}\sin(\beta))-\nu_1S_2\right]((f_1)^2-\nu_2S_2)\left[(f_2)^2-(f_1)^2+(f_2)^2+($ wij. 11032 cest(0) + Vi2 sin(80² - (Vi2 sin(2) - Ui2 cest(0)²)(P, P, + 3.5.) -(#.5. + F.5.) (2021 abov) = 132 cmc/(1) (132 cmc/(1) + V/2 abov((1) - x. A.]) (...) $8.m_1^2\left[\frac{1}{2}\right] 112\cos(\beta) + V12\sin(\beta)^2 - (V12\sin(\beta) - 112\cos(\beta))^2\left[(\beta,\beta_1+2,S_1) - (12\cos(\beta))^2\right](\beta,\beta_2+2,S_2) - (12\cos(\beta))^2\left[(\beta,\beta_2+2,S_2) - (12\cos(\beta))^2\right](\beta,\beta_2+2,S_2)\right]$ $(P_1, S_1 + P_1, S_1)$ [(Vi3 sin(p) - U32 ces(p)) (U32 ces(p) + Vi2 sin(p)) - r_1 A_0] (fr $\frac{1}{2}f_{1}\left[\frac{1}{2}U(2\cos(\beta) + V(2\sin(\beta)^{2} - (V(2\sin(\beta) - U(2\cos(\beta))^{2}))]F_{1}F_{2} + S_{1}S_{2}\right] (P_1S_1 + P_1S_2)$ [(V12 sin(β) - 132 cos(β)) (132 cos(β) + V12 sin(β) - v_1S_2 [(f_2 + $-f_2 \hat{f}_1 \hat{f}_1 \hat{X} \hat{f}_2 \cos(\beta t + V \hat{f}_2 \sin(\beta t)^2 - (V \hat{f}_2 \sin(\beta t - U \hat{f}_2 \cos(\beta t)^2) \hat{f}_2 F_1 + S_1 S_2)$ $(P_1, S_1 + P_1, S_2)$ [(V)2 sin(β) - U(2 cos(β)) (U(2 cos(β) + V)2 sin(β)) - $v_1 A_0$](f_2 + $- \frac{1}{2} \int_{0}^{2} \left(\left[(UZ \cos(\beta) + VZ \sin(\beta))^{2} - (VZ \sin(\beta) - UZ \cos(\beta))^{2} \right] (P, P, + 5, 5) \right)$ $(P,S_1+P,S_2)\left[({\rm Vi2}\sin(p)-{\rm Ui2}\cos(p))\,({\rm Ui2}\cos(p)+{\rm Vi2}\sin(p))-\nu_f\,A_2\right](f_1+{\rm Ui2}\sin(p))-\nu_f\,A_2)\right](f_2+{\rm Ui2}\sin(p))$ $m_{11}^{0}([0.012 \cos(\beta 0 + V12 \sin(\beta 0)^{2} - (V12 \sin(\beta 0 - U12 \cos(\beta 0)^{2})(P, P_{1} + S, F_{2}))$ (P.5.+ P.5.) (V)2 sin(P - U)2 cos(P) (U)2 cos(P + V)2 sin(P) - r. A. [] w¹. w¹ [[[132 cost(0) + V(2 sin(2))² - (V(2 sin(0) - 132 cost(2))²](P. P. + S. S.). (P. 5 + P. 5) [(V)2 sin(P - U)2 ces(P) (U)2 ces(P + V)2 sin(P) - r, A_0]] + - 5. w² (30)2 cost(0 + V(2 sin(2))² - (V(2 sin(3) - U(2 cost(0)²)(P, P, + 5, 3))

 $\frac{1}{1-4} + \frac{1}{2} \left[\frac{1}{2} (U_1^2 \cos(\beta) + V_1^2 \sin(\beta))^2 - (V_1^2 \sin(\beta) - U_1^2 \cos(\beta))^2 \right] (P, P_1 + 5, \mathbb{F}_2) - \frac{1}{2} + \frac{1}{2} \left[\frac{1}{2} + \frac{1}{2}$

$$\begin{split} & f = \int_{0}^{1} \int_{0}^{\infty} \log \left[\log \log(n) + V \ln \log(n) - V \ln \log(n) - V \ln \log(n) + \int_{0}^{1} \int_{0}^{1} \int_{0}^{1} \log \left[\log \log(n) + V \ln \log(n) + V \ln \log(n) + V \ln \log(n) + \int_{0}^{1} \log \left[\log \log(n) + V \ln \log(n) + \int_{0}^{1} \int_{0}^{1} \int_{0}^{1} \log \left[\log \log(n) + V \ln \log(n) + V \ln \log(n) + V \ln \log(n) + \int_{0}^{1} \int_{0}^{1} \int_{0}^{1} \int_{0}^{1} \log \left[\log \log(n) + V \ln \log(n) + \int_{0}^{1} \log \left[\log (n) + \int_{0}^{1} \log (n) + \int_$$

$$\begin{split} & \frac{4}{9} q_1^{-1} w_{1,1}^{-1} [(1) \mathbb{E} 2 \cos(\beta) + \mathbb{V} 2 \sin(\beta)^2 - (\mathbb{V} 2 \sin(\beta) - \mathbb{E} 2 \cos(\beta) t^2](\beta, P_1 + S, S_1) - (P_1 + S_1 + P_2 + S_1) [(1) \mathbb{E} 2 \cos(\beta) + \mathbb{V} 2 \sin(\beta) - v_1 / S_1)] - (P_1 + S_1 + S_1) [(1) \mathbb{E} 2 \cos(\beta) + \mathbb{V} 2 \sin(\beta) - v_1 / S_1)] - (P_1 + S_1 + \mathbb{V} 2 \sin(\beta) - \mathbb{V} + \mathbb{V} 2 \sin(\beta) - v_1 / S_1)] - (P_1 + S_1 + \mathbb{V} + \mathbb{V$$

