Systematic study of 1-Loop correction on sparticle decay widths using GRACE/SUSY-loop

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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 MSSM

$$F_{W^\pm} = (\partial_\mu \pm ie\tilde{\alpha}A_\mu \pm igc_W\tilde{\beta}Z_\mu)W^{\pm\mu}$$
$$\pm i\xi_W \frac{g}{2}(v + \tilde{\delta}_h h^0 + \tilde{\delta}_H H^0 \pm i\tilde{\kappa}G^0)G^\pm \quad (1)$$

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

$$F_\gamma = \partial_\mu A^\mu \quad (3)$$

Gauge invariant scheme[1]
→ gauge invariance check
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

[1] J.Fujimoto et al., Phys.Rev.D75, 113002('07)

Renormalization Scheme

Electroweak (ELWK) corrections

* On-Mass-Shell scheme

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

* Sfermion sector

$\rightarrow$ residue conditions,
$\tilde{f}_1 - \tilde{f}_2$ decoupling conditions,
SU(2) relations for $\left(\tilde{\ell}_L - \tilde{\nu}_L\right), \left(\tilde{u}_L - \tilde{d}_L\right)$

$$\delta Z^{ext}_{\tilde{t}_2\tilde{t}_2} \neq 0, \quad \delta Z^{ext}_{\tilde{b}_2\tilde{b}_2} \neq 0 \qquad (4)$$

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)
(former version : fictitious mass of gluon, λ)

$$d = 4 - 2\varepsilon$$

$$= 4 + 2\bar{\varepsilon} \quad (5)$$

$$C_{UV} = \frac{1}{\varepsilon}, C_{IR} = \frac{1}{\bar{\varepsilon}} \quad (6)$$

3. MSSM parameters(SPS1a')

GUT scale input parameter

$$m_0 = 100\,\text{GeV}$$
$$m_{1/2} = 250\,\text{GeV}$$
$$A_0 = -100\,\text{GeV}$$
$$\mu > 0$$
$$\tan\beta = 10$$

$$M\tilde{e}_1 = 126\,\text{GeV} \quad M\tilde{e}_2 = 190\,\text{GeV} \quad M\tilde{\nu}_e = 173\,\text{GeV}$$
$$M\tilde{\mu}_1 = 125\,\text{GeV} \quad M\tilde{\mu}_2 = 190\,\text{GeV} \quad M\tilde{\nu}_\mu = 173\,\text{GeV}$$
$$M\tilde{\tau}_1 = 108\,\text{GeV} \quad M\tilde{\tau}_2 = 195\,\text{GeV} \quad M\tilde{\nu}_\tau = 171\,\text{GeV}$$
$$M\tilde{u}_1 = 546\,\text{GeV} \quad M\tilde{u}_2 = 563\,\text{GeV} \quad M\tilde{d}_1 = 546\,\text{GeV}$$
$$M\tilde{d}_2 = 569\,\text{GeV} \quad M\tilde{c}_1 = 546\,\text{GeV} \quad M\tilde{c}_2 = 563\,\text{GeV}$$
$$M\tilde{s}_1 = 546\,\text{GeV} \quad M\tilde{s}_2 = 569\,\text{GeV} \quad M\tilde{t}_1 = 369\,\text{GeV}$$
$$M\tilde{t}_2 = 584\,\text{GeV} \quad M\tilde{b}_1 = 450\,\text{GeV} \quad M\tilde{b}_2 = 544\,\text{GeV}$$
$$M\tilde{\chi}_1^0 = 98\,\text{GeV} \quad M\tilde{\chi}_2^0 = 185\,\text{GeV} \quad M\tilde{\chi}_3^0 = 405\,\text{GeV}$$
$$M\tilde{\chi}_4^0 = 420\,\text{GeV} \quad M\tilde{\chi}_1^+ = 184\,\text{GeV} \quad M\tilde{\chi}_2^+ = 421\,\text{GeV}$$
$$M_{\tilde{g}} = 610\,\text{GeV} \quad M_{A^0} = 425\,\text{GeV} \quad \mu = 399\,\text{GeV}$$
$$M_1 = 100\,\text{GeV} \quad M_2 = 198\,\text{GeV}$$
$$M_t = 178\,\text{GeV} \quad M_b = 4.7\,\text{GeV}$$

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 $m_{\tilde{g}} < m_t + m_{\tilde{t}_2}$)

