Present Status of GRACE/SUSY-loop

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Contents

1. Motivation

- The best candidate for BSM
  - Search for SUSY particles @LHC&ILC
- Precision study @ILC

The accuracy of theoretical prediction should be less than the accuracy of experimental measurement

- 1-loop correction to major possible decays of sfermion and gluino with GRACE/SUSY-loop

2. GRACE system

1. Generates all Feynman diagrams automatically
2. Generates physical amplitudes automatically
3. Incorporates libraries
   (Loop integral, Kinematics, etc.)
4. Integrates the matrix element by the adaptive Monte Carlo method (BASES)
5. Does Monte Carlo event generation (SPRING)
6. Enables various self-check for the results
   (UV cancellation, IR cancellation, NLG invariance, …)

Other automatic SUSY 1-loop systems
SloopS(Boudjema et al., 05), FeynArt/Calc(Hahn, 01, 06)

Nonlinear gauge (NLG) fixing terms in the electroweak sector of MSSM

$$L_{\rm gf} = -\frac{1}{\xi_W}\left|F_{W^+}\right|^2 - \frac{1}{2\xi_Z}(F_Z)^2 - \frac{1}{2\xi_\gamma}\left(F_\gamma\right)^2$$: gauge fixing terms

$$F_{W^+} = (\partial_\mu + ie\tilde{\alpha}A_\mu + igc_W\tilde{\beta}Z_\mu)W^{+\mu} + i\xi_W\frac{g}{2}(v + \tilde{\delta}_h h^0 + \tilde{\delta}_H H^0 + i\tilde{\kappa}G^0)G^+$$

$$F_Z = \partial_\mu Z^\mu + \xi_Z\frac{g_Z}{2}(v + \tilde{\varepsilon}_h h^0 + \tilde{\varepsilon}_H H^0)G^0 \qquad F_\gamma = \partial_\mu A^\mu$$

Gauge invariant scheme[1] ➡ gauge invariance test

➡ independence of physical results on NLG parameters

$(\tilde{\alpha}, \tilde{\beta}, \tilde{\delta}_h, \tilde{\delta}_H, \tilde{\kappa}, \tilde{\varepsilon}_h, \tilde{\varepsilon}_H)$: NLG parameters

- Extend NLG formalism in section 5

[1] J.Fujimoto et al., Nucl. Phys. (Proc. Suppl.) 157 (2006) 157; Phys.Rev.D75, 113002('07)

Renormalization Scheme

Electroweak corrections

* On-Mass-Shell scheme

e.g. $\mathrm{Re}\,\hat{\Pi}_W(M_W^2) = 0$ $\quad \hat{\Pi}_W(q^2) = \Pi_W(q^2) + \delta M_W^2 - \delta Z_W(q^2 - M_W^2)$

$\rightarrow$ mass shifts occur for $h^0, H^\pm, \tilde{\chi}^0_{2,3,4}$

* Sfermion sector

$\rightarrow$ residue conditions: $\delta Z_{\tilde{f}\tilde{f}} = \frac{\partial}{\partial q^2}\Sigma(q^2)\Big|_{q^2 \to m^2_{\tilde{f}}} \equiv \Sigma'(m^2_{\tilde{f}})$

$\tilde{f}_1 - \tilde{f}_2$ decoupling conditions:

$$\frac{1}{2}\delta Z_{\tilde{f}_i \tilde{f}_j} = -\frac{\Sigma_{\tilde{f}_i \tilde{f}_j}(m^2_{\tilde{f}_j})}{m^2_{\tilde{f}_i} - m^2_{\tilde{f}_j}}, \quad i \neq j$$

external wave function: $\delta Z^{ext}_{\tilde{t}_2 \tilde{t}_2} \neq 0, \ \delta Z^{ext}_{\tilde{b}_2 \tilde{b}_2} \neq 0$

QCD/SUSYQCD corrections

* light quarks(u,d,c,s) and gluon
  $\Rightarrow$ DR-bar scheme
  $\rightarrow$ PDF, parton-shower, …

* massive quarks(b,t), squark and gluino
  $\Rightarrow$ On-Mass-Shell scheme

* IR regularization… $1/\bar{\varepsilon}$ (Dimensional)

$$d = 4 - 2\varepsilon = 4 + 2\bar{\varepsilon}$$

$$C_{UV} = \frac{1}{\varepsilon}, \; C_{IR} = \frac{1}{\bar{\varepsilon}}$$

3. Stop decay (2-body decay)

- stop1 decay
- gluino decay

} decay widths in the 1-loop order

⇓

using the SPS1a' parameter set
in the framework of the MSSM

⇓

K.Iizuka, et al., POS (RADCOR2009) 068 [hep-ph/1001.2800]

MSSM parameters(SPS1a')

GUT scale input parameter

$m_0 = 100\,\text{GeV}$

$m_{1/2} = 250\,\text{GeV}$

$A_0 = -100\,\text{GeV}$

$\mu = 399\,\text{GeV}$

$\tan\beta = 10$

$M\tilde{e}_1 = 126\,\text{GeV}$	$M\tilde{e}_2 = 190\,\text{GeV}$	$M\tilde{\nu}_e = 173\,\text{GeV}$
$M\tilde{\mu}_1 = 125\,\text{GeV}$	$M\tilde{\mu}_2 = 190\,\text{GeV}$	$M\tilde{\nu}_\mu = 173\,\text{GeV}$
$M\tilde{\tau}_1 = 108\,\text{GeV}$	$M\tilde{\tau}_2 = 195\,\text{GeV}$	$M\tilde{\nu}_\tau = 171\,\text{GeV}$
$M\tilde{u}_1 = 546\,\text{GeV}$	$M\tilde{u}_2 = 563\,\text{GeV}$	$M\tilde{d}_1 = 546\,\text{GeV}$
$M\tilde{d}_2 = 569\,\text{GeV}$	$M\tilde{c}_1 = 546\,\text{GeV}$	$M\tilde{c}_2 = 563\,\text{GeV}$
$M\tilde{s}_1 = 546\,\text{GeV}$	$M\tilde{s}_2 = 569\,\text{GeV}$	$M\tilde{t}_1 = 369\,\text{GeV}$
$M\tilde{t}_2 = 584\,\text{GeV}$	$M\tilde{b}_1 = 450\,\text{GeV}$	$M\tilde{b}_2 = 544\,\text{GeV}$
$M\tilde{\chi}_1^0 = 98\,\text{GeV}$	$M\tilde{\chi}_2^0 = 185\,\text{GeV}$	$M\tilde{\chi}_3^0 = 405\,\text{GeV}$
$M\tilde{\chi}_4^0 = 420\,\text{GeV}$	$M\tilde{\chi}_1^+ = 184\,\text{GeV}$	$M\tilde{\chi}_2^+ = 421\,\text{GeV}$
$M_{\tilde{g}} = 610\,\text{GeV}$	$M_{A^0} = 425\,\text{GeV}$	
$M_1 = 100\,\text{GeV}$	$M_2 = 198\,\text{GeV}$	

$(M_t = 178\,\text{GeV}, M_b = 4.1\,\text{GeV})$

Possible decay modes

- sfermion

$$\tilde{q} \to q\tilde{\chi}_i^0, \tilde{q} \to q'\tilde{\chi}_k^+ \quad i = 1,2,3,4 \quad k = 1,2$$

(~~$\tilde{q} \to \tilde{g}q$~~ because of $m_{\tilde{q}} < m_{\tilde{g}}$)