 $\left(P_1X + P_1X\right)\left(|XXI\sin(\beta) - XXI\cos(\beta)||XXI\sin(\beta) - v_1A_1|\right)$ $m_{f} \left[4 m_{f} \left[-\frac{1}{2 m_{f}^{2} m_{f}^{2}} 2 \left[(512 \cos q) + Vi2 \sin q) q^{2} - (Vi2 \sin q) - Ui2 \cos q) q^{2} \right] (F, F_{f} + 5, T_{f}) - Vi2 \sin q q - Ui2 \cos q) q^{2} \right]$ [P.5.+P.5.] [(V[2 sin(0 - U[2 cos(0) / U[2 cos(0 + V[2 sin(0) - v. A_{2}]])/5]² $\frac{1}{1\,\mathrm{sel}} 2 \left[(U2\cos(\beta) + V2\sin(\beta))^2 - (V2\sin(\beta - U2\cos(\beta))^2) (P, P_1 + S, F_2) - (V2\sin(\beta - U2\cos(\beta))^2) (P, P_1 + S, F_2) \right]$ $\{P_1,S_1+P_1,S_2\}\{(\forall 12\sin(\beta)-U12\cos(\beta))|(U12\cos(\beta)+\forall 12\sin(\beta))-\nu_1,S_2\}\{(f_2)^2+(f_$ 20100 $V(2 \sin(05)^2 - (V(2 \sin(05) - U(2 \cos(05)^2))[P_1P_2 + S_1S_2] -$ 17-5 + P.5.1 (VI2 sin(R - UI2 cos(R) / UI2 cos(R + VI2 sin(R) - r. A.1)(5)² $\frac{1}{2} \left[\left[U[2] \cos(\beta) + V[2] \sin(\beta) \hat{r} - (V[2] \sin(\beta) - U[2] \cos(\beta) \hat{r} \right] (P, P_1 + S, S_1) \right] \right]$ (P, A + P, S) (V)2 similar - U(2 contributing contribu * *** 10512 conth + Yi2 sinth* - (Yi2 sinth - Vi2 conth*1(P, P, + S, Z)) $[P_1,S_1+P_1,S_2]\left\{(V(2\sin(\beta)-U(2\cos(\beta)))(U(2\cos(\beta)+V(2\sin(\beta))-\nu_1,A_2))+\right.$ $\frac{4}{2} f_1([0.312 \cos(\beta) + V12 \sin(\beta))^2 - (V12 \sin(\beta) - U12 \cos(\beta))^2] [P, P_1 + S, S_1]$ $\left[P_{1}S_{1}+P_{1}S_{2}\right]\left[\left(\mathsf{VI2}\sin(\beta)-\mathsf{UI2}\cos(\beta)\right)\left[\mathsf{UI2}\cos(\beta)+\mathsf{VI2}\sin(\beta)\right)-r_{1}S_{2}\right]\right]+$ $= \left(\left| \left| \sum_{i=1}^{n} \cos(\beta_i^2) + \sum_{i=1}^{n} \sin(\beta_i^2)^2 - \left(\sum_{i=1}^{n} \sin(\beta_i^2) - \sum_{i=1}^{n} \cos(\beta_i^2)^2 \right) \left(P_i P_j + \hat{x}_i S_j \right) \right) \right)$ $\frac{1}{2\,\mathrm{sd}_2} 2\,\mathrm{sd}_2 \left[[3.52\,\mathrm{sm}_2 0] + \mathrm{Vi2}\,\mathrm{sing}(0^2 - \mathrm{Vi2}\,\mathrm{sing}(1 - \mathrm{Ui2}\,\mathrm{sm}_2 0^2)] \left[P_1 P_2 + S_1 T_2 \right] \right]$ [P.A + P.S.] (Yes shot) - Videouth UR anoth + Yes shoth - e.A. [104] + Inj.m. V12xin(012 - (V12xin(0) - U12xin(012))[A, P, + 5, 5,]-(P.A.+ P.S.) (Yi2 shoft - U3 south 102 south + Yi2 shoft - e.A. [IGA] $\frac{1}{2 \min_{k} m_{1}} 2 f_{1}([3.02 \cos(\beta) + V12 \sin(\beta)]^{2} - (V12 \sin(\beta) - U12 \cos(\beta))^{2}) [P, P_{1} = 5, 5] - \frac{1}{2 \min_{k} m_{1}} 2 f_{1}([3.02 \cos(\beta) + V12 \sin(\beta)])^{2} - (V12 \sin(\beta) - U12 \cos(\beta))^{2} - (V12 \sin(\beta) + U12 \cos(\beta))^{2} - (V12 \cos(\beta) + (V12 \cos(\beta) + U12 \cos(\beta))^{2} - (V12 \cos(\beta) + (V12 \cos(\beta) + (V12 \cos(\beta) + (V12 \cos(\beta)))^{2} - (V12 \cos(\beta) + (V12 \cos(\beta)))^{2} - (V12 \cos(\beta) + (V12 \cos(\beta)))^{2} - (V12 \cos(\beta))^{2} - (V12 \cos(\beta) + (V12 \cos(\beta)))^{2} - (V12 \cos(\beta) + (V12 \cos(\beta)))^{2} - (V12 \cos(\beta))^{2} - (V12 \cos(\beta$ $[P_{-}S_{1}+P_{-}X_{1}][[V]I]\sin[qq]-UII\cos[qD_{1}UII\cos[qq]+VII]\sin[qD_{1}-r_{1}A_{1}]][QII^{2}-r_{1}A_{1}][QII^{2}-r_{1}A_{2}][QII$ $\frac{1}{1.m} 2 \left[\left[(112\cos(p_1^2 + V12\sin(p_1^2) - (V12\sin(p_1^2 - U12\cos(p_1^2)^2)(P_1, P_1 + S_1S_1) - U12\cos(p_1^2)^2 \right] \right] \right]$ [P.5.+P.5] [W2 sint3 - U2 cos(2) (U2 cos(3 + V2 sint3) - r.A. [1(5)] $\frac{8}{2} m_{ij} \left[\left[U U 2 \cos(\beta) + V 12 \sin(\beta) \right]^2 - \left(V 12 \sin(\beta) - U 12 \cos(\beta) \right]^2 \right] \left(P, P_1 + S, S_1 \right) \right]$

$$\begin{split} & \left[P,S,+P,S\right]\left(1^{2}\Omega^{2}\sin(\beta)-U\Omega^{2}\cos(\beta)U\Omega^{2}\cos(\beta)+V\Omega^{2}\sin(\beta)-r_{1},h_{0}\right]\left(f\right)-\\ & \frac{4}{3}m_{0}^{2}\left(\left[U\Omega^{2}\cos(\beta)+V\Omega^{2}\sin(\beta)^{2}-(V\Omega^{2}\sin(\beta)-U\Omega^{2}\cos(\beta)^{2}\right]\left(f,P_{1}+S,Z\right)- \right. \end{split}$$