4. Squark decay

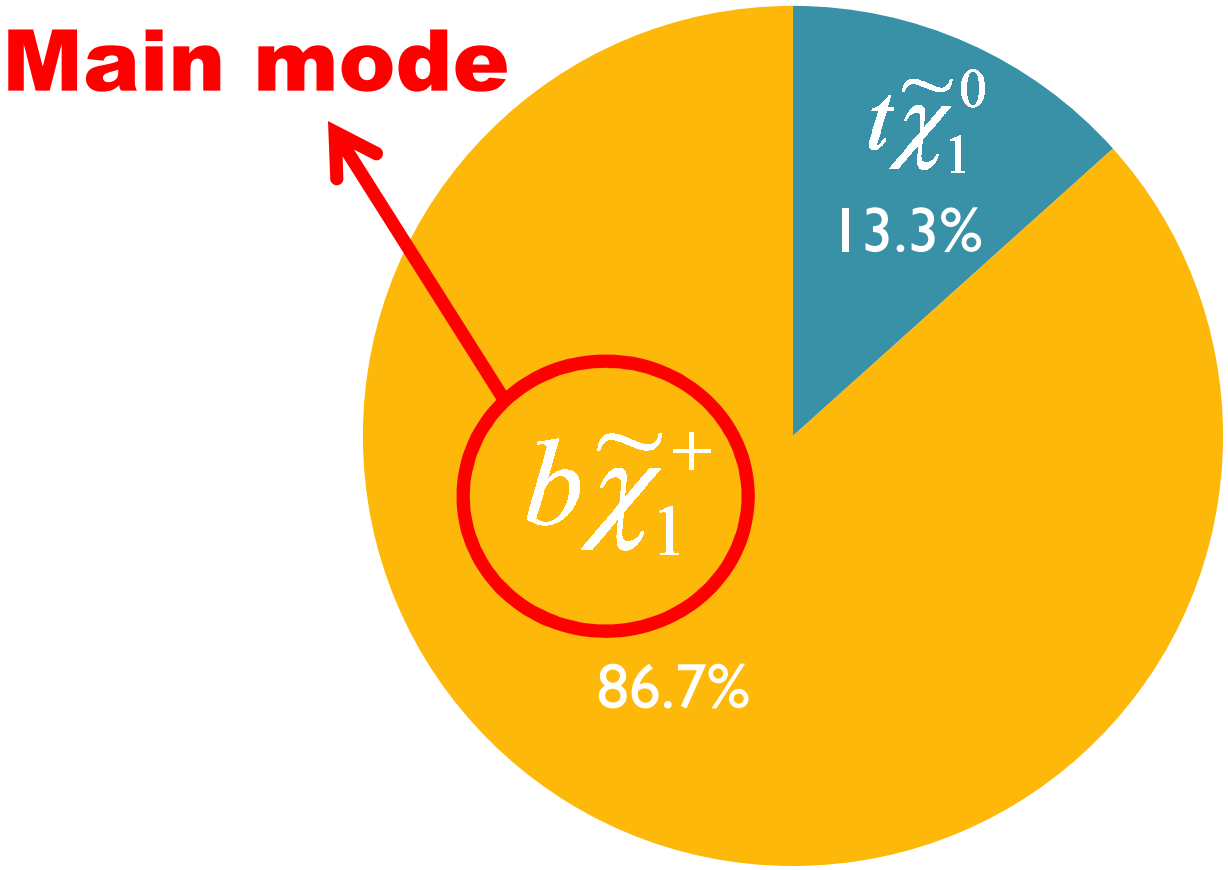
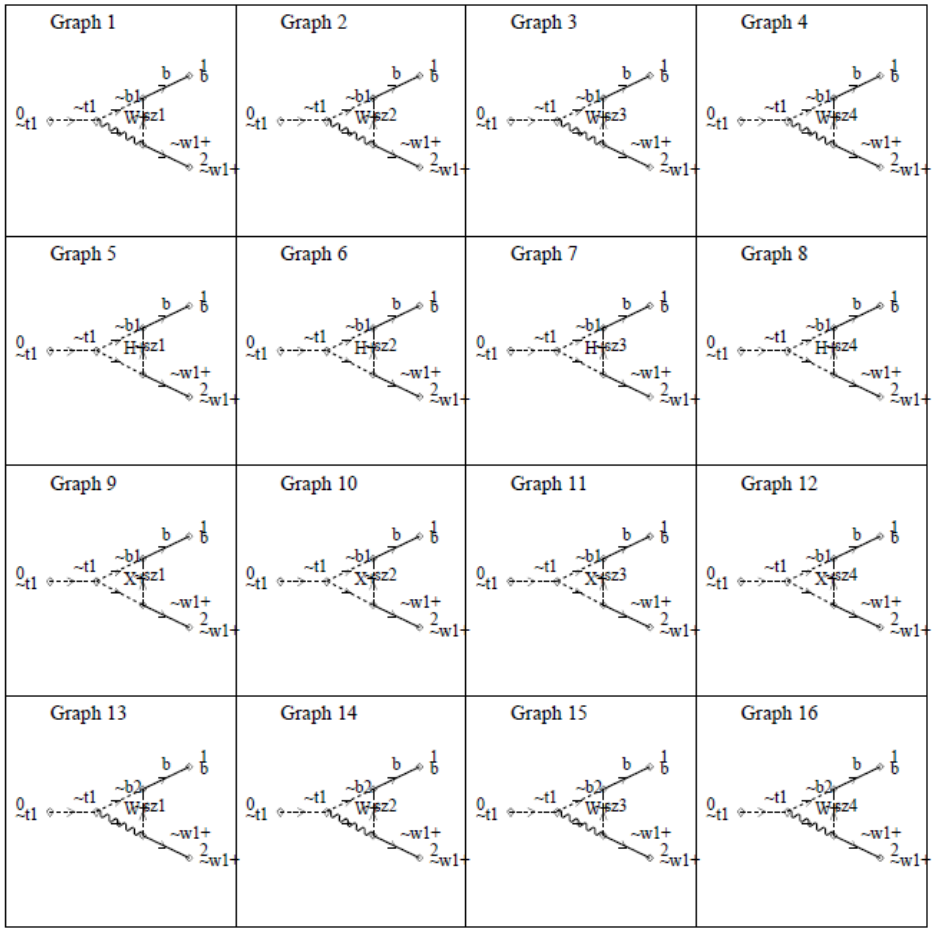
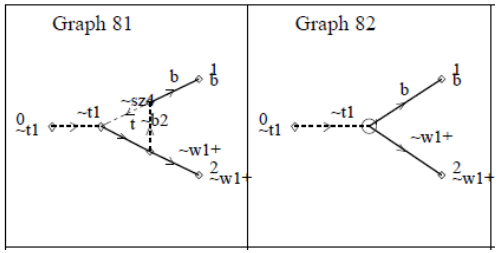


Fig.1: stop1 decay BR (tree)

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

Feynman diagrams(ELWK 1-loop)





82 diagrams

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

- ✓ Independence of nonlinear gauge parameters (NLG)

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

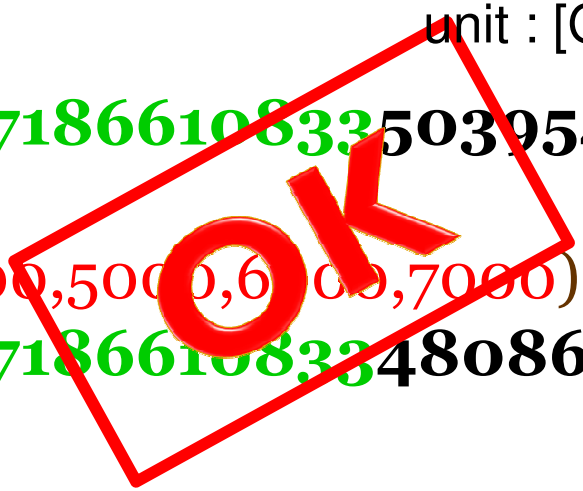
unit : [GeV]