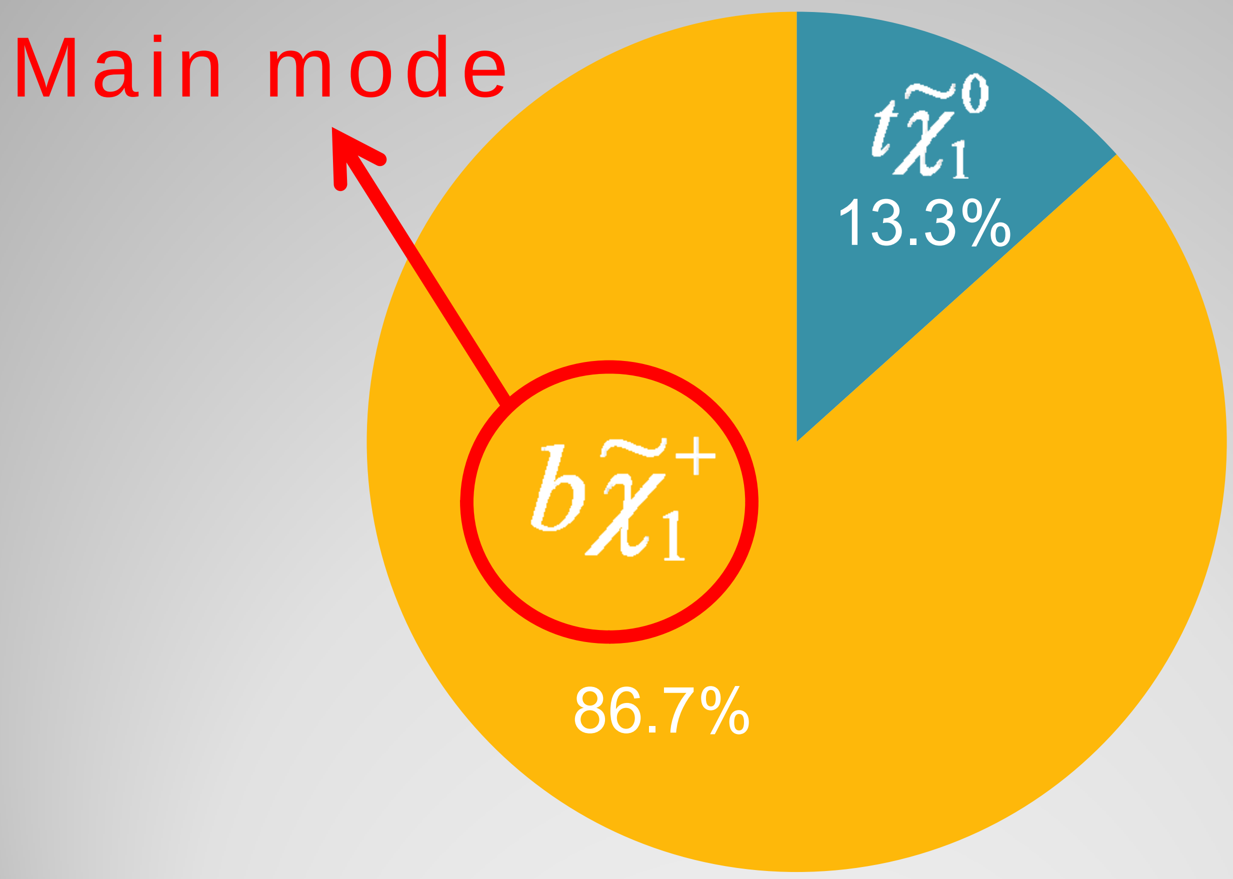
$$\tilde{l} \to l\tilde{\chi}_i^0, \tilde{l} \to l'\tilde{\chi}_k^+$$

- gluino

$$\tilde{g} \to q\tilde{q}_j \quad j = 1,2$$

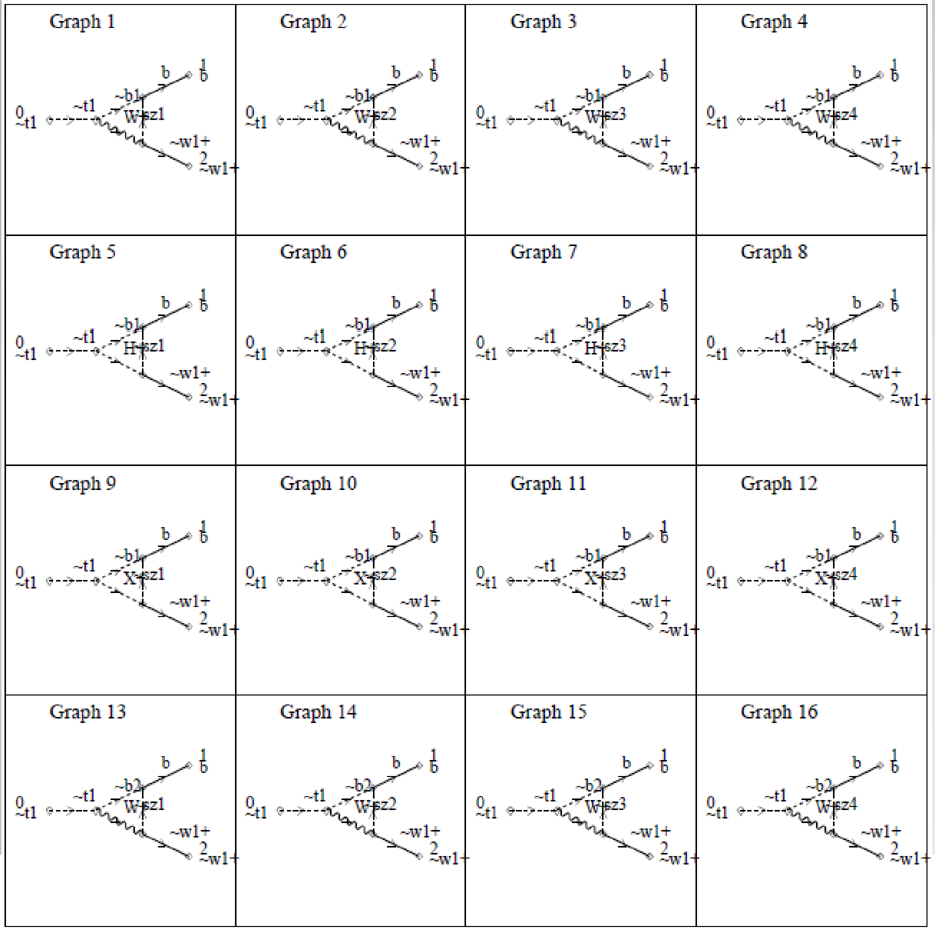
(~~$\tilde{g} \to t\tilde{t}_2$~~ because of $m_{\tilde{g}} < m_t + m_{\tilde{t}_2}$)

Branching ratio of stop1 decay (tree)



Details of $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^+$ (1)

Feynman diagrams (Electroweak 1-loop)



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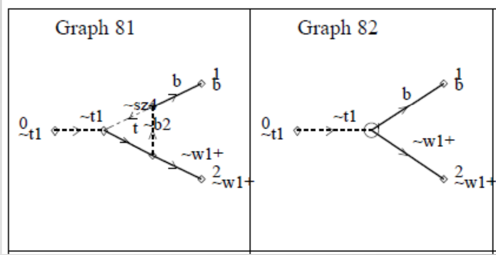