 $(P_1 S_1 + P_1 S_2)$ $(Vi2 single - Ui2 cost f(t) (Ui2 cost f(t) + Vi2 single) - v_2 S_2)$ $-m_{11}^2m_{21}(0)U(2\cos(\beta) + V(2\sin(\beta))^2 - (V(2\sin(\beta) - U(2\cos(\beta))^2)(P_1P_1 + S,S_1))$ $(P_1S_1 + P_1S_2)(Vi2 \operatorname{single} - Ui2 \operatorname{cost}(0)(Ui2 \operatorname{cost}(0) + Vi2 \operatorname{single}) - v_2S_2))$ $\frac{n}{2}\int_{\mathbb{T}}m_{\tilde{Q}_{1}}\left[\left|\left|\mathcal{M}(2\cos(\beta)+V(2\sin(\beta))-V(2\sin(\beta))-V(2\sin(\beta))\right|\right]\left|P,P_{1}+S,S_{1}\right|\right]$ $(P_1S_1 + P_1S_2)(|V|2 \sin(\beta) - U|2 \cos(\beta))(U|2 \cos(\beta) + V|2 \sin(\beta)) - v_1A_2|)$ $\stackrel{0}{=} f_{1} m_{1} \left[(31) (2 \cos(\beta) + V) (2 \sin(\beta))^{2} - (V) (2 \sin(\beta) - U) (2 \cos(\beta))^{2} \right] (P, P, + 3.5)$ $(P_1S_1 + P_1S_2)(|\nabla i2 \sin(\beta) - U2\cos(\beta))(U2\cos(\beta) + V2\sin(\beta) - v_1S_2))$ 4 [](U2 cost() + V2 sin(2)² - (V2 sin(2) - U2 cost(2)²)(2; P₁ + S, S) + (P, S + P, S) (VI2 sin(d) – UI2 con(d) (UI2 con(d) + VI2 sin(d)) – v. A₁ (1(6)) $\frac{1}{3 \text{ m}_{0}^{2}} 2 m_{\widetilde{Q}} \left[\left| (112 \cos(\beta) + \text{Vi2} \sin(\beta))^{2} - (\text{Vi2} \sin(\beta) - \text{Ui2} \cos(\beta))^{2} \right| \left(P, P \right) + \delta_{1} S_{0} \right] \right]$ $-2 f_1 || (112 \cos(\beta) + Vi2 \sin(\beta))^2 - (Vi2 \sin(\beta) - Ui2 \cos(\beta))^2 || P_1 P_1 + S_1 S_1 ||$ 3 44, 44, $(P_1, S_1 + P_1, S_2)$ (Vi2 sin(β) - Ui2 cos(β) (Ui2 cos(β) + Vi2 sin(β) - $v_1 X_2$ () (f_2)² $-2f_2[(1)12\cos(\beta) + Vi2\sin(\beta))^2 - (Vi2\sin(\beta) - Ui2\cos(\beta))^2)[\beta; \beta] + 5(\beta_1) +$ 3 10 10 $(P_1S_1 + P_1S_2)|||V||2 \sin(\beta) - U||2 \cos(\beta)||U||2 \cos(\beta) + V||2 \sin(\beta)| - v_1S_2|||(f_1)|^2$ $\frac{1}{2 \min} 2 \left| \left| \left(132 \cos(\beta) + V12 \sin(\beta) \right)^2 - \left(V12 \sin(\beta) - 132 \cos(\beta) \right)^2 \right| \left(P, P \right) + S, S \right) + \right.$ (P, A + P, S) (V2 since - U2 cost (0.052 cost (0 + V2 since - v, A))(6)² $\frac{8}{-\pi_{1,1}}[(U2\cos(\beta) + V2\sin(\beta))^{2} - (V2\sin(\beta) - U2\cos(\beta))^{2}](P, P_{1} + S, S_{1}) +$ $(P_1, S_1 + P_1S_2)$ (Vi2 sin(β) - Ui2 cos(β) (Ui2 cos(β) + Vi2 sin(β) - $v_1 \Lambda_0$ [(f_2 $-m_1^2$ [[] U[2 cos(β) = V[2 sin(β U]² - (V[2 sin(β) - U[2 cos(β U]²] [P, P, + S, S,] + $(P_1S_1 + P_1S_2)$ (Vi2 sin(β) - Ui2 cos(β) (Ui2 cos(β) + Vi2 sin(β)) - v_1A_2 () - m1, m, (10) (2 cm (2) + V(2 sim(2))² - (V(2 sim(2)) - U(2 cm (2))²) (P, P, + X, S,) = $(P_1S_1 + P_1S_2)(|\nabla \Omega \sin(\beta) - U\Omega \cos(\beta))(|\Omega 2\cos(\beta) + \nabla \Omega \sin(\beta)) - v_1A_2|) +$ $\frac{4}{\pi}f_1 \approx_{\mathcal{H}} \left[\left(U \Omega \cos(\beta) + V \Omega \sin(\beta) \right)^2 - \left(V \Omega \sin(\beta) - U \Omega \cos(\beta) \right)^2 \right] \left(P, P_1 + S, S_1 \right) + \\$ $(P, S, +P, S)/(N/2 \sin(\beta) - U/2 \cos(\beta))/(U/2 \cos(\beta) + N/2 \sin(\beta)) - v, \Lambda_0))$ $\frac{4}{2}f_{2}m_{[1]}([3Ul2\cos(p) + Vl2\sin(p)]^{2} - (Vl2\sin(p) - Ul2\cos(p)^{2})(P, P, + S, S)) +$

 $(P_1, S_1 + P_1, S_2)$ (Vi2 single - Ui2 cos(β U (Ui2 cos(β) + Vi2 sin(β U - v_2, S_3))

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The spinor helicity formalism (SHF) (a pragmatic point of view) Notation

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Spinor Helicity Formalism (a pragmatic point of view)



Massless Case (textbooks)

The SHF is based in the following observation:

Fields with spin-1 transform in the $(\frac{1}{2}, \frac{1}{2})$ representation of the Lorentz group.

So we are able to express the 4-momentum of any particle as a biespinor: $p_{\mu} \rightarrow p_{a\dot{a}}$

$$p_{a\dot{a}} = p_{\mu}\sigma^{\mu}_{a\dot{a}} \qquad (1) \qquad u_{-}(\vec{p}) = \begin{pmatrix} \phi_{a} \\ 0 \end{pmatrix}$$

$$u_{-}(\vec{p})\bar{u}_{-}(\vec{p}) = \frac{1}{2}(1-\gamma_{5})(-p) = \begin{pmatrix} 0 & -p_{a\dot{a}} \\ 0 & 0 \end{pmatrix} \qquad p_{a\dot{a}} = -\phi_{a}\phi^{*}_{\dot{a}} \qquad (2)$$

$$= -\phi_{a}\phi^{*}_{\dot{a}} \qquad (2)$$

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The key of the SHF is to considerate ϕ_a as the fundamental object and express the momenta of the particles in terms of ϕ_a .