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

Ans = 0.151171157527971271866108335039543 23

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

Ans = 0.151171157527971271866108334808638 36



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

✓Ultraviolet divergence is canceled? (Cuv part dependence)

Case 1 : (Cuv=0) unit : [GeV]

Ans = 0.15117115752797127186610833503954323

Case 2 : (Cuv=1000)

Ans = 0.15117115752797127186[illegible]80279397801

OK

✓Infrared divergence is canceled? (λ dependence)

λ : fictitious photon mass

Case 1 : ($\lambda=1\times10^{-24}$)

Ans = 0.15117115752797127186610833[illegible]03954323

Case 2 : ($\lambda=1\times10^{-27}$)

Ans = 0.15117115752797127186610833519983020

OK

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

- ✓ELWK corrections : Check of cancellation

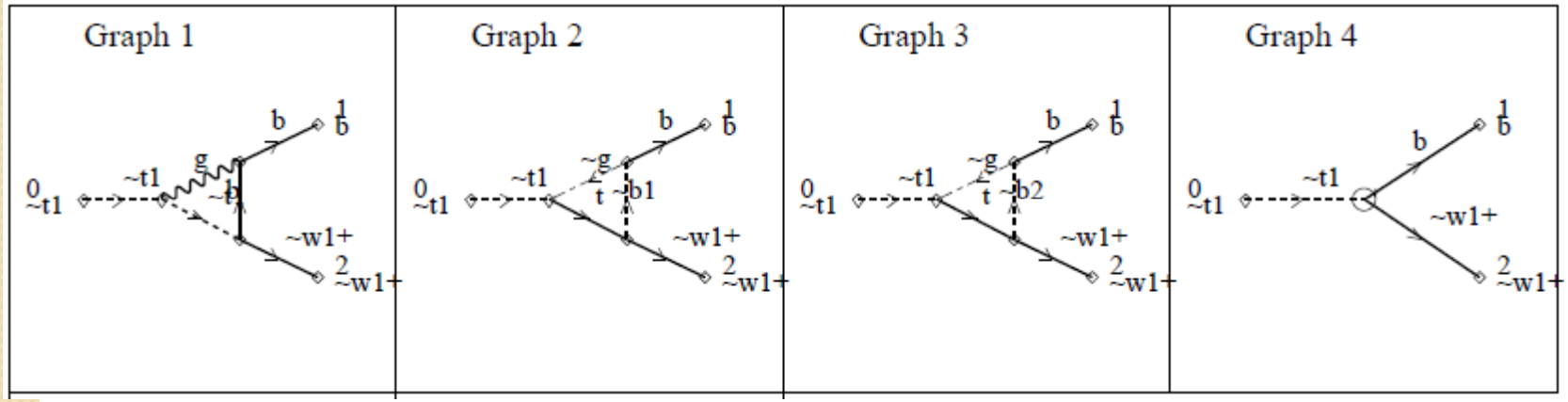
Born : 1.4326728 [GeV]

Table1: check of cancellation (ELWK) 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%

※mass regularization (λ) scheme : -7.1%

Summary of stop1 decay

Table4: summary of stop1 decay unit : [GeV]

	tree	δΓ (QCD) / δΓ (ELWK)	δΓ/tree(QCD) / δΓ/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%

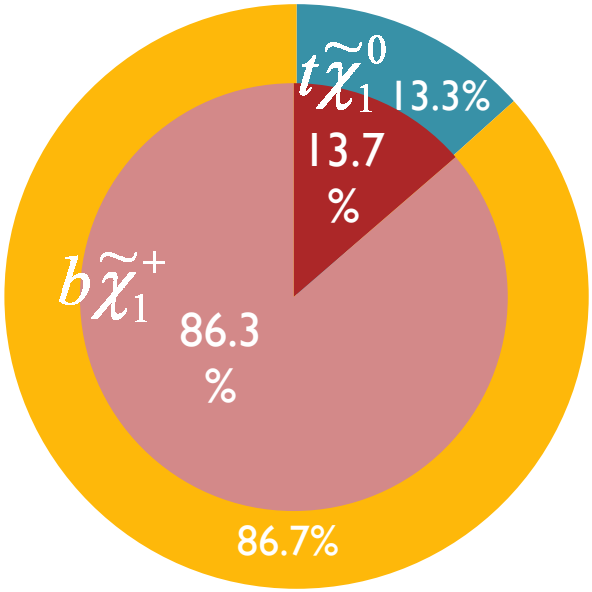


Fig.2: stop1 decay BR (tree&1-loop)

total decay width

Γ (tree) : 1.65 [GeV]
Γ (QCD) : 1.55 [GeV]
Γ (ELWK) : 1.87 [GeV]
Γ (1-loop) : 1.77 [GeV]

