

Imprint of quark flavor violating SUSY in $h(125)$ decays at ILC

K. Hidaka
Tokyo Gakugei University

Collaboration with
H. Eberl, E. Ginina (HEPHY Vienna)

References:

Phys. Rev. D 91 (2015) 015007 [arXiv:1411.2840 [hep-ph]]
JHEP 1606 (2016) 143 [arXiv:1604.02366 [hep-ph]]
IJMP A34 (2019) 1950120 [arXiv:1812.08010 [hep-ph]]

ILCX2021, 27 Oct. 2021, KEK

1. Introduction

- *What is the SM-like Higgs boson discovered at LHC?*
- *It can be the SM Higgs boson.*
- *It can be a Higgs boson of New Physics.*
- *This is one of the most important issues in the present particle physics field!*
- *Here we study a possibility that it is the lightest Higgs boson h^0 of the Minimal Supersymmetric Standard Model (MSSM), focusing on the decays $h^0(125) \rightarrow c \bar{c}, b \bar{b}, b \bar{s}, \gamma\gamma, g g$.*

2. MSSM with QFV

Key parameters in this study are:

* *QFV parameters: $\tilde{c}_{L/R} - \tilde{t}_{L/R}$ & $\tilde{s}_{L/R} - \tilde{b}_{L/R}$ mixing parameters*

* *QFC parameter: $\tilde{t}_L - \tilde{t}_R$ & $\tilde{b}_L - \tilde{b}_R$ mixing parameters*

$M^2_{Q23} = (\tilde{c}_L - \tilde{t}_L \text{ mixing parameter})$

$M^2_{U23} = (\tilde{c}_R - \tilde{t}_R \text{ mixing parameter})$

$M^2_{D23} = (\tilde{s}_R - \tilde{b}_R \text{ mixing parameter})$

$T_{U23} = (\tilde{c}_R - \tilde{t}_L \text{ mixing parameter})$

$T_{U32} = (\tilde{c}_L - \tilde{t}_R \text{ mixing parameter})$

$T_{U33} = (\tilde{t}_L - \tilde{t}_R \text{ mixing parameter})$

$T_{D23} = (\tilde{s}_R - \tilde{b}_L \text{ mixing parameter})$

$T_{D32} = (\tilde{s}_L - \tilde{b}_R \text{ mixing parameter})$

$T_{D33} = (\tilde{b}_L - \tilde{b}_R \text{ mixing parameter})$

3. Constraints on the MSSM

We respect the following experimental and theoretical constraints:

- (1) The recent LHC limits on the masses of squarks, sleptons, gluino, charginos and neutralinos.*
- (2) The constraint on $(m_{A/H^\pm}, \tan\beta)$ from recent MSSM Higgs boson search at LHC.*
- (3) The constraints on the QFV parameters from the B & K meson data.*

$$B(b \rightarrow s \gamma) \quad \Delta M_{B_s} \quad B(B_s \rightarrow \mu^+ \mu^-) \quad B(B_u^+ \rightarrow \tau^+ \nu) \text{ etc.}$$

- (4) The constraints from the observed Higgs boson mass and couplings at LHC ; e.g.
 $121.6 \text{ GeV} < m_{h^0} < 128.6 \text{ GeV}$ (allowing for theoretical uncertainty) ,
 $0.71 < \kappa_b < 1.43$ (ATLAS), $0.56 < \kappa_b < 1.70$ (CMS)*
- (5) The experimental limit on SUSY contributions to the electroweak ρ parameter
 $\Delta\rho(\text{SUSY}) < 0.0012$.*
- (6) Theoretical constraints from the vacuum stability conditions for the trilinear couplings $T_{U\alpha\beta}$ and $T_{D\alpha\beta}$.*

4. Parameter scan for $h^0 \rightarrow c \bar{c}, b \bar{b}, b \bar{s}$

- We compute the decay widths $\Gamma(h^0 \rightarrow c \bar{c})$, $\Gamma(h^0 \rightarrow b \bar{b})$, and $\Gamma(h^0 \rightarrow b \bar{s})$ at full 1-loop level in the **MSSM with QFV**.
- We take parameter scan ranges as follows:

$$1 \text{ TeV} < M_{\text{SUSY}} < 5 \text{ TeV}$$

$$10 < \tan\beta < 80$$

$$2500 < M_3 < 5000 \text{ GeV}$$

$$100 < M_2 < 2500 \text{ GeV}$$

$$100 < M_1 < 2500 \text{ GeV}$$

$$100 < \mu < 2500 \text{ GeV}$$

$$1350 < m_{A(\text{pole})} < 6000 \text{ GeV}$$

etc. etc.