Highly convenient and powerful notation

If p and k are the momenta and ϕ_a , κ_a their associated spinors, we can define the following products of spinors:

$$[pk] = \phi^a \kappa_a = \bar{u}_+(\vec{p})u_-(\vec{k}) = -[kp]$$
(3)

$$\langle pk \rangle = \phi_{\dot{a}}^* \kappa^{*\dot{a}} = \bar{u}_-(\vec{p})u_+(\vec{k}) = -\langle kp \rangle \tag{4}$$

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Massless Dirac Spinor and Polarization vectors

$$\begin{aligned} |p] &= u_{-}(\mathbf{p}) = v_{+}(\mathbf{p}) ,\\ |p\rangle &= u_{+}(\mathbf{p}) = v_{-}(\mathbf{p}) ,\\ [p] &= \overline{u}_{+}(\mathbf{p}) = \overline{v}_{-}(\mathbf{p}) , \end{aligned}$$

$$\langle p| = \overline{u}_{-}(\mathbf{p}) = \overline{v}_{+}(\mathbf{p}) \; .$$

With the spinor products

$$\bar{u}_{-}(\vec{p}) u_{-}(\vec{k}) = 0$$
 (5)

$$\bar{u}_{+}(\vec{p}) u_{+}(\vec{k}) = 0$$
 (6)

$$\varepsilon^{\mu}_{+}(k) = -\frac{\langle q | \gamma^{\mu} | k]}{\sqrt{2} \langle q | k \rangle} ,$$

$$\varepsilon^{\mu}_{-}(k) = -\frac{|q|\gamma^{\mu}|k\rangle}{\sqrt{2}[q\,k]} ,$$

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$$\langle pk] = [pk\rangle = 0 \tag{7}$$

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Some properties of spinors products that are needed to compute scattering amplitudes are the following:

 $\langle i|\gamma_{\mu}|j] = [j|\gamma_{\mu}|i\rangle,$ [ij] = -[ji], $\langle i|\gamma_{\mu}|j]\langle k|\gamma^{\mu}|l] = 2\langle ik\rangle[lj],$ $\langle ij \rangle = [ji]^*,$ $\langle ab \rangle \langle cd \rangle = \langle ac \rangle \langle bd \rangle + \langle ad \rangle \langle cb \rangle,$ $\langle ij \rangle [ji] = \langle ij \rangle \langle ij \rangle^* = |\langle ij \rangle|^2,$ $\sum \langle ik \rangle [kj] = 0,$ $\langle ij \rangle [ji] = -2k_i \cdot k_j = s_{ij},$ Bryan Larios SILAFAE XI

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What about massive particles ?

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Light Cone Decomposition (LCD)

Let \mathbf{p}^{μ} be any time-like 4-momentum, we can decompose it into 2 light-like four momenta as follows.

$$p^{\mu} \equiv r^{\mu} + \alpha q^{\mu} \qquad . \tag{8}$$

 $\langle a | \gamma^{\mu} | r]$

Two body NLSP Stop decay $(\tilde{t} \rightarrow t \tilde{G})$

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Gravitino wave functions	

We will consider a model in a local supersymmetric field theory ($\mathcal{N} = 1$ SUGRA) where the gravitino is the lightest supersymmetric particle (LSP), therefore a good DM candidate.

$$\begin{split} \tilde{\Psi}^{\mu}_{++}(p) &= \epsilon^{\mu}_{+}(p)u_{+}(p), \\ \tilde{\Psi}^{\mu}_{--}(p) &= \epsilon^{\mu}_{-}(p)u_{-}(p) \\ \tilde{\Psi}^{\mu}_{+}(p) &= \sqrt{\frac{2}{3}}\epsilon^{\mu}_{0}(p)u_{+}(p) + \frac{1}{\sqrt{3}}\epsilon^{\mu}_{+}(p)u_{-}(p), \\ \tilde{\Psi}^{\mu}_{-}(p) &= \sqrt{\frac{2}{3}}\epsilon^{\mu}_{0}(p)u_{-}(p) + \frac{1}{\sqrt{3}}\epsilon^{\mu}_{-}(p)u_{+}(p). \end{split}$$

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 $\begin{array}{c} & \text{Outline} \\ \text{Introduccin} \\ \text{Motivation} \\ \text{Spinor Helicity Formalism} \\ \text{Applications} \\ \text{Gravitino} \\ \text{Monophoton signal in LSP gravitino production} \\ \text{Conclusions} \end{array} \text{Two body NLSP Stop decay } (\tilde{t} \rightarrow t \, \tilde{G})$

Two body NLSP Stop decay ($\tilde{t} \rightarrow t G$)





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Squaring the helicity amplitudes of the last Table, we obtain the following expression for the total squared amplitud

$$\langle |\mathcal{M}|^2 \rangle = |\mathcal{M}_{-+}|^2 + |\mathcal{M}_{+-}|^2,$$
 (10)

$$=\frac{\left(s_{r_{2}q_{2}}^{4}-(m_{t}m_{\tilde{G}})^{4}\right)\left(s_{r_{2}q_{2}}^{2}-(m_{t}m_{\tilde{G}})^{2}\right)}{3M^{2}m_{\tilde{G}}^{2}s_{r_{2}q_{2}}^{3}},$$
(11)

$$=\frac{(m_{\tilde{t}}^2-m_{\tilde{G}}^2-m_t^2)\big((m_{\tilde{t}}^2-m_t^2-m_{\tilde{G}}^2)^2-4m_t^2m_{\tilde{G}}^2\big)}{3M^2m_{\tilde{G}}^2},$$
 (12)

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$$\begin{array}{c} \text{Outline} \\ \text{Introduccin} \\ \text{Motivation} \\ \text{Spinor Helicity Formalism} \\ \text{Applications} \\ \text{Gravitino} \\ \text{Monophoton signal in LSP gravitino production} \\ \text{Conclusions} \end{array} \text{Two body NLSP Stop decay } (\tilde{t} \rightarrow t \; \tilde{G})$$

To appreciate the power and efficiency of the SHF, we can remember the completeness relation for the spin-3/2 Gravitino Field that is needed in the traditional approach.

$$\begin{split} \sum_{\tilde{\lambda}=1}^{3} \Psi_{\mu}(\vec{p}_{1},\tilde{\lambda})\overline{\Psi}_{\nu}(\vec{p}_{1},\tilde{\lambda}) &= -(\not\!\!p_{1}+m_{\tilde{G}}) \times \left\{ \left(g_{\mu\nu}-\frac{p_{\mu}p_{\nu}}{m_{\tilde{G}}^{2}}\right) \\ &-\frac{1}{3} \left(g_{\mu\sigma}-\frac{p_{\mu}p_{\sigma}}{m_{\tilde{G}}^{2}}\right) \left(g_{\nu\lambda}-\frac{p_{\nu}p_{\lambda}}{m_{\tilde{G}}^{2}}\right) \gamma^{\sigma} \gamma^{\lambda} \right\} \end{split}$$

And we still need to take into account other fields to compute the trace.

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 $e^+e^- \rightarrow \gamma \, \tilde{G} \, \tilde{G}$

Using the SUSY QED model constructed by Mawatari and Oexl (arXiv:1402.3223v2), and applying the SHF we will compute the scattering amplitude for the $e^+e^- \rightarrow \gamma \tilde{G} \tilde{G}$ reaction. It is important to mention that the cross sections for this reaction has been computed numerically, so it is interesting have an analytical result.

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Feynman Diagrams



Figure: Feynman Diagrams for $e^+e^- \rightarrow \gamma \tilde{G} \tilde{G}$

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We have 5 Feynman diagrams each on them with 5 external (massless) particles, each particle have two helicity states (\pm), in principle we need to compute 2^5 helicity amplitudes for each diagram.