3-body decay of light stop

$$\tilde{t}_1 \to b W^+ \tilde{\chi}_1^0$$

$$m_{\tilde{t}_1} > m_b + m_W + m_{\chi_1^0}$$

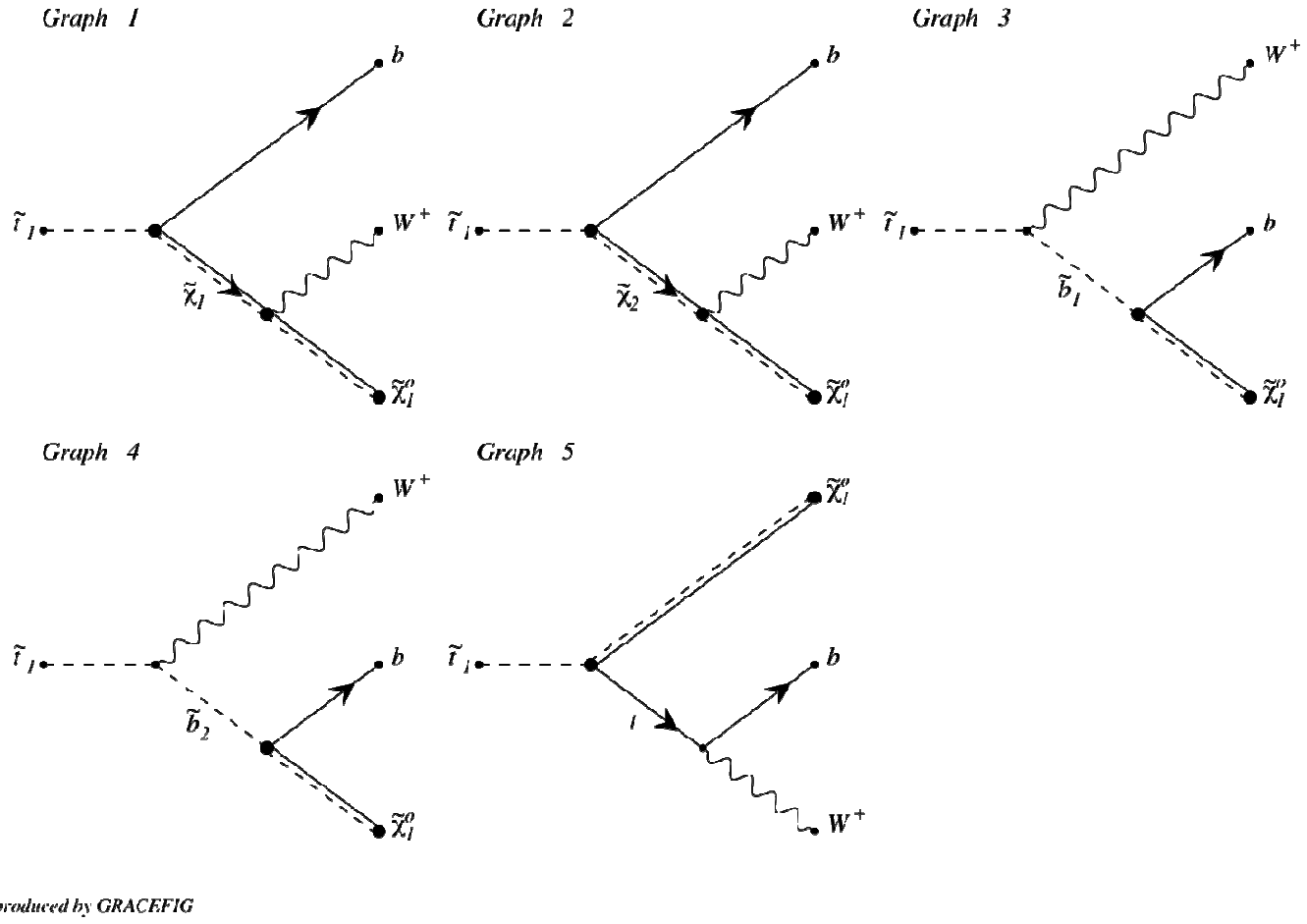
$$m_{\tilde{t}_1} < m_t + m_{\chi_1^0} \qquad m_{\tilde{t}_1} < m_b + m_{\chi_1^+}$$

$$m_{\tilde{t}_1} = 300\text{GeV} \qquad m_{\tilde{\chi}_1^0} = 195\text{GeV}$$

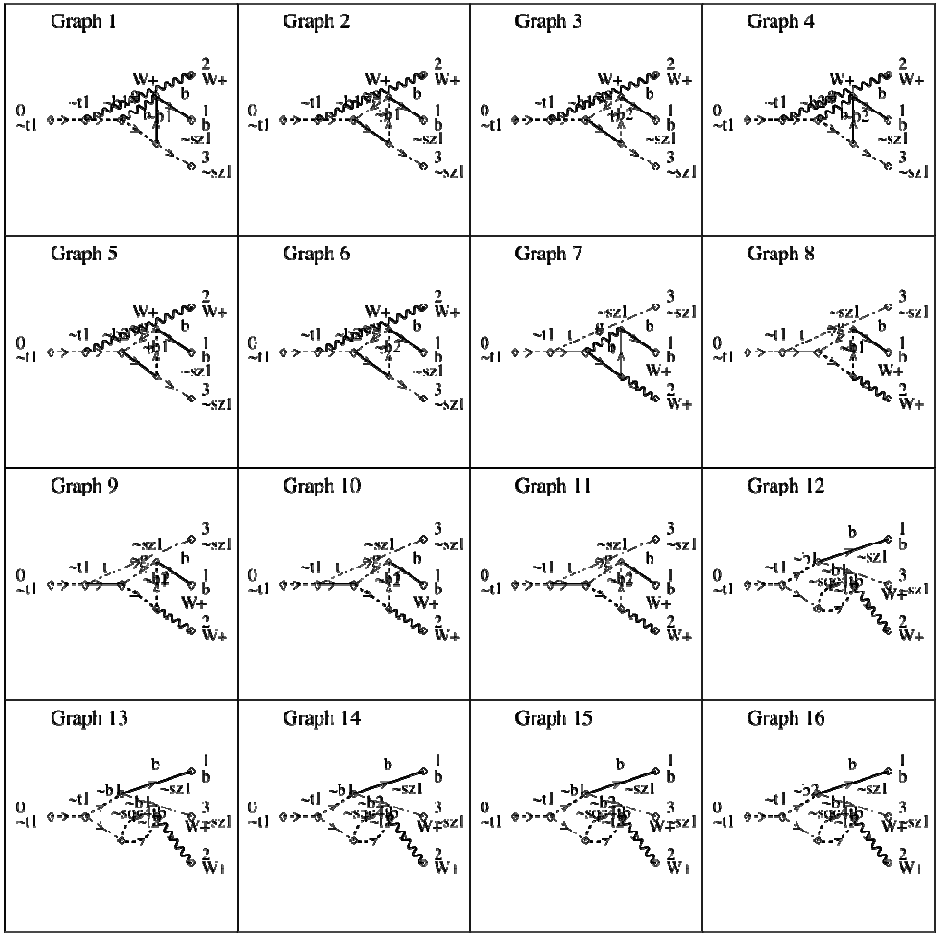
$$M_2 = 400\text{GeV} \qquad m_{\tilde{\chi}_1^+} = 396\text{GeV}$$