82 diagrams

Details of $\tilde{t}_1 \to b\tilde{\chi}_1^+$ (2)

✓Independence of nonlinear gauge parameters (NLG)

$$(\tilde{\alpha}, \tilde{\beta}, \tilde{\delta}_h, \tilde{\delta}_H, \tilde{\kappa}, \tilde{\varepsilon}_h, \tilde{\varepsilon}_H) : \textit{NLG parameters}$$

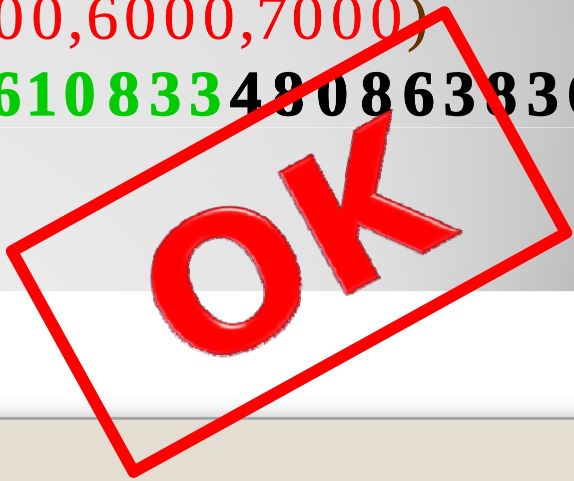
unit : [GeV]

Case 1 : (0,0,0,0,0,0,0)

Ans = 0.15117115752797127186610833503954323

Case 2 : (1000,2000,3000,4000,5000,6000,7000)

Ans = 0.15117115752797127186610833480863836



Details of $\tilde{t}_1 \to b\tilde{\chi}_1^+$ (3)

✓Ultraviolet divergence is canceled? (Cuv part dependence)

unit : [GeV]

Case 1 : (Cuv=0)

Ans = **0.15117115752797127186610833503954323**

Case 2 : (Cuv=1000)

Ans = **0.151171157527971271865901802793978 01**

OK

✓Infrared divergence is canceled? (λ dependence)

λ : fictitious photon mass

unit : [GeV]

Case 1 : ($\lambda = 1 \times 10^{-24}$)

Ans = **0.15117115752797127186610833503954323**

Case 2 : ($\lambda = 1 \times 10^{-27}$)

Ans = **0.151171157527971271866108335199 8[illegible]020**

OK

Details of $\tilde{t}_1 \to b\tilde{\chi}_1^+$ (4)

✓ Electroweak corrections : test of cancellation

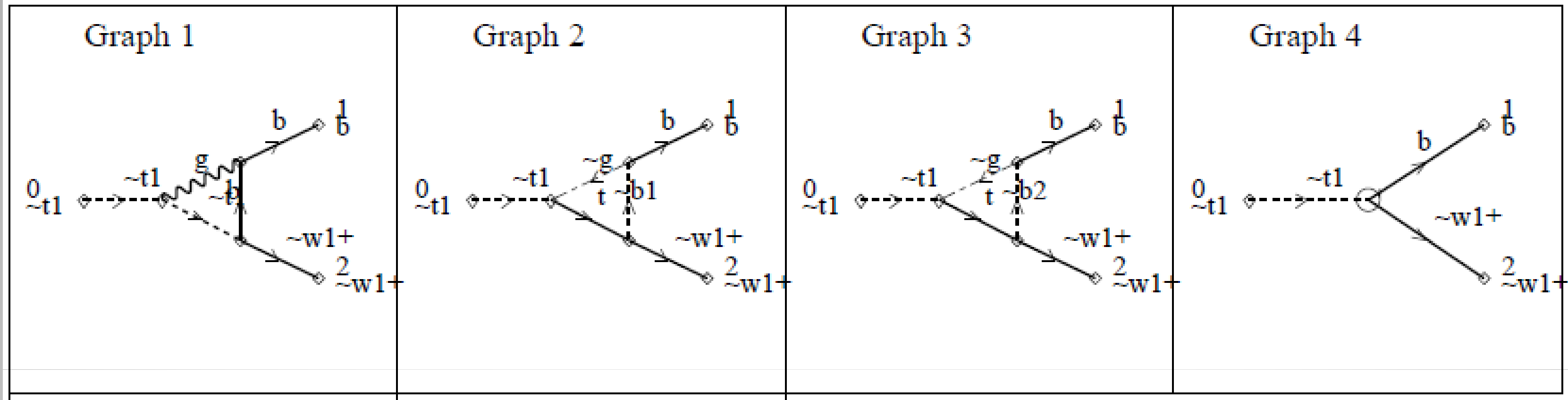
Born : 1.4326728 [GeV]

Table1: test of cancellation (Electroweak) unit : [GeV]

Cuv	0	1000	0	0
λ	10^{-24}	10^{-24}	10^{-27}	10^{-24}
kc	10^{-3}	10^{-3}	10^{-3}	10^{-5}
loop	-0.06256	-0.06256	-0.09364	-0.06256
soft	0.21373	0.21373	0.24481	0.19301
hard	0.04849	0.04849	0.04849	0.06921
sum	0.19966	0.19966	0.19966	0.19966
correction	13.9%	13.9%	13.9%	13.9%

Details of $\tilde{t}_1 \to b\tilde{\chi}_1^+$ (5)

Feynman diagrams(QCD 1-loop)



4 diagrams

Details of $\tilde{t}_1 \to b\tilde{\chi}_1^+$ (6)

✓Infrared divergence is canceled? (Cir part dependence)

Table2: cancellation check of IR unit : [GeV]

graph No. \ Cir	0	1000
1	-1.8937129	-299.3588218
2	-0.1893653	-0.1893653
3	-0.0064516	-0.0064516
4 (counter term)	0.8352818	73.8007086
soft	-3.7518778	220.7478043
sum	-5.0061258	-5.0061259

Details of $\tilde{t}_1 \to b\tilde{\chi}_1^+$ (7)

✓QCD corrections : Check of cancellation

Born : 1.4326728 [GeV]

Table3: check of cancellation (QCD) unit : [GeV]

Cuv	0	1	0	0
Cir	0	0	1	0
kc	10^{-3}	10^{-3}	10^{-3}	10^{-4}
loop	-1.254	-1.254	-1.479	-1.254
soft	-3.752	-3.752	-3.527	-4.786
hard	4.905	4.905	4.905	5.939
sum	-0.100	-0.100	-0.100	-0.099
correction	-7.1%	-7.1%	-7.1%	-7.1%