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Feynman Diagrams

Ampb[-1, -1, -1, -1, -1]	1	Ampc[-1, -1, -1, -1, -1]		Ampe[-1, -1, -1, -1, -1]	1	A[-1, -1, -1, -1, -1]	1	(A[-1, -1, -1, -1, -1])	
Ampb[-1, -1, -1, -1, 1]		Ampc[-1, -1, -1, -1, 1]		Ampe[-1, -1, -1, -1, 1]		Ampa[-1, -1, -1, -1, 1]		A[-1, -1, -1, -1, 1]	
Ampb[-1, -1, -1, 1, -1]		Ampc[-1, -1, -1, 1, -1]		Ampe[-1, -1, -1, 1, -1]		Ampa[-1, -1, -1, 1, -1]		Ampd[-1, -1, -1, 1, -1]	
Ampb[-1, -1, -1, 1, 1]		Ampc[-1, -1, -1, 1, 1]		Ampe[-1, -1, -1, 1, 1]		A[-1, -1, -1, 1, 1]		Ampd[-1, -1, -1, 1, 1]	
Ampb[-1, -1, 1, -1, -1]		Ampc[-1, -1, 1, -1, -1]		Ampe[-1, -1, 1, -1, -1]		A[-1, -1, 1, -1, -1]		Ampd[-1, -1, 1, -1, -1]	
Ampb[-1, -1, 1, -1, 1]		Ampc[-1, -1, 1, -1, 1]		Ampe[-1, -1, 1, -1, 1]		Ampa[-1, -1, 1, -1, 1]		Ampd[-1, -1, 1, -1, 1]	
Ampb[-1, -1, 1, 1, -1]		Ampc[-1, -1, 1, 1, -1]		Ampe[-1, -1, 1, 1, -1]		Ampa[-1, -1, 1, 1, -1]		A[-1, -1, 1, 1, -1]	
Ampb[-1, -1, 1, 1, 1]		Ampc[-1, -1, 1, 1, 1]		Ampe[-1, -1, 1, 1, 1]		A[-1, -1, 1, 1, 1]		A[-1, -1, 1, 1, 1]	
Ampb[-1, 1, -1, -1, -1]		Ampc[-1, 1, -1, -1, -1]		Ampe[-1, 1, -1, -1, -1]		Ampa[-1, 1, -1, -1, -1]		Ampd[-1, 1, -1, -1, -1]	
A[-1, 1, -1, -1, 1]		A[-1, 1, -1, -1, 1]		A[-1, 1, -1, -1, 1]		Ampa[-1, 1, -1, -1, 1]		Ampd[-1, 1, -1, -1, 1]	
Ampb[-1, 1, -1, 1, -1]		Ampc[-1, 1, -1, 1, -1]		Апре[-1, 1, -1, 1, -1]		Ampa[-1, 1, -1, 1, -1]		Ampd[-1, 1, -1, 1, -1]	
Ampb[-1, 1, -1, 1, 1]		Ampc[-1, 1, -1, 1, 1]		Ampe[-1, 1, -1, 1, 1]		Ampa[-1, 1, -1, 1, 1]		Ampd[-1, 1, -1, 1, 1]	
Ampb[-1, 1, 1, -1, -1]		Ampc[-1, 1, 1, -1, -1]		Ampe[-1, 1, 1, -1, -1]		Ampa[-1, 1, 1, -1, -1]		Ampd[-1, 1, 1, -1, -1]	
A[-1, 1, 1, -1, 1]		A[-1, 1, 1, -1, 1]		Ampe[-1, 1, 1, -1, 1]		Ampa[-1, 1, 1, -1, 1]		Ampd[-1, 1, 1, -1, 1]	
Ampb[-1, 1, 1, 1, -1]		Ampc[-1, 1, 1, 1, -1]		Ampe[-1, 1, 1, 1, -1]		Ampa[-1, 1, 1, 1, -1]		Ampd[-1, 1, 1, 1, -1]	
Ampb[-1, 1, 1, 1, 1]		Ampc[-1, 1, 1, 1, 1]		A[-1, 1, 1, 1, 1]		Ampa[-1, 1, 1, 1, 1]		Ampd[-1, 1, 1, 1, 1]	
Ampb[1, -1, -1, -1, -1]	· 1	Ampc[1, -1, -1, -1, -1]	<u>۰</u>	A[1, -1, -1, -1, -1]	•	Ampa[1, -1, -1, -1, -1]	· ·	Ampd[1, -1, -1, -1, -1]	
Ampb[1, -1, -1, -1, 1]		Ampc[1, -1, -1, -1, 1]		Ampe[1, -1, -1, -1, 1]		Ampa[1, -1, -1, -1, 1]		Ampd[1, -1, -1, -1, 1]	
A[1, -1, -1, 1, -1]		A[1, -1, -1, 1, -1]		Ampe[1, -1, -1, 1, -1]		Ampa[1, -1, -1, 1, -1]		Ampd[1, -1, -1, 1, -1]	
Ampb[1, -1, -1, 1, 1]		Ampc[1, -1, -1, 1, 1]		Ampe[1, -1, -1, 1, 1]		Ampa[1, -1, -1, 1, 1]		Ampd[1, -1, -1, 1, 1]	
Ampb[1, -1, 1, -1, -1]		Ampc[1, -1, 1, -1, -1]		Ampe[1, -1, 1, -1, -1]		Ampa[1, -1, 1, -1, -1]		Ampd[1, -1, 1, -1, -1]	
Ampb[1, -1, 1, -1, 1]		Ampc[1, -1, 1, -1, 1]		Ampe[1, -1, 1, -1, 1]		Ampa[1, -1, 1, -1, 1]		Ampd[1, -1, 1, -1, 1]	
A[1, -1, 1, 1, -1]		A[1, -1, 1, 1, -1]		A[1, -1, 1, 1, -1]		Ampa[1, -1, 1, 1, -1]		Ampd[1, -1, 1, 1, -1]	
Ampb[1, -1, 1, 1, 1]		Ampc[1, -1, 1, 1, 1]		Ampe[1, -1, 1, 1, 1]		Ampa[1, -1, 1, 1, 1]		Ampd[1, -1, 1, 1, 1]	
Ampb[1, 1, -1, -1, -1]		Ampc[1, 1, -1, -1, -1]		Ampe[1, 1, -1, -1, -1]		A[1, 1, -1, -1, -1]		A[1, 1, -1, -1, -1]	
Ampb[1, 1, -1, -1, 1]		Ampc[1, 1, -1, -1, 1]		Ampe[1, 1, -1, -1, 1]		Ampa[1, 1, -1, -1, 1]		A[1, 1, -1, -1, 1]	
Ampb[1, 1, -1, 1, -1]		Ampc[1, 1, -1, 1, -1]		Ampe[1, 1, -1, 1, -1]		Ampa[1, 1, -1, 1, -1]		Ampd[1, 1, -1, 1, -1]	
Ampb[1, 1, -1, 1, 1]		Ampc[1, 1, -1, 1, 1]		Ampe[1, 1, -1, 1, 1]		A[1, 1, -1, 1, 1]		Ampd[1, 1, -1, 1, 1]	
Ampb[1, 1, 1, -1, -1]		Ampc[1, 1, 1, -1, -1]		Ampe[1, 1, 1, -1, -1]		A[1, 1, 1, -1, -1]		Ampd[1, 1, 1, -1, -1]	
Ampb[1, 1, 1, -1, 1]		Ampc[1, 1, 1, -1, 1]		Ampe[1, 1, 1, -1, 1]		Ampa[1, 1, 1, -1, 1]		Ampd[1, 1, 1, -1, 1]	
Ampb[1, 1, 1, 1, -1]		Ampc[1, 1, 1, 1, -1]		Ampe[1, 1, 1, 1, -1]		Ampa[1, 1, 1, 1, -1]		A[1, 1, 1, 1, -1]	
Ampb[1, 1, 1, 1, 1]	1 1	Ampc[1, 1, 1, 1, 1]		Ampe[1, 1, 1, 1, 1]	1	A[1, 1, 1, 1, 1]	J	(A[1, 1, 1, 1, 1])	