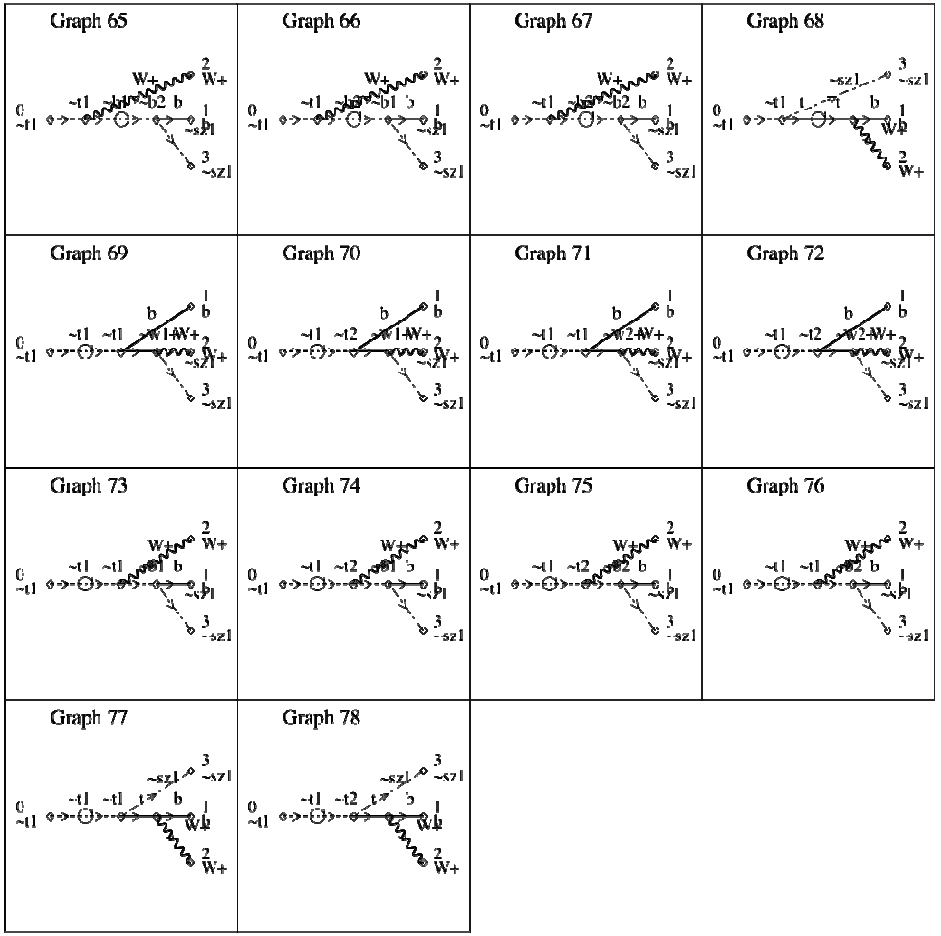
$$\mu = -750\text{GeV} \qquad m_{\tilde{g}} = 1390\text{GeV}$$

Feynman diagrams (tree)



Feynman diagrams (QCD 1-loop)





$$\tilde{t}_1 \to bW^+\tilde{\chi}_1^0$$

✓QCD corrections : Check of cancellation

Born : 6.637×10^{-7} [GeV]

Table5: check of cancellation (QCD) unit : [GeV]

λ	10^{-24}	10^{-27}	10^{-24}
kc	10^{-3}	10^{-3}	10^{-5}
loop+soft ($\times10^{-7}$)	-4.289	-4.290	-7.174
hard ($\times10^{-7}$)	5.251	5.251	8.135
sum ($\times10^{-7}$)	0.962	0.963	0.963
correction	14.5%	14.5%	14.5%