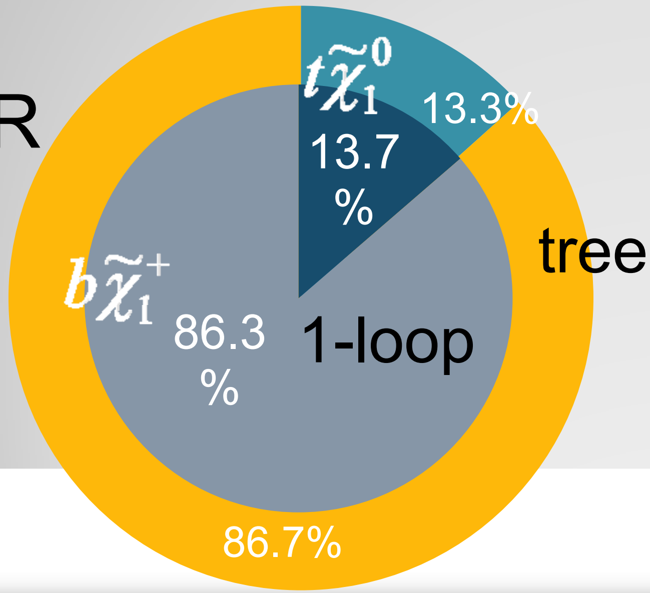
Summary of stop1 decay

Table4: summary of stop1 decay

unit : [GeV]

	tree	$\delta\Gamma$ (QCD) / $\delta\Gamma$ (ELWK)	$\delta\Gamma$/tree(QCD) / $\delta\Gamma$/tree(ELWK)	total
$\tilde{t}_1 \to b\tilde{\chi}_1^+$	1.43267	-0.104 / 0.200	-7.1% / 13.9%	6.8%
$\tilde{t}_1 \to t\tilde{\chi}_1^0$	0.22067	0.00461 / 0.01681	2.1% / 7.6%	9.7%

BR



total decay width

Γ(tree) : 1.65 [GeV]

Γ(QCD) : 1.55 [GeV]

Γ(Electroweak) : 1.87 [GeV]

Γ(1-loop) : 1.77 [GeV]

4. Stop decay (3-body decay)

- stop1 decay

  decay width in the 1-loop order

  ↓

  using another MSSM parameter set

  ↓

  3-body decay can occur

MSSM parameters

$M_{\tilde{t}_1} = 278.9\ \text{GeV} - 600\text{GeV}$ $M_{\tilde{t}_2} = 600\ \text{GeV}$

$M_{\tilde{b}_1} = 330\ \text{GeV}$ $M_{\tilde{\nu}} = 317\ \text{GeV}$

$M_{\tilde{\chi}_1^0} = 194.58\ \text{GeV}$ $M_{\tilde{\chi}_1^+} = 396.12\ \text{GeV}$

$M_{\tilde{g}} = 1390\ \text{GeV}$

$M_2 = 400\ \text{GeV}$ $\mu = -750\ \text{GeV}$

$(M_t = 178\ \text{GeV}, M_b = 4.1\text{GeV}, M_W = 80.22\ \text{GeV})$

Experimental limits from Tevatron & LEP2:

$M_{\tilde{t}_1} > 95.7\text{GeV}$ $M_{\tilde{\chi}_1^0} > 46\text{GeV}$ $M_{\tilde{\chi}_1^+} > 94\text{GeV}$

$M_{\tilde{b}_1} > 89\text{GeV}$ $M_{\tilde{g}} > 308\text{GeV}$ $M_{\tilde{q}} > 379\text{GeV}$

3-body decay

$M_{\tilde{t}_1} = 278.9\text{GeV} - 368.6\text{GeV}$

$\tilde{t}_1 \rightarrow b W^{+} \tilde{\chi}_1^{0}$ major decay mode

$\tilde{t}_1 \rightarrow b\, l^{+} \tilde{\nu}_l$ minor decay mode

2-body decay

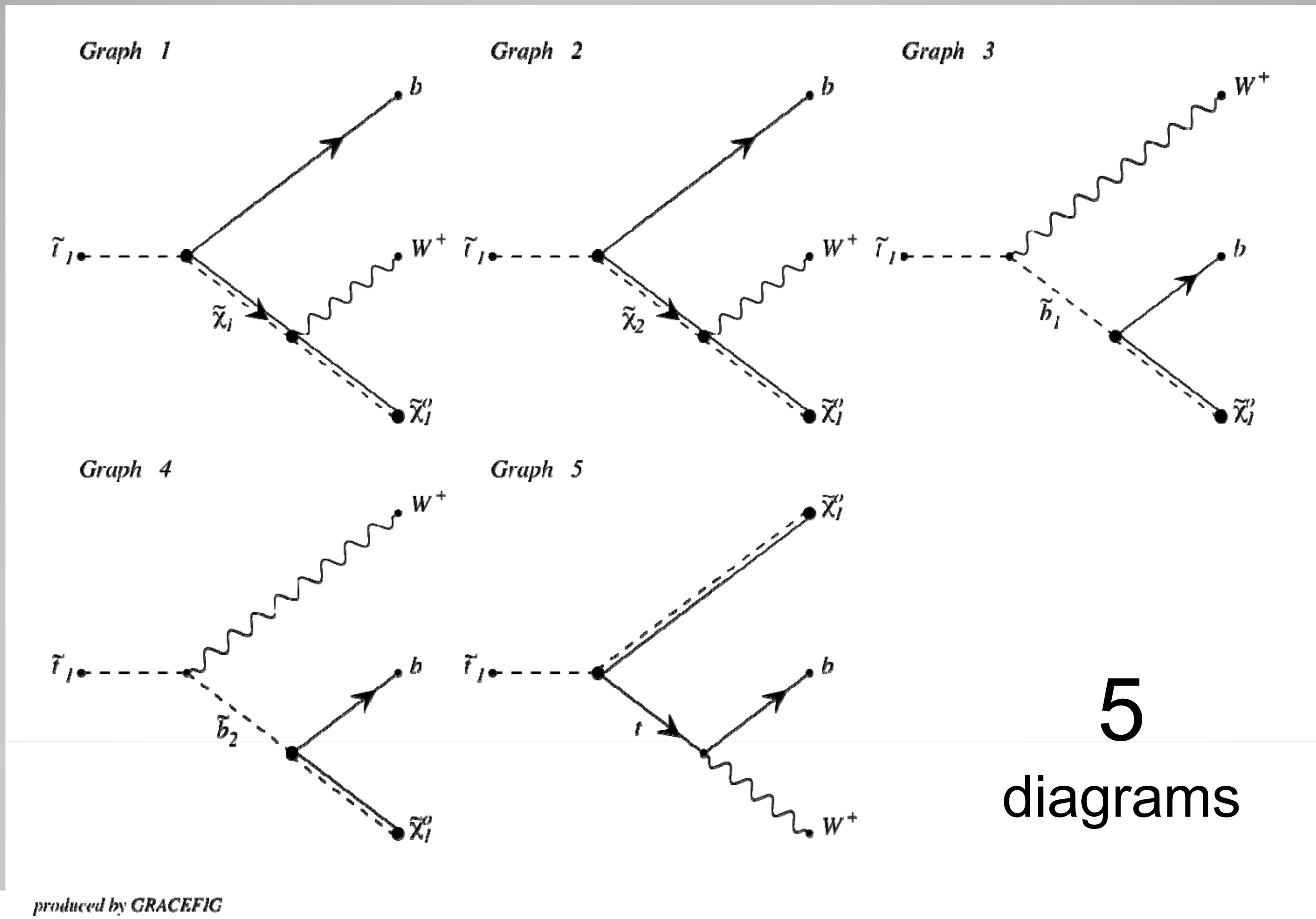
$M_{\tilde{t}_1} > 368.6\text{GeV}$

$$\tilde{t}_1 \rightarrow t\, \tilde{\chi}_1^0 \quad \left(M_{\tilde{t}_1} > M_t + M_{\tilde{\chi}_1^0} = 368.6\text{GeV} \right)$$

$$\tilde{t}_1 \rightarrow b\, \tilde{\chi}_1^+ \quad \left(M_{\tilde{t}_1} > M_b + M_{\tilde{\chi}_1^+} = 400.2\text{GeV} \right)$$