Figure: All the helicity amplitudes

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 $e^+e^- \rightarrow \gamma \, \tilde{G} \, \tilde{G}$

One of the several and marvelous advantages of the helicity amplitudes is that it is easy to identify the symmetries as well as the null helicity amplitudes. We already know that the terms $\langle xy \rangle$ and $[xy \rangle$ are zero, a small program could help us to find which helicity amplitude is zero.

$$\mathcal{A}^{a}_{-+--+} \approx \left(\bar{v}_{+}(2) \not \epsilon_{-}(3) \not q u_{-}(1) \bar{u}_{+}(5) v_{-}(4) \right), \tag{14}$$

$$\mathcal{A}^{a}_{-+--+} \approx [54) = 0.$$
 (15)

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Counting helicity amplitudes

0	1	(0		0	\	0	(0)
0		0		0		0	0
0		0		0		0	0
0		0		0		0	0
0		0		0		D	0
0		0		0		0	0
0		0		0		0	0
0		0		0		0	0
0		0		0		0	0
A[-1, 1, -1, -1, 1]		A[-1, 1, -1, -1, 1]		A[-1, 1, -1, -1, 1]		A[-1, 1, -1, -1, 1]	A[-1, 1, -1, -1, 1]
0		0		0		0	0
0		0		0		0	0
0		0		0		D	0
A[-1, 1, 1, -1, 1]		0		A[-1, 1, 1, -1, 1]		A[-1, 1, 1, -1, 1]	0
0		A[-1, 1, 1, 1, -1]		0		0	D
0		0		0		0	A[-1, 1, 1, 1, 1]
0	1.	0	*	0	+	D	A[1, -1, -1, -1, -1]
0		A[1, -1, -1, -1, 1]		0		0	0
A[1, -1, -1, 1, -1]		0		A[1, -1, -1, 1, -1]		A[1, -1, -1, 1, -1]	0
0		0		0		0	0
0		0		0		0	0
0		0		0		0	0
A[1, -1, 1, 1, -1]		A[1, -1, 1, 1, -1]		A[1, -1, 1, 1, -1]		$A[1_{1} - 1_{1} 1_{1} 1_{2} - 1]$	A[1, -1, 1, 1, -1]
0		0		0		0	0
0		0		0		0	0
0		0		0		0	0
0		0		0		0	0
0		0		0		D	0
0		0		0		0	0
0		0		0		0	0
0		0		0		0	0
0)	0		0		0	0

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We started our problem with **160** helicity amplitudes, but just looking at the possible helicity states of the external particles we found that there are only **20** helicity amplitudes to compute. Applying complex conjugation we really need to compute half of the final helicity amplitudes. *At the end, just the* **6%** *of the work will be done and without the help of any machine if one desires.*

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The total modulus squared amplitude is as follows:

$$|\mathcal{M}|^{2} = \sum_{perm} |A_{\lambda_{1}\lambda_{2}\lambda_{3}\lambda_{4}\lambda_{5}}|^{2}$$

= 2(|\mathcal{A}_{-++++}|^{2} + |\mathcal{A}_{-++++}|^{2} + |\mathcal{A}_{-+++++}|^{2} + |\mathcal{A}_{-+++++}|^{2})

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where each squared helicity amplitude takes the form:

$$|\mathcal{A}_{-++-+}|^{2} = \frac{16C^{2}|s_{24}|^{2}|s_{15}||s_{34}|}{[(z^{2} - m_{\tilde{e}_{-}}^{2})(r^{2} - m_{\tilde{e}_{-}}^{2})]^{2}|s_{23}|}$$
(16)

$$|\mathcal{A}_{-+++-}|^2 = \frac{128D^{-}|s_{34}||s_{25}||s_{12}||s_{24}|}{[q'^2(r'^2 - m_{\chi_O}^2)]^2}$$
(17)

$$|\mathcal{A}_{-++++}|^2 = \frac{8E^2|s_{34}|^2|s_{24}||s_{15}|}{[(l'^2 - m_{\chi_0}^2)(x^2 - m_{\tilde{e}_-}^2)]^2}$$
(18)

$$\begin{aligned} |\mathcal{A}_{-+-+}|^2 &= |s_{23}||s_{34}||s_{51}|\xi_1^2 + |s_{34}|^2|s_{45}||s_{51}|\xi_2^2 \\ &+ 2\boldsymbol{Re}[\xi_1\xi_2|s_{51}||s_{34}|[23]|\langle 34\rangle[45]\langle 52\rangle] \end{aligned} \tag{19}$$

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Conclusions

Conclusions 2-body Z boson decay $Z(p_1) \rightarrow f(p_2)\overline{f}(p_3)$ 3-body Muon Decay $\mu(p_1) \rightarrow \overline{\nu}_{e^-}(p_2) \nu_{\mu}(p_3) e^-(p_4)$

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- We compute **analytically** the total scattering amplitude for the reaction $e^+e^- \rightarrow \gamma \tilde{G} \tilde{G}$.
- It was shown that the **SHF** is a powerful method, in fact it is much more economic than the traditional approach.
- With the complete result (e⁺e⁻ → γ G̃G̃), it is possible to compare the cross section with the numerical results.
- From this point, we can now start to do physics.

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Conclusions

2-body Z boson decay $Z(p_1) \rightarrow f(p_2)f(p_3)$ 3-body Muon Decay $\mu(p_1) \rightarrow \bar{\nu}_{e^-}(p_2) \nu_{\mu}(p_3) e^-(p_4)$

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Thank you

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Conclusions

2-body Z boson decay $Z(p_1) \rightarrow f(p_2)\overline{f}(p_3)$ 3-body Muon Decay $\mu(p_1) \rightarrow \overline{\nu}_{e^-}(p_2) \nu_{\mu}(p_3) e^-(p_4)$

In spite of the tremendous difficulties lying ahead, I feel that S-matrix theory is far from dead and that . . . much new interesting mathematics will be created by attempting to formalize it.