mass regularization (λ) scheme

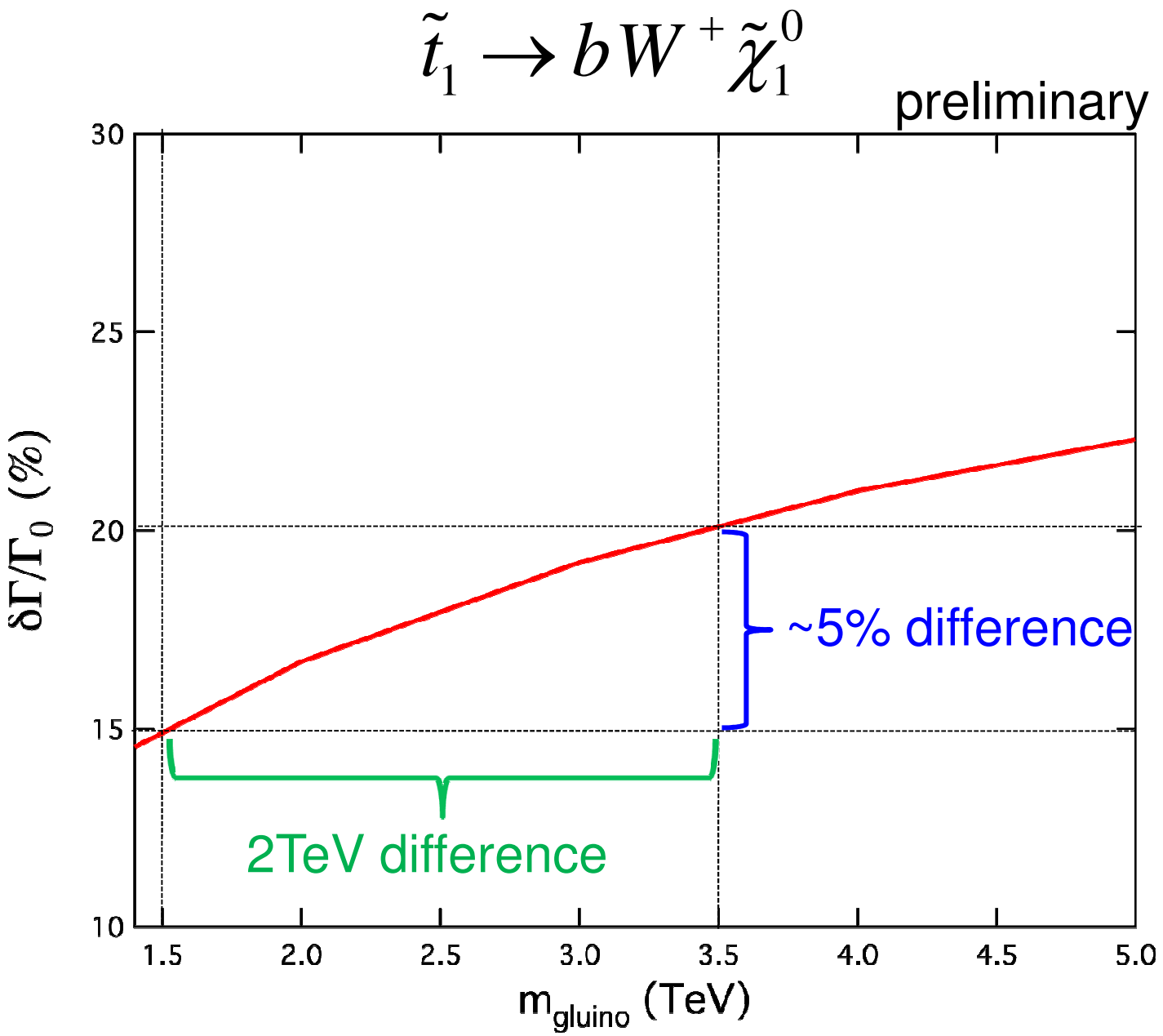


Fig.3: gluino mass VS. 1-loop correction

5. Gluino decay

SPS1a'

Table6: summary of gluino decay

unit : [GeV]

	tree	δΓ (QCD) δΓ (ELWK)	δΓ/tree(QCD) δΓ/tree(ELWK)	total
$\tilde{g} \to b\tilde{b}_1$	3.73207	-0.67035 0.09205	-18.0% 2.5%	-15.5%
$\tilde{g} \to t\tilde{t}_1$	1.05812	-0.13785 0.01232	-13.0% 1.2%	-16.8%

preliminary

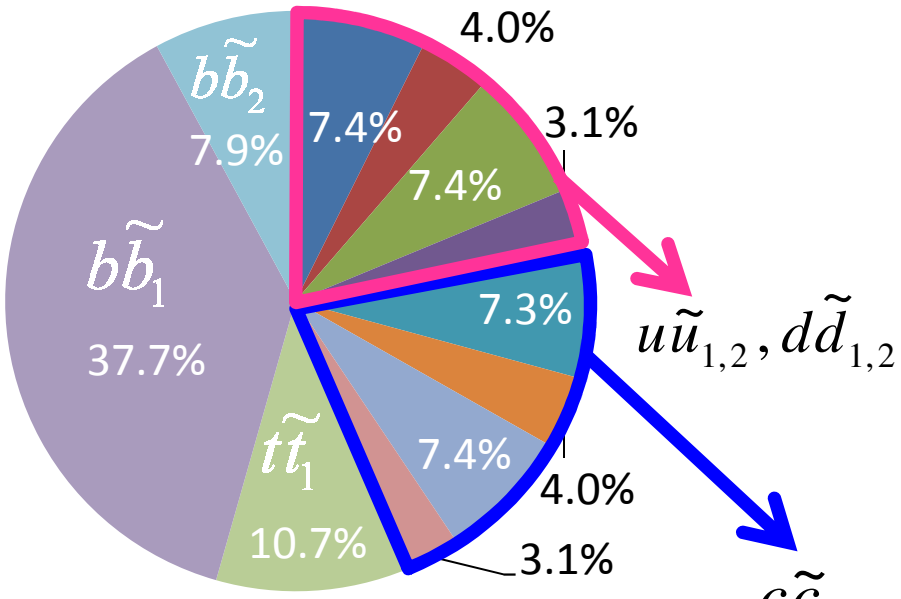


Fig.4: gluino decay BR (tree)

total decay width

Γ (tree) : 9.91 [GeV]
Γ (QCD) : 8.95 [GeV]
Γ (ELWK) : 10.09 [GeV]
Γ (1-loop) : 9.12 [GeV]

SPS1a'

Table6: summary of gluino decay

unit : [GeV]

	tree	δΓ (QCD) / δΓ (ELWK)	δΓ/tree(QCD) / δΓ/tree(ELWK)	total
$\tilde{g} \to b\tilde{b}_1$	3.73207	-0.67035 0.09205	-18.0% 2.5%	-15.5%
$\tilde{g} \to t\tilde{t}_1$	1.05812	-0.13785 0.01232	-13.0% 1.2%	-16.8%

preliminary

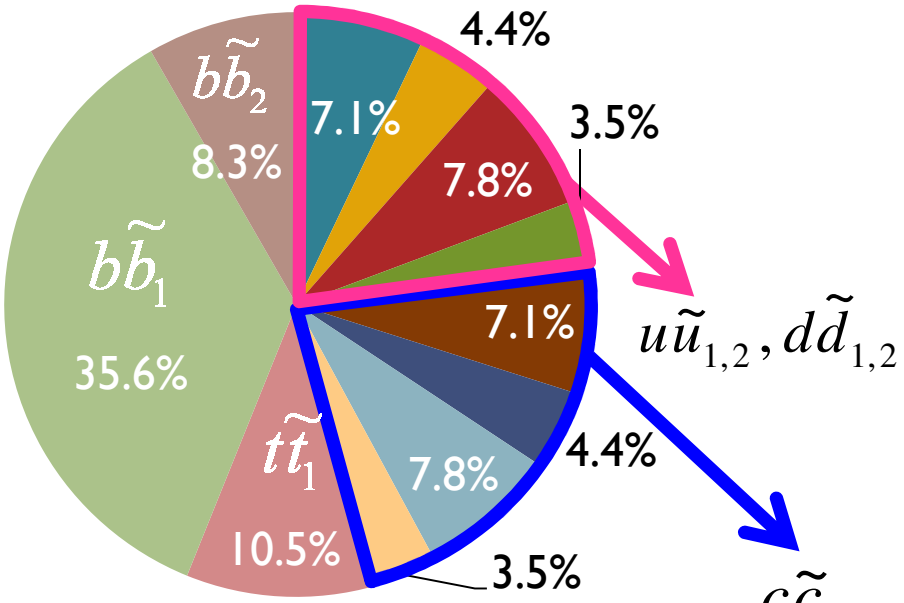


Fig.5: gluino decay BR (1-loop)