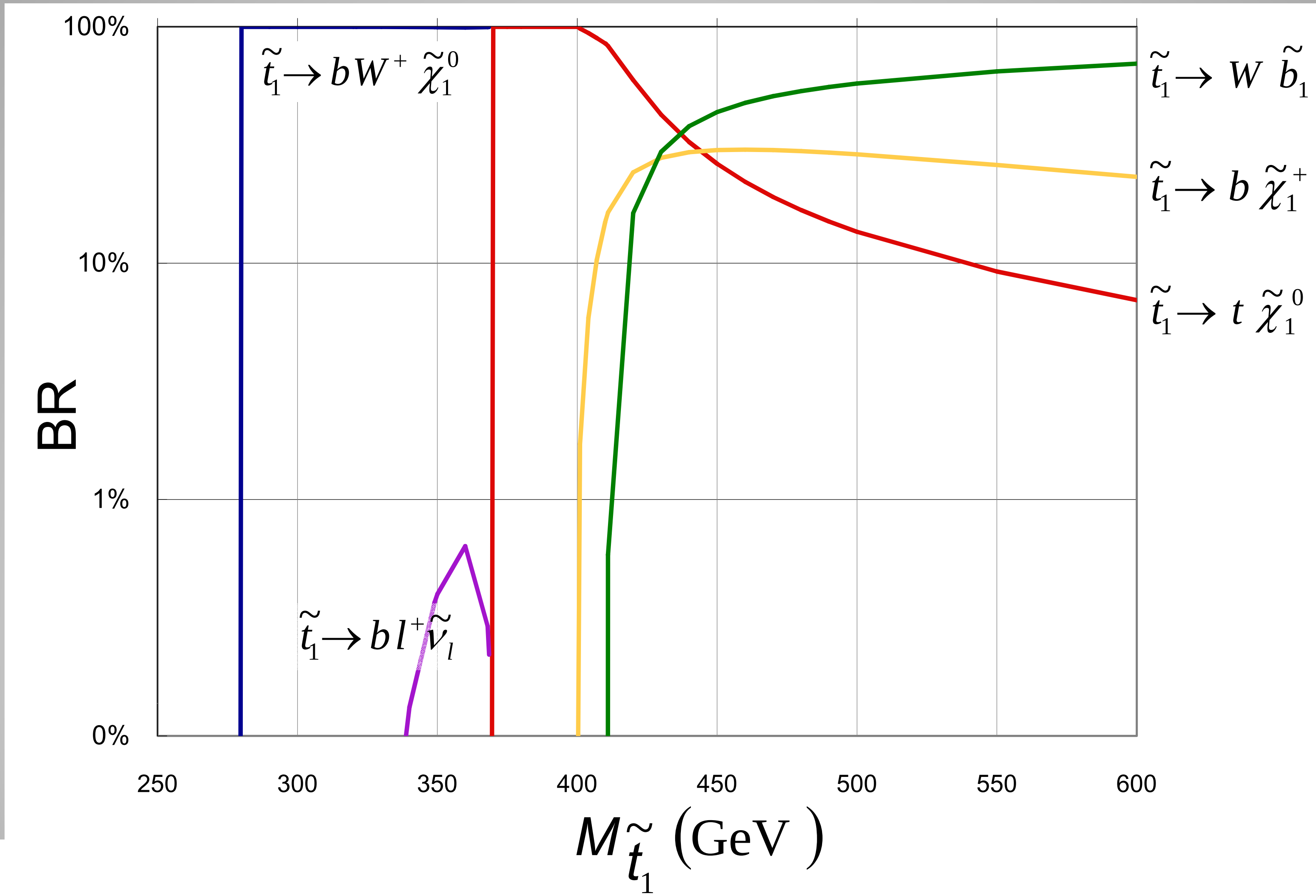
$$\tilde{t}_1 \rightarrow W\, \tilde{b}_1 \quad \left(M_{\tilde{t}_1} > M_W + M_{\tilde{b}_1} = 410.2\text{GeV} \right)$$

Feynman diagrams $\tilde{t}_1 \rightarrow b W^+ \tilde{\chi}_1^0$ (tree)