"Tullio Regge"

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2-body Higgs decay $h(p_1) \rightarrow f(p_2)f(p_3)$

From the Feynman diagram we get the helicity amplitudes (HAs) (as is usual)



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2-body Higgs decay $h(p_1) \rightarrow f(p_2)f(p_3)$

Let me compute these HAs step by step

•
$$\bar{u}_{-}(p_{2}), \bar{u}_{+}(p_{2})$$

 $\mathcal{M}_{\lambda_{2}\lambda_{3}}(p_{1}, p_{2}, p_{3}) = \frac{m_{f}}{v} \overline{u}_{\lambda_{2}}(p_{2}) v_{\lambda_{3}}(p_{3})$ (21)
• $v_{-}(p_{3}), v_{+}(p_{3})$

We see that there are 4 HAs, these are -+, --, +-++ (In the massless case there are just 2, +- and -+).

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Conclusions 2-body Z boson decay $Z(p_1) \rightarrow f(p_2)\overline{f}(p_3)$ 3-body Muon Decay $\mu(p_1) \rightarrow \overline{\nu}_{e^-}(p_2) \nu_{\mu}(p_3) e^-(p_4)$

2-body Higgs decay $h(p_1) \rightarrow f(p_2)\overline{f}(p_3)$

$$\mathcal{M}_{--} = \frac{m_f}{v} \bar{u}_{-}(2) v_{-}(3) \tag{22}$$

$$= \frac{m_f}{v} \left(\frac{m_f}{[q_2 r_2]} [q_2| + \langle r_2| \right) \left(-\frac{m_f}{[r_3 q_3]} |q_3] + |r_3 \rangle \right) \tag{23}$$

$$= \frac{m_f}{v} \left(-\frac{m_f^2 [q_2 q_3]}{[q_2 r_2] [r_3 q_3]} + \frac{m_f}{[q_2 r_2]} [q_2 r_3) - \frac{0}{[r_3 q_3]} + \langle r_2 r_3 \rangle \right) \tag{24}$$

$$= \frac{m_f}{v} \left(-\frac{m_f^2 [q_2 q_3]}{[q_2 r_2] [r_3 q_3]} + \langle r_2 r_3 \rangle \right) \tag{25}$$

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For this special example we will use simultaneous LCD (SLCD),

$$p_{2} = r_{2} - \frac{m_{f}^{2}}{2r_{2} \cdot q_{2}}q_{2}$$

$$p_{3} = r_{3} - \frac{m_{f}^{2}}{2r_{3} \cdot q_{3}}q_{3}$$
(26)
(27)

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$$\begin{array}{c} \text{Outline} \\ \text{Introduccin} \\ \text{Motivation} \\ \text{Spinor Helicity Formalism} \\ \text{Applications} \\ \text{Gravitino} \\ \text{Monophoton signal in LSP gravitino production} \\ \end{array} \qquad \begin{array}{c} \text{Conclusions} \\ \text{Conclusions} \\ \text{Conclusions} \\ \text{Conclusions} \\ \end{array} \qquad \begin{array}{c} \text{Conclusions} \\ \text{Conclusions} \\ \text{Conclusions} \\ \text{Conclusions} \\ \text{Conclusions} \\ \end{array}$$

For this special example we will use simultaneous LCD (SLCD),

$$p_{2} = r_{2} - \frac{m_{f}^{2}}{2r_{2} \cdot q_{2}}q_{2}$$
(28)
$$p_{3} = q_{2} - \frac{m_{f}^{2}}{2q_{2} \cdot r_{2}}r_{2}$$
(29)

We choose $r_3 = q_2$ and $q_3 = r_2$, this will reduce our calculations.

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2-body Higgs decay $h(p_1) \rightarrow f(p_2)f(p_3)$

Returning to the HA \mathcal{M}_{--} and taking into account SLCD, we have

$$\mathcal{M}_{--} = \frac{m_f}{v} \left(-\frac{m_f^2 [q_2 r_2]}{[q_2 r_2] [q_2 r_2]} + \langle r_2 q_2 \rangle \right)$$
(30)
$$= \frac{m_f}{v} \left(-\frac{m_f^2}{[q_2 r_2]} + \langle r_2 q_2 \rangle \right) = \frac{m_f}{v [q_2 r_2]} (-m_f^2 + \langle r_2 q_2 \rangle [q_2 r_2])$$
(31)
$$= \frac{m_f}{v [q_2 r_2]} (-m_f^2 + s_{q_2 r_2})$$
(32)

$$\begin{array}{c} & \text{Outline} \\ \text{Introduccin} \\ \text{Motivation} \\ \text{Spinor Helicity Formalism} \\ \text{Applications} \\ \text{Gravitino} \\ \text{Monophoton signal in LSP gravitino production} \\ \end{array} \qquad \begin{array}{c} \text{Conclusions} \\ \text{2-body } Z \text{ boson decay } Z(p_1) \rightarrow \bar{f}(p_2)\bar{f}(p_3) \\ \text{3-body Muon Decay } \mu(p_1) \rightarrow \bar{\nu}_{e^-}(p_2) \nu_{\mu}(p_3) e^-(p_4) \end{array}$$

We do not need to compute \mathcal{M}_{++} , we just complex conjugate \mathcal{M}_{--} (one of the greatest advantages of the SHF).

$$\mathcal{M}_{++} = \frac{m_f}{v \langle q_2 r_2 \rangle} (-m_f^2 + s_{q_2 r_2})$$
(33)

As you can guess we shall compute just one HA (\mathcal{M}_{-+})

= 0

$$\mathcal{M}_{-+} = \frac{m_f}{v} \bar{u}_{-}(2) v_{+}(3) = \frac{m_f}{v} \left(\frac{m_f}{[q_2 r_2]} [q_2| + \langle r_2| \right) \left(|q_2] - \frac{m_f}{\langle r_2 q_2 \rangle} |r_2 \rangle \right)$$
(34)
$$\propto [q_2 q_2]^{-0} [q_2 r_2]^{+0} \langle r_2 q_2 \rangle^{-0} (r_2 r_2)^{+0}$$
(35)

$$\begin{array}{c} & \text{Outline} \\ \text{Introduccin} \\ & \text{Motivation} \\ \text{Spinor Helicity Formalism} \\ & \text{Applications} \\ & \text{Gravitino} \\ \text{Monophoton signal in LSP gravitino production} \\ \end{array} \\ \begin{array}{c} \text{Conclusions} \\ \text{2-body } Z \text{ boson decay } Z(p_1) \rightarrow f(p_2) \overline{f}(p_3) \\ \text{3-body Muon Decay } \mu(p_1) \rightarrow \overline{\nu}_{e^-}(p_2) \nu_{\mu}(p_3) e^-(p_4) \end{array}$$