- In the parameter scan, all of the relevant experimental and theoretical constraints are imposed.
- **377180** parameter points are generated and **3208** points survive the constraints.

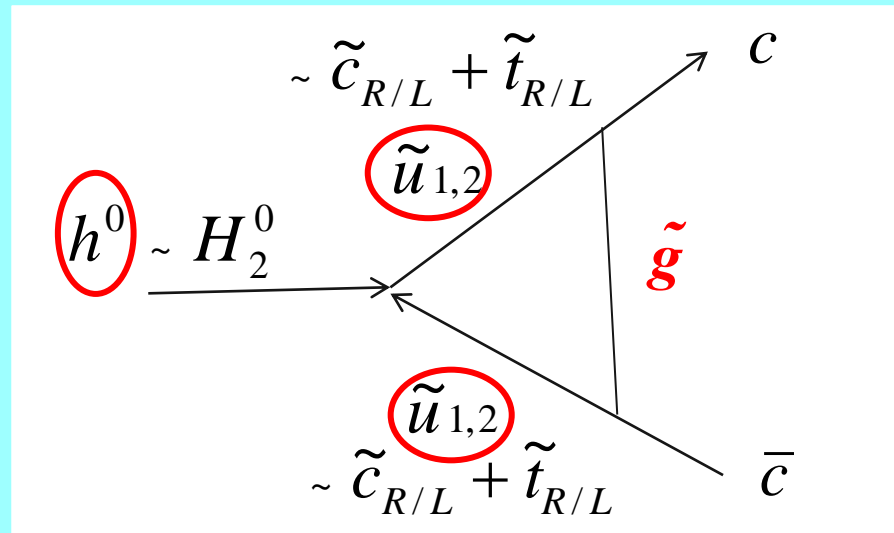
5. $h^0 \rightarrow c \bar{c}, b \bar{b}, b \bar{s}$ in the MSSM

- We compute the decay widths $\Gamma(h^0 \rightarrow c \bar{c})$, $\Gamma(h^0 \rightarrow b \bar{b})$, and $\Gamma(h^0 \rightarrow b \bar{s})$ at full 1-loop level in the DRbar renormalization scheme in the *MSSM with QFV*.
- Main 1-loop correction to $h^0 \rightarrow c \bar{c}$:
 - gluino - su loops [su = (\tilde{t} - \tilde{c} mixture)]*
can be enhanced by large trilinear couplings $T_{U23}, T_{U32}, T_{U33}$
- Main 1-loop corrections to $h^0 \rightarrow b \bar{b}$ & $b \bar{s}$:
 - gluino - sd loops [sd = (\tilde{b} - \tilde{s} mixture)]*
can be enhanced by large trilinear couplings $T_{D23}, T_{D32}, T_{D33}$
 - chargino - su loops [su = (\tilde{t} - \tilde{c} mixture)]*
can be enhanced by large trilinear couplings $T_{U23}, T_{U32}, T_{U33}$

In large $\tilde{c}_{R/L} - \tilde{t}_{R/L}$ & $\tilde{t}_L - \tilde{t}_R$ mixing scenario;

$$h^0 \sim H_2^0$$

$$\tilde{u}_{1,2} \sim \tilde{c}_{R/L} + \tilde{t}_{R/L}$$



In our scenario, “trilinear couplings” ($\tilde{c}_R - \tilde{t}_L - H_2^0$, $\tilde{c}_L - \tilde{t}_R - H_2^0$, $\tilde{t}_L - \tilde{t}_R - H_2^0$ couplings) = $(T_{U23} T_{U32}, T_{U33})$ are large!

$\tilde{u}_{1,2} - \tilde{u}_{1,2} - h^0$ couplings are large!