total decay width

Γ (tree) : 9.91 [GeV]
Γ (QCD) : 8.95 [GeV]
Γ (ELWK) : 10.09 [GeV]
Γ (1-loop) : 9.12 [GeV]

Comparison with reference[2]

$\tilde{g} \rightarrow t\tilde{t}_1$

[2] W. Beenakker et al., “STOP DECAYS IN SUSY-QCD”

Input parameter set: m0 = 400 GeV, A0 = 200 GeV, μ > 0

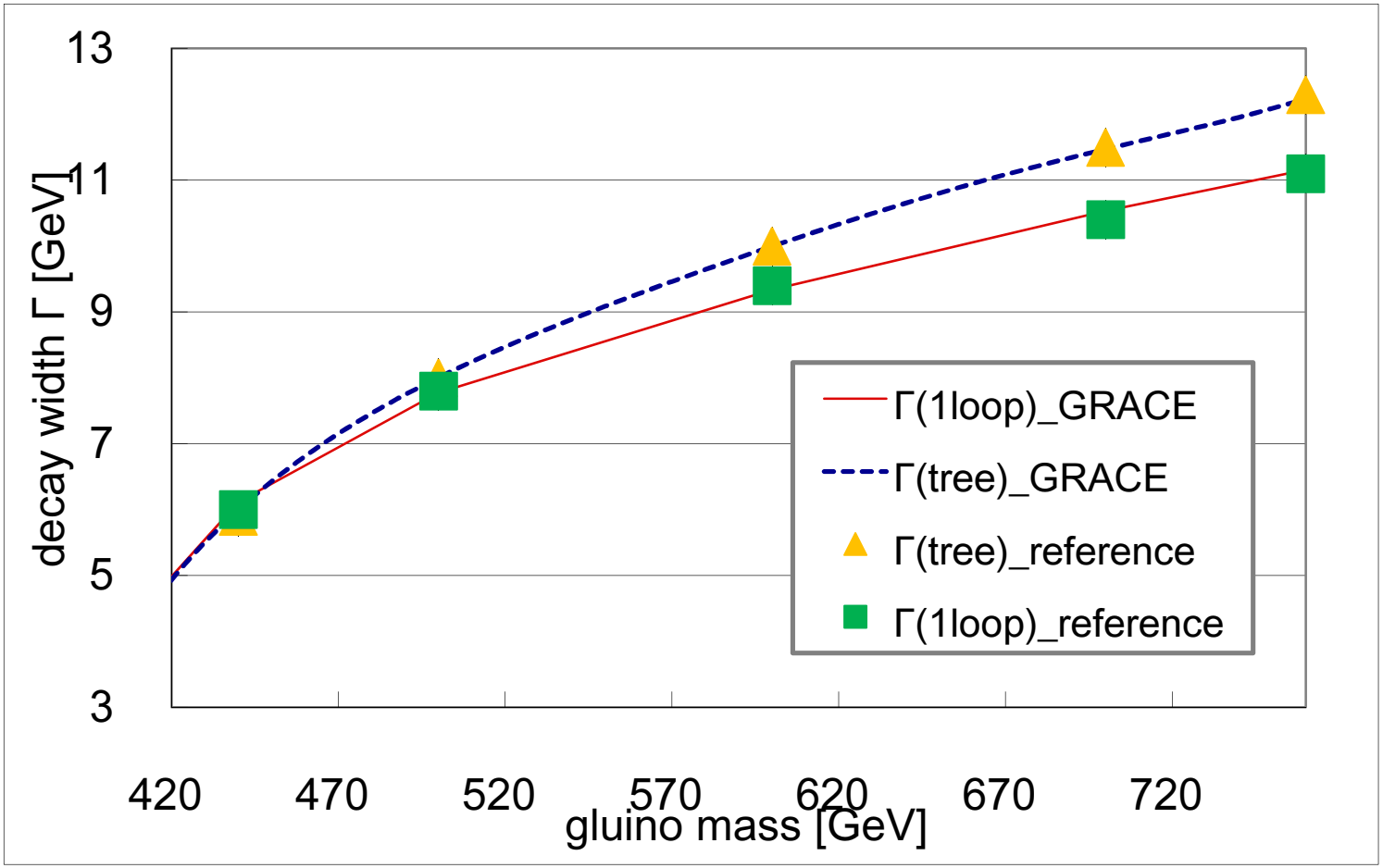


Fig.6: gluino mass VS. decay width

6. Summary

- GRACE/SUSY upgrade
  QCD/SQCD correction … DR-bar scheme
- Physical processes
  2-body & 3-body decays
  sfermion $\tilde{f}$, gluino $\tilde{g}$
  (chargino $\tilde{\chi}^{+}$, neutralino $\tilde{\chi}^{0}$)
  $\rightarrow$ calculated already

  J.Fujimoto et al., Phys.Rev.D75, 113002('07)

Future plan

To extend the range for multi-body channels

Backup

References

[1] J.Fujimoto, T.Ishikawa, M.Jimbo, T.Kon, Y.Kurihara, M.Kuroda, Phys.Rev.D75, 113002('07)

[2] W. Beenakker, R. Höpker, T. Plehn and P. M. Zerwas "STOP DECAYS IN SUSY-QCD" hep-ph/9610313v1, 10 Oct 1996 **Z.Phys.C75:349-356,1997**