Finally the averaged squared amplitude is then:

$$\langle |\mathcal{M}|^2 \rangle = 2|\mathcal{M}_{--}|^2 = \frac{2m_f^2}{v^2 s_{q_2 q_3}} (s_{q_2 q_3} - m_f^2)^2 = \frac{y^2}{v^2} (1 - 4y^2),$$

(37)

with $y = \frac{m_f}{M_b}$. Then the decay width Γ goes as follows

$$\Gamma(h \to f\bar{f}) = \frac{\alpha_W M_h y^2}{8} (1 - 4y^2)^{3/2}.$$

(38)

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2-body Z boson decay $Z(p_1) \rightarrow f(p_2)f(p_3)$

Again from the Feynman diagram we get the helicity amplitudes



$\lambda_1\lambda_2\lambda_3$	$\mathcal{M}_{\lambda_1\lambda_2\lambda_3}$
++-	$\frac{1}{2}g_{Z}\frac{\langle p_{2} \gamma_{\mu} r_{1}\rangle}{\sqrt{2}\langle r_{1}p_{2}\rangle}(v_{f}-a_{f})[p_{2} \gamma^{\mu} p_{3}\rangle = \frac{g_{Z}(v_{f}-a_{f})}{\sqrt{2}}\frac{\langle p_{2}p_{3}\rangle[r_{1}p_{2}\rangle}{\langle r_{1}p_{2}\rangle}$
0+-	$\frac{1}{2}g_Z\left(\frac{1}{M}r_{1\mu} + \frac{M}{2p_{12}}p_{2\mu}\right)(v_f - a_f)[p_2 \gamma^{\mu} p_3\rangle = \frac{g_Z(v_f - a_f)}{\sqrt{2M}}\langle r_1 p_3\rangle[r_1 p_2] = 0$
-+-	$\frac{1}{2}g_Z \frac{\langle r_1 \gamma_\mu p_2 \rangle}{\sqrt{2}[p_2 r_1]} (v_f - a_f) [p_2 \gamma^\mu p_3 \rangle = 0$

$$\begin{array}{c} \text{Outline} \\ \text{Introduccin} \\ \text{Motivation} \\ \text{Spinor Helicity Formalism} \\ \text{Applications} \\ \text{Gravitino} \\ \text{Monophoton signal in LSP gravitino production} \\ \end{array} \qquad \begin{array}{c} \text{Conclusions} \\ \text{2-body } Z \text{ boson decay } Z(p_1) \rightarrow f(p_2) \overline{f}(p_3) \\ \text{3-body Muon Decay } \mu(p_1) \rightarrow \overline{\nu}_{e^-}(p_2) \nu_{\mu}(p_3) e^-(p_4) \end{array}$$

Finally the squared averaged scattering amplitude is as follows

$$\left\langle |\mathcal{M}|^2 \right\rangle = \frac{1}{3} \left(|\mathcal{M}_{++-}|^2 + |\mathcal{M}_{--+}|^2 \right) = \frac{g_Z^2 M^2}{3} \left(|v_f|^2 + |a_f|^2 \right)$$
(40)

The decay width for this channel is then:

$$\Gamma\left(Z \to f\bar{f}\right) = \frac{g_Z^2 M}{48\pi} \left(|v_f|^2 + |a_f|^2\right). \tag{4}$$

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$$\begin{array}{c} \text{Outline} \\ \text{Introduccin} \\ \text{Motivation} \\ \text{Spinor Helicity Formalism} \\ \text{Applications} \\ \text{Gravitino} \\ \text{Monophoton signal in LSP gravitino production} \\ \text{Conclusions} \end{array} \begin{array}{c} \text{Conclusions} \\ \text{Conclusions} \\ \text{Conclusions} \\ \text{Conclusions} \\ \text{Conclusions} \end{array}$$

3-body Muon Decay $\mu(p_1) \rightarrow \bar{\nu}_{e^-}(p_2) \overline{\nu_{\mu}(p_3) e^-(p_4)}$

From the Feynman diagram we get the helicity amplitudes (HAs) (as is usual)

$$\mu \longrightarrow e \qquad \mathcal{M}_{\lambda_1 \lambda_2 \lambda_3 \lambda_4} = \left(\frac{g_W}{\sqrt{8}M_W}\right)^2 \left[\bar{u}_{\lambda_3}(p_3)\gamma^{\mu}(1-\gamma_5)u_{\lambda_1}(p_1)\right] \left[\bar{u}_{\lambda_4}(p_4)\gamma_{\mu}(1-\gamma_5)v_{\lambda_2}(p_2)\right],$$
$$= \left(\frac{g_W}{\sqrt{8}M_W}\right)^2 \mathcal{A}_{\lambda_3 \lambda_1}^{\mu} \mathcal{B}_{\mu \lambda_4 \lambda_2},$$

$\lambda_1\lambda_2\lambda_3\lambda_4$	$\mathcal{A}^{\mu\lambda_{3}\lambda_{1}}$	$\mathcal{B}^{\lambda_4\lambda_2}_\mu$	${\cal A}^{\mu\lambda_3\lambda_1}{\cal B}^{\lambda_4\lambda_2}_\mu$	\mathcal{M} $(p_2 = q_1, p_3 = q_4)$
+-+-	$2[p_3 \gamma^\mu r_1\rangle$	$2[r_4 \gamma_\mu p_2\rangle$	$4\langle p_2r_1 angle\langle p_3r_4 angle$	$\left(rac{g_W}{\sqrt{2}m_\mu} ight)^2 \langle p_2 r_1 angle [p_3 r_4]$
+++-	$2[p_3 \gamma^{\mu} r_1\rangle$	$\frac{2m_e}{[q_4r_4]}[q_4 \gamma_\mu p_2\rangle$	$4 \frac{m_e}{[q_4 r_4]} \langle p_2 r_1 \rangle \langle p_3 q_4 \rangle$	0
++	$\frac{2m_{\mu}}{\langle r_1 q_1 \rangle} [p_3 \gamma^{\mu} q_1 \rangle$	$2[r_4 \gamma_\mu p_2\rangle$	$4rac{m_{\mu}}{\langle r_1q_1 angle}\langle p_2q_1 angle [p_3r_4]$	0
-++-	$rac{2m_{\mu}}{\langle r_1q_1 angle}[p_3 \gamma^{\mu} q_1 angle$	$\frac{2m_e}{[q_4r_4]}[q_4 \gamma_{\mu} p_2\rangle$	$4 rac{m_{\mu}m_e}{\langle r_1q_1 \rangle [q_4r_4]} \langle p_2q_1 \rangle [p_3q_4]$	0

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The squared and averaged amplitude for the muon decay is:

$$\langle |\mathcal{M}^{+-+-}|^2 \rangle = \frac{1}{2} |\mathcal{M}^{+-+-}|^2 = 2 \left(\frac{g_W}{M_W}\right)^4 (p_1 \cdot p_2) (p_3 \cdot p_4)$$
(42)

From this result we can arrive to the decay width, which agrees with result of textbooks.

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