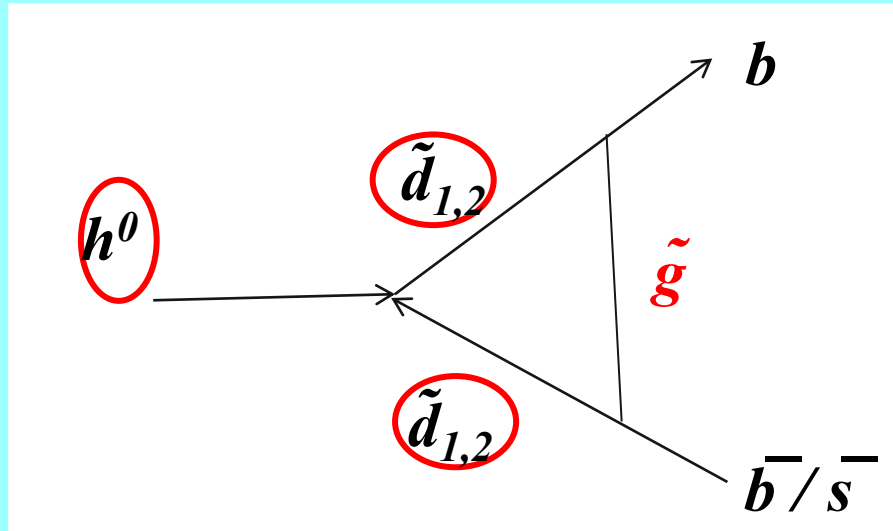
Gluino loop contributions can be large!

Deviation of $\Gamma(h^0 \rightarrow c \bar{c})$ from SM width can be large!

In large $\tilde{s}_{R/L} - \tilde{b}_{R/L}$ & $\tilde{b}_L - \tilde{b}_R$ mixing scenario;

$$h^0 \sim -s\alpha H_1^0 + c\alpha H_2^0$$

$$\tilde{d}_{1,2} \sim \tilde{s}_{R/L} + \tilde{b}_{R/L}$$



*In our scenario, “trilinear couplings” ($T_{D23} T_{D32}, T_{D33}$) = $(\tilde{s}_R - \tilde{b}_L - H_1^0, \tilde{s}_L - \tilde{b}_R - H_1^0, \tilde{b}_L - \tilde{b}_R - H_1^0$ couplings) *are large!**

$\tilde{d}_{1,2} - \tilde{d}_{1,2} - h^0$ couplings are large!

Gluino loop contributions can be large!

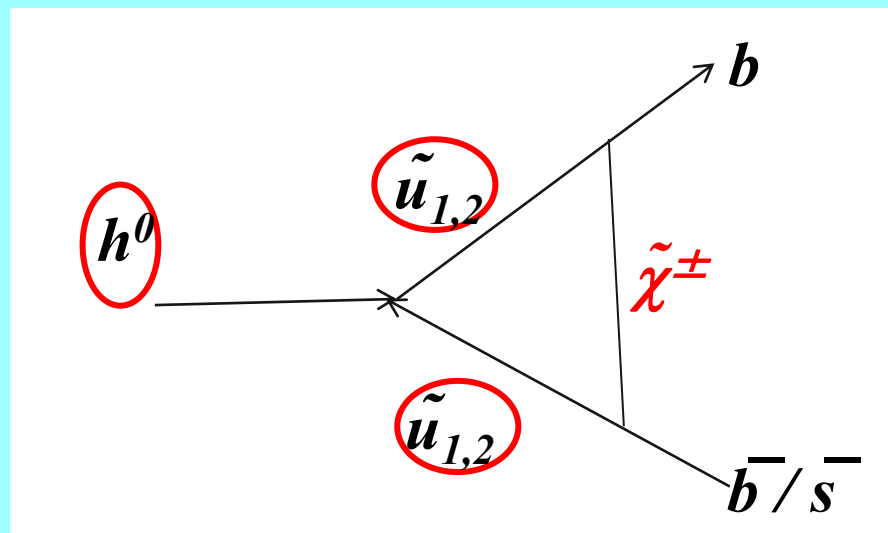
Deviation of $\Gamma(h^0 \rightarrow b \bar{b}/\bar{s})$ from SM width can be large!

In large $\tilde{c}_{R/L} - \tilde{t}_{R/L}$ & $\tilde{t}_L - \tilde{t}_R$ mixing scenario;

$$h^0 \sim H_2^0$$

$$\tilde{u}_{1,2} \sim \tilde{c}_{R/L} + \tilde{t}_{R/L}$$

$$\tilde{\chi}^\pm \sim \tilde{W}^\pm + \tilde{H}^\pm$$



In our scenario, “trilinear couplings” ($\tilde{c}_R - \tilde{t}_L - H_2^0$, $\tilde{c}_L - \tilde{t}_R - H_2^0$, $\tilde{t}_L - \tilde{t}_R - H_2^0$ couplings) = $(T_{U23} T_{U32}, T_{U33})$ are large!

$\tilde{u}_{1,2} - \tilde{u}_{1,2} - h^0$ couplings are large!

Chargino loop contributions can be large!

Deviation of $\Gamma(h^0 \rightarrow b \bar{b}/\bar{s})$ from SM width can be large!