Performance of computation: sample $\tilde{b}_2 \to \tilde{\chi}_1^+ t$

- Case-1 : tree : Intel Core2(1.06GHz, 1.014GB)
  - 2-body(tree) : less than 0.1[s] (one p.s. point)
  - 3-body(photon radiation) : 3[s] per iteration (MC integral, Ncall = 100,000)
- Case-2: 1-loop : Intel Xeon E5430(2.66GHz, 4GB)
  - From graph generation to making executable: < 1[m]
  - Source code(Matrix Element) : 672 lines (FORTRAN)
  - Executable module : 20[MB]
  - 2-body(1-loop) : 0.5[s] (one p.s. point)

Comparison to reference[3] (stop1 decay)

	tree	δΓ/tree(QCD) / δΓ/tree(ELWK)	treeBR	treeBR (GHS)	1loopBR	1loopBR (GHS)
$\tilde{t}_1 \to b\tilde{\chi}_1^+$	0.209	-19.9% / 3.0%	94.2%	94.2	93.7%	93.5%
$\tilde{t}_1 \to t\tilde{\chi}_1^0$	3.401	-10.9% / 1.7%	5.8%	5.8%	6.3%	6.5%

[3] Jaume Guasch, Wolfgang Hollik, Joan Sola
"Fermionic decays of sfermions: a complete discussion at one-loop order"
hep-ph/0207364v2, 3 Dec 2002

Physical result

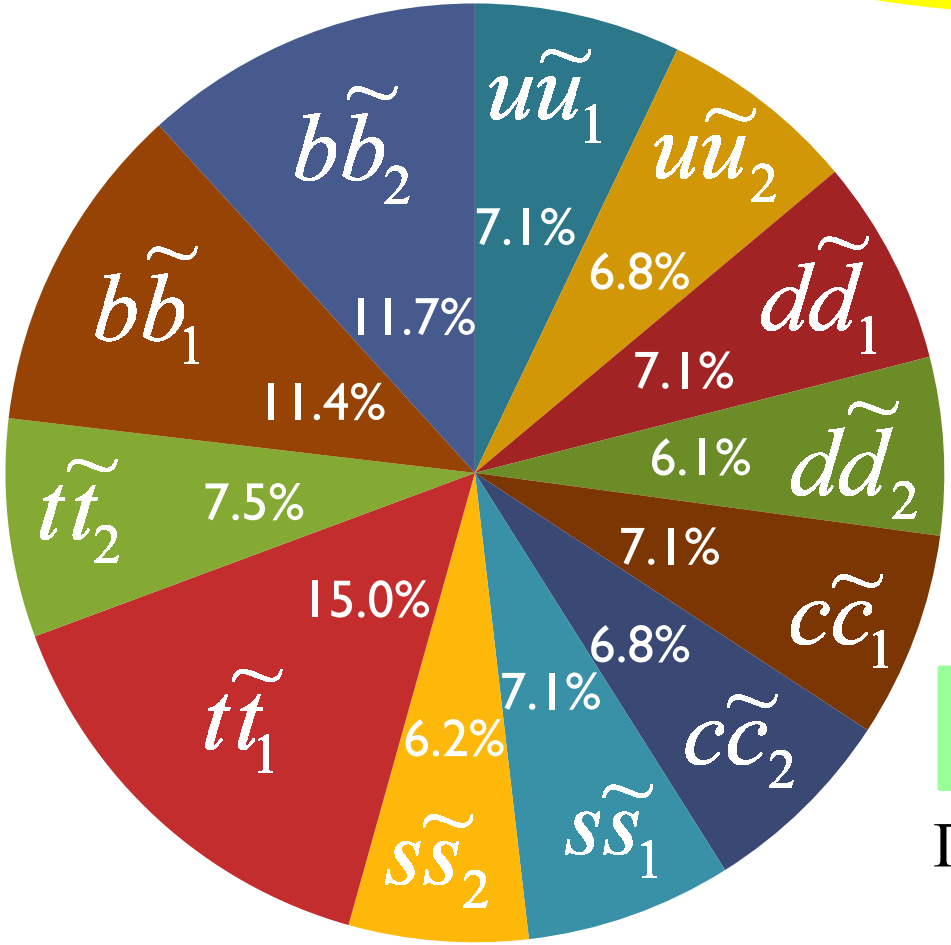
SPS1a'

$$\tilde{g} \to t\tilde{t}_1 \to t(b\tilde{\chi}_1^+)$$

- Branching ratio(tree) : 9.25%
- Branching ratio(tree+QCDcorr.) : 9.67%
- Branching ratio(tree+ELWKcorr.) : 9.26%
- Branching ratio(tree+1loopcorr.) : 9.69%

Gluino decay BR (tree)

light stop scenario



total decay width

Γ (tree) : 314.18 [GeV]

Fig.7:gluino decay BR (tree)

Mass Shifts in SPS1a' parameter set

For Higgs : $h^0, H^{\pm}$

$$m_S^2 - \left(m_S^{tree}\right)^2 - \hat{\Sigma}_S\left(m_S^2\right) = 0 \qquad (7)$$

$$\begin{cases} m_{h^0} : 89.30 \rightarrow 107.12\,\text{GeV} \\ m_{H^{\pm}} : 432.43 \rightarrow 432.75\,\text{GeV} \end{cases}$$

For Neutralinos : $\chi_2^0, \chi_3^0, \chi_4^0$

$$m_\chi - m_\chi^{tree} - \hat{\Sigma}_\chi\left(m_\chi\right) = 0 \qquad (8)$$

$$\begin{cases} m_{\chi_2^0} : 184.55 \rightarrow 184.62\,\text{GeV} \\ m_{\chi_3^0} : 405.14 \rightarrow 398.30\,\text{GeV} \\ m_{\chi_4^0} : 420.49 \rightarrow 413.39\,\text{GeV} \end{cases}$$

where $\hat{\Sigma}_S, \hat{\Sigma}_\chi$: renormalized self-energy functions