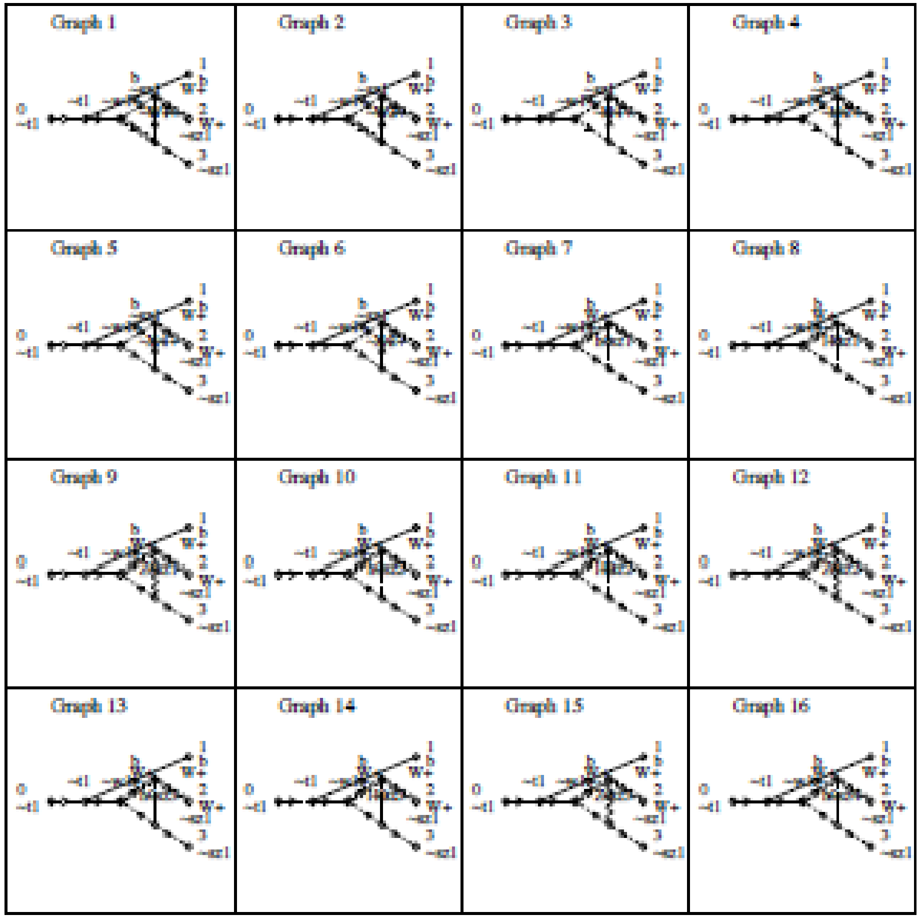


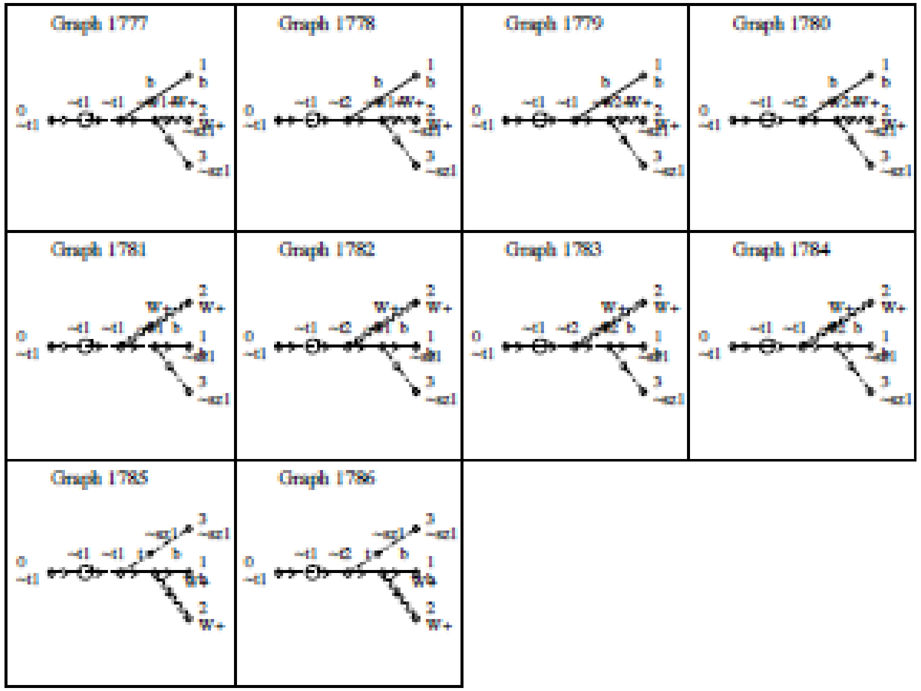
5
diagrams

Branching ratio of stop1 decay vs. $M_{\tilde{t}_1}$



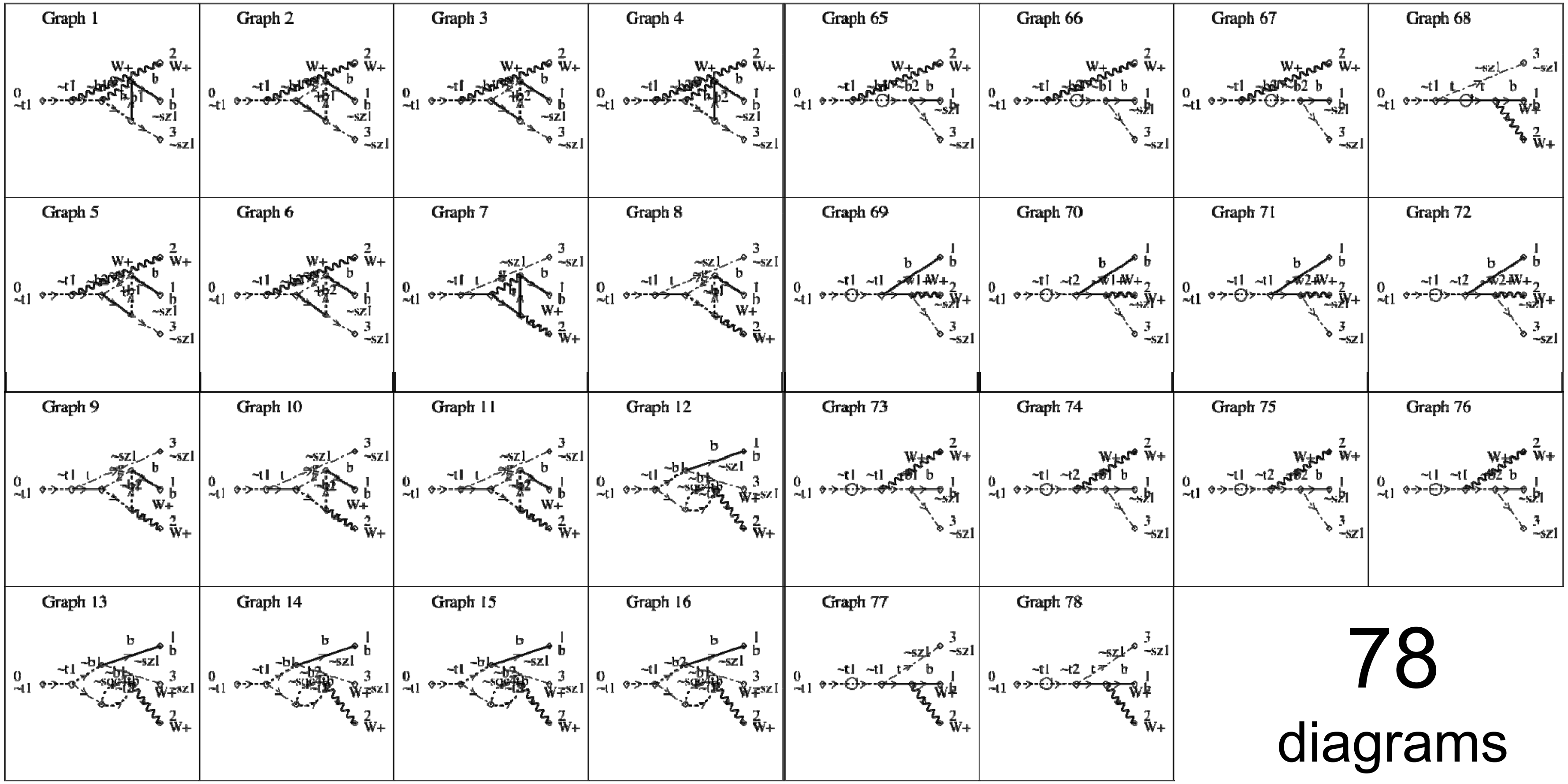
Feynman diagrams (Electroweak 1-loop)





1786
diagrams

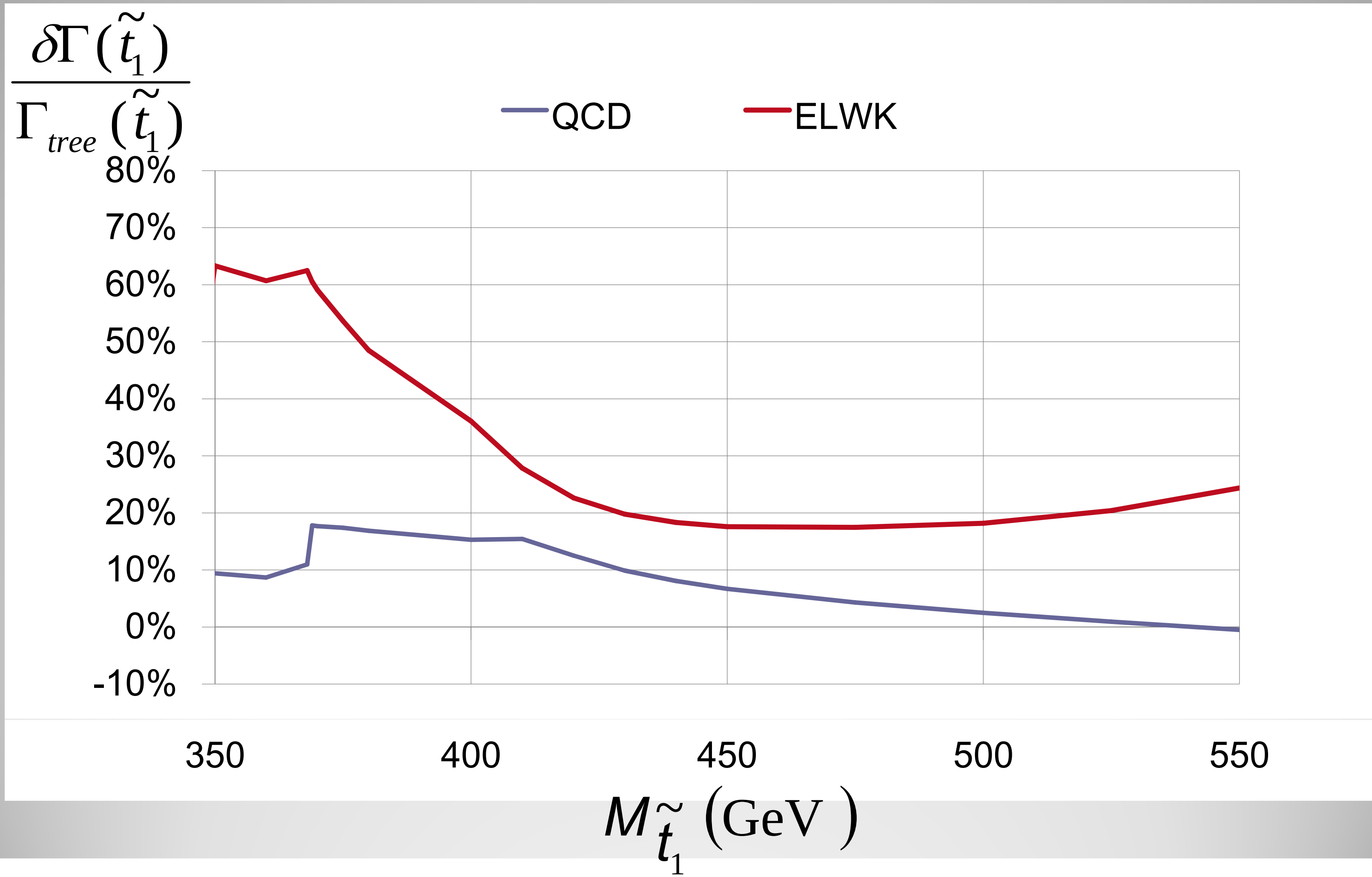
Feynman diagrams (QCD 1-loop)



78

diagrams

1-loop corrections for total width of stop1 vs. $M_{\tilde{t}_1}$



5. Sfermion-NLG

NLG formalism is extend as follows:

$$F_{W^+} = (\partial_\mu + ie\tilde{\alpha}A_\mu + igc_W\tilde{\beta}Z_\mu)W^{+\mu} + i\xi_W \frac{g}{2}(v + \tilde{\delta}_h h^0 + \tilde{\delta}_H H^0 + i\tilde{\kappa}G^0)G^+$$

$$+ i\xi_W g\left[\sum_{ij}\left\{\tilde{c}_{ij}^{du}\left(\tilde{d}_i^*\tilde{u}_j\right) + \tilde{c}_{ij}^{sc}\left(\tilde{s}_i^*\tilde{c}_j\right) + \tilde{c}_{ij}^{bt}\left(\tilde{b}_i^*\tilde{t}_j\right)\right\} + \sum_i\left\{\tilde{c}_i^e\left(\tilde{e}_i^*\tilde{\nu}_e\right) + \tilde{c}_i^\mu\left(\tilde{\mu}_i^*\tilde{\nu}_\mu\right) + \tilde{c}_i^\tau\left(\tilde{\tau}_i^*\tilde{\nu}_\tau\right)\right\}\right]$$

$$F_{W^-} = (\partial_\mu - ie\tilde{\alpha}A_\mu - igc_W\tilde{\beta}Z_\mu)W^{-\mu} - i\xi_W \frac{g}{2}(v + \tilde{\delta}_h h^0 + \tilde{\delta}_H H^0 - i\tilde{\kappa}G^0)G^-$$

$$- i\xi_W g\left[\sum_{ij}\left\{\tilde{c}_{ij}^{ud}\left(\tilde{u}_i^*\tilde{d}_j\right) + \tilde{c}_{ij}^{cs}\left(\tilde{c}_i^*\tilde{s}_j\right) + \tilde{c}_{ij}^{tb}\left(\tilde{t}_i^*\tilde{b}_j\right)\right\} + \sum_i\left\{\tilde{c}_i^e\left(\tilde{\nu}_e^*\tilde{e}_i\right) + \tilde{c}_i^\mu\left(\tilde{\nu}_\mu^*\tilde{\mu}_i\right) + \tilde{c}_i^\tau\left(\tilde{\nu}_\tau^*\tilde{\tau}_i\right)\right\}\right]$$

$$F_Z = \partial_\mu Z^\mu + \xi_Z \frac{g_Z}{2}(v + \tilde{\varepsilon}_h h^0 + \tilde{\varepsilon}_H H^0)G^0$$

$$+ \xi_Z g_Z\left[\sum_{ij}\left\{\tilde{c}_{ij}^{uu}\left(\tilde{u}_i^*\tilde{u}_j\right) + \tilde{c}_{ij}^{dd}\left(\tilde{d}_i^*\tilde{d}_j\right) + \tilde{c}_{ij}^{cc}\left(\tilde{c}_i^*\tilde{c}_j\right) + \tilde{c}_{ij}^{ss}\left(\tilde{s}_i^*\tilde{s}_j\right) + \tilde{c}_{ij}^{tt}\left(\tilde{t}_i^*\tilde{t}_j\right) + \tilde{c}_{ij}^{bb}\left(\tilde{b}_i^*\tilde{b}_j\right)\right\}\right.$$

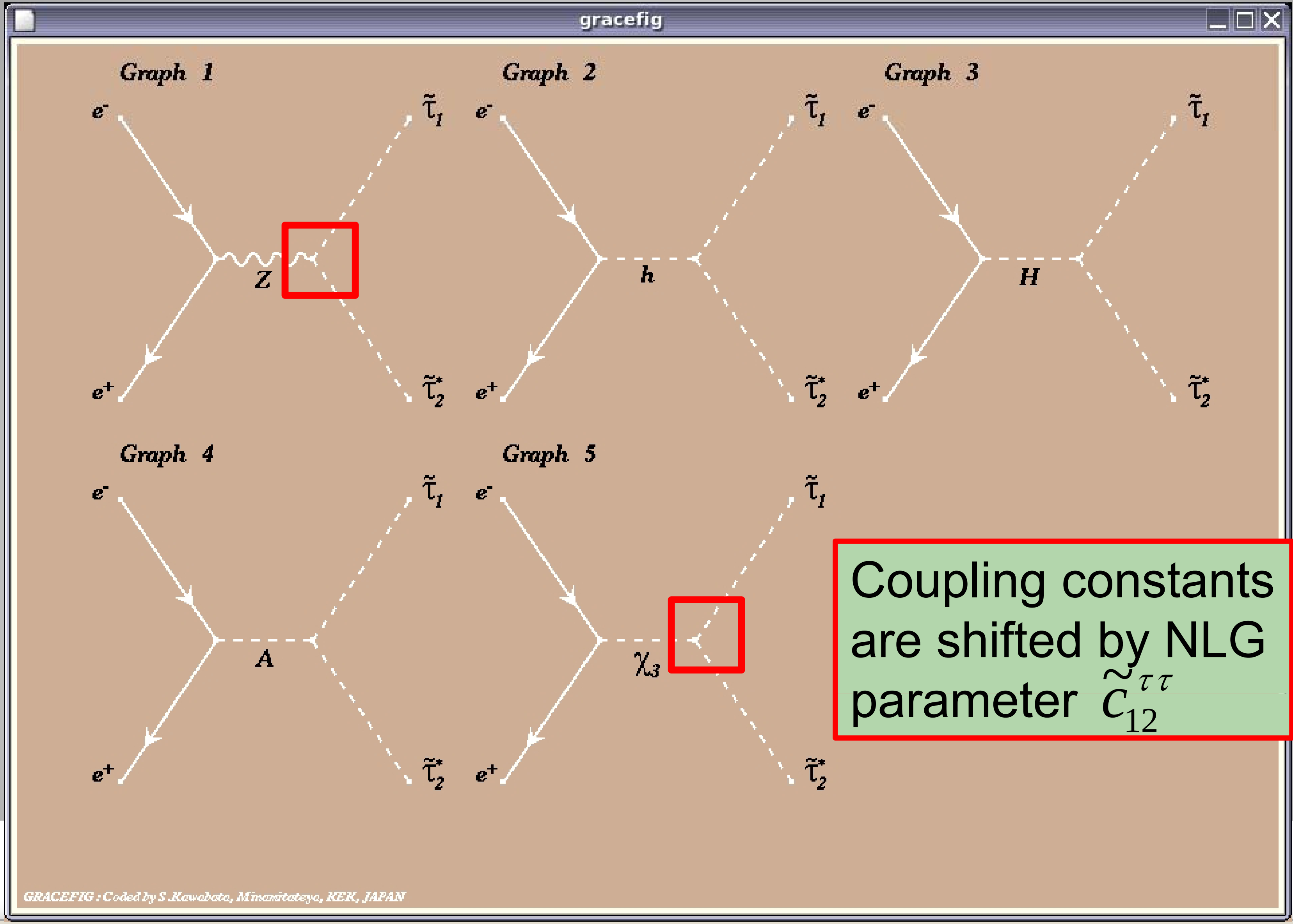
$$\left. + \tilde{c}^{\nu_e\nu_e}\left(\tilde{\nu}_e^*\tilde{\nu}_e\right) + \tilde{c}^{\nu_\mu\nu_\mu}\left(\tilde{\nu}_\mu^*\tilde{\nu}_\mu\right) + \tilde{c}^{\nu_\tau\nu_\tau}\left(\tilde{\nu}_\tau^*\tilde{\nu}_\tau\right) + \sum_{ij}\left\{\tilde{c}_{ij}^{ee}\left(\tilde{e}_i^*\tilde{e}_j\right) + \tilde{c}_{ij}^{\mu\mu}\left(\tilde{\mu}_i^*\tilde{\mu}_j\right) + \tilde{c}_{ij}^{\tau\tau}\left(\tilde{\tau}_i^*\tilde{\tau}_j\right)\right\}\right]$$

Vertices are tested in tree-level order

tested processes	NLG parameters
$\tilde{\nu}_\tau + \tilde{\nu}_\tau^* \to \tilde{\nu}_\tau + \tilde{\nu}_\tau^*$	$\tilde{c}^{\nu_\tau \nu_\tau} = \text{param}$
$\tilde{\nu}_\tau + \tilde{\nu}_\tau^* \to \tilde{\tau}_i + \tilde{\tau}_j^* \; (i, j = 1,2)$	$\tilde{c}^{\nu_\tau \nu_\tau} = \text{param}, \; \tilde{c}_{ij}^{\tau\tau} = 1$
$\tilde{\nu}_\tau + \tilde{\nu}_\tau^* \to \tilde{\tau}_i + \tilde{\tau}_j^* \; (i, j = 1,2)$	$\tilde{c}_i^{\tau} = \text{param} \left(, \tilde{c}_j^{\tau} = \text{param} \right)$
$\tilde{\tau}_i + \tilde{\tau}_j^* \to \tilde{\tau}_k + \tilde{\tau}_l^* \; (i, j, k, l = 1,2)$	$\tilde{c}_{ij}^{\tau\tau} = \text{param} \left(, \; \tilde{c}_{kl}^{\tau\tau} = 1 \right)$
$\tilde{\nu}_\tau + \tilde{\nu}_\tau^* \to \tilde{\nu}_\mu + \tilde{\nu}_\mu^*$	$\tilde{c}^{\nu_\tau \nu_\tau} = \text{param}, \tilde{c}^{\nu_\mu \nu_\mu} = 1$
$\tilde{\nu}_\tau + \tilde{\nu}_\tau^* \to \tilde{\mu}_i + \tilde{\mu}_j^* \; (i, j = 1,2)$	$\tilde{c}^{\nu_\tau \nu_\tau} = 1, \; \tilde{c}_{ij}^{\mu\mu} = \text{param}$
$\tilde{\nu}_\tau^* + \tilde{\tau}_i \to \tilde{\nu}_\mu^* + \tilde{\mu}_j \; (i, j = 1,2)$	$\tilde{c}_j^{\mu} = \text{param}, \tilde{c}_i^{\tau} = 1$
$\tilde{\tau}_i^* + \tilde{\nu}_\tau \to \tilde{\mu}_j^* + \tilde{\nu}_\mu \; (i, j = 1,2)$	$\tilde{c}_j^{\mu} = \text{param}, \tilde{c}_i^{\tau} = 1$
$\tilde{\tau}_i + \tilde{\tau}_j^* \to \tilde{\mu}_k + \tilde{\mu}_l^* \; (i, j, k, l = 1,2)$	$\tilde{c}_{ij}^{\tau\tau} = \text{param}, \; \tilde{c}_{kl}^{\mu\mu} = 1$

param=-2000, -1000, 0, 1000, 2000

Example $e^- + e^+ \to \tilde{\tau}_1 + \tilde{\tau}_2^*$



Coupling constants are shifted by NLG parameter $\tilde{c}_{12}^{\tau\tau}$

Parameters:

$M\tilde{\tau}_1 = 495.8363\,\mathrm{GeV} \quad M\tilde{\tau}_2 = 508.2332\,\mathrm{GeV} \quad (M_e = 300\,\mathrm{GeV})$

Numerical results $\left(\sqrt{s} = 1500\,\mathrm{GeV}\right)$

$\tilde{C}_{12}^{\tau\tau}$ = {
0: ANS = 8.9792964724402614470699931753014867
10000: ANS = 8.9792964724402614470699931753013881

OK

$\tilde{C}_{12}^{\tau\tau}$ =0:	$\tilde{C}_{12}^{\tau\tau}$ =10000:
M(1, 1)=	M(1, 1)=
0.10269237512119918812995945384209772E-02	0.10269449195937336652852973634412653E-02
M(1, 4)=	M(1, 4)=
-0.38529019804590944104014323681077317E-03	-0.66404570223518680945209228534251260E-03
M(1, 5) =	M(1, 5) =
-0.29070005693539901125229604898770801E-05	-0.50235966130396134337994982683375445E-05
M(4, 5)=	M(4, 5)=
0.10425754169753368492956162927317175	0.10453629720172296229797357832170511
M(5, 5)=	M(5, 5)=
0.78661937057133369193446324698668517E-03	0.79083139427696315459131349752335842E-03

6. Summary

- ✓ QCD and Electroweak 1-loop corrections
  for 2-body and 3-body decays of lighter stop
  ⇨ calculated by GRACE/SUSY-loop

- ✓ $\delta\Gamma$(Electroweak) > $\delta\Gamma$(QCD) : possible
  originated from large Yukawa correction of top

- ✓ NLG formalism is extend
  ⇨ including sfermion bilinear forms
  ⇨ tests are completed in tree-level order