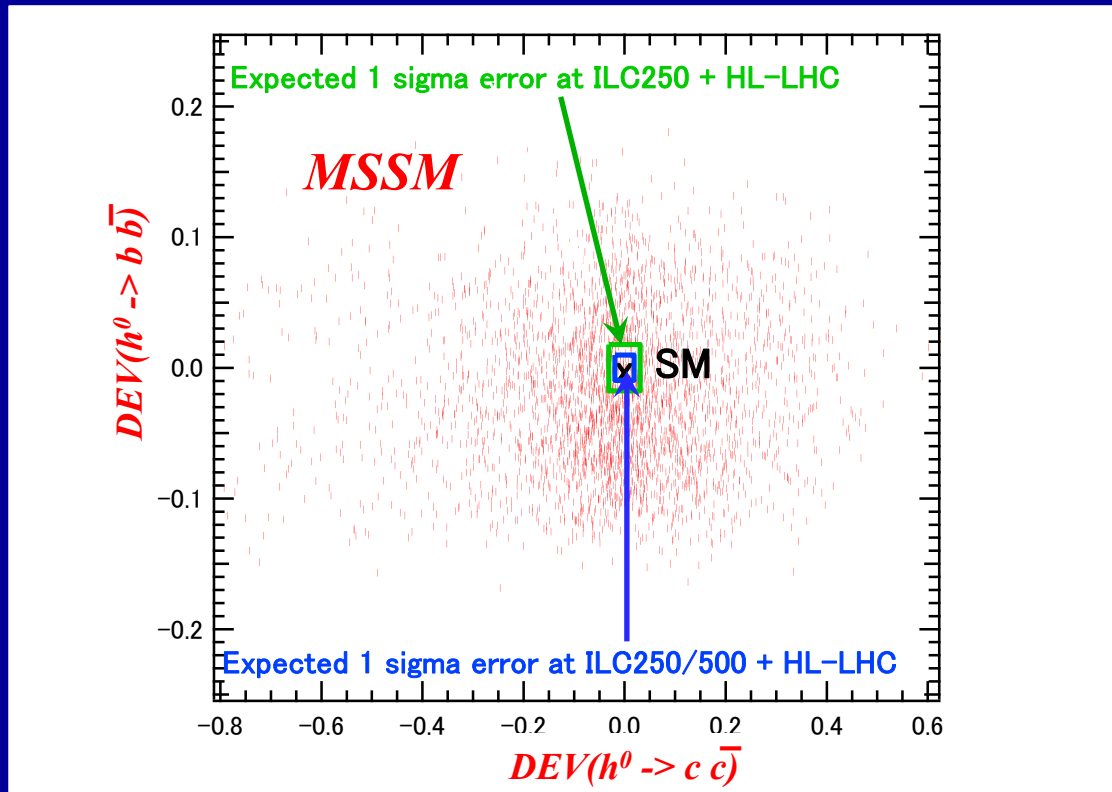
5.1 Deviation of the width from the SM prediction

- The deviation of the width from the SM prediction:

$$DEV(h^0 \rightarrow X \bar{X}) = \Gamma(h^0 \rightarrow X \bar{X})_{MSSM} / \Gamma(h^0 \rightarrow X \bar{X})_{SM} - 1$$

$$X = c, b$$

Scatter plot in $DEV(h^0 \rightarrow c \bar{c}) - DEV(h^0 \rightarrow b \bar{b})$ plane



- $DEV(h^0 \rightarrow c \bar{c})$ and $DEV(h^0 \rightarrow b \bar{b})$ can be very large simultaneously!:
 $DEV(h^0 \rightarrow c \bar{c})$ can be as large as $\sim \pm 60\%$.
 $DEV(h^0 \rightarrow b \bar{b})$ can be as large as $\sim \pm 20\%$.
- **ILC can observe such large deviations from SM at high significance (arXiv:1908.11299)!**:
 $\Delta DEV(h^0 \rightarrow c \bar{c}) = (3.60\%, 2.40\%, 1.58\%)$ at (ILC250, ILC500, ILC1000)
 $\Delta DEV(h^0 \rightarrow b \bar{b}) = (1.98\%, 1.16\%, 0.94\%)$ at (ILC250, ILC500, ILC1000)

5.2 $BR(h^0 \rightarrow b \bar{s} / s \bar{b})$

$BR(h^0 \rightarrow b \bar{s} / s \bar{b}) \cong 0$ (SM)

$BR(h^0 \rightarrow b \bar{s} / s \bar{b})$ can be as large as $\sim 0.17\%$ (MSSM with QFV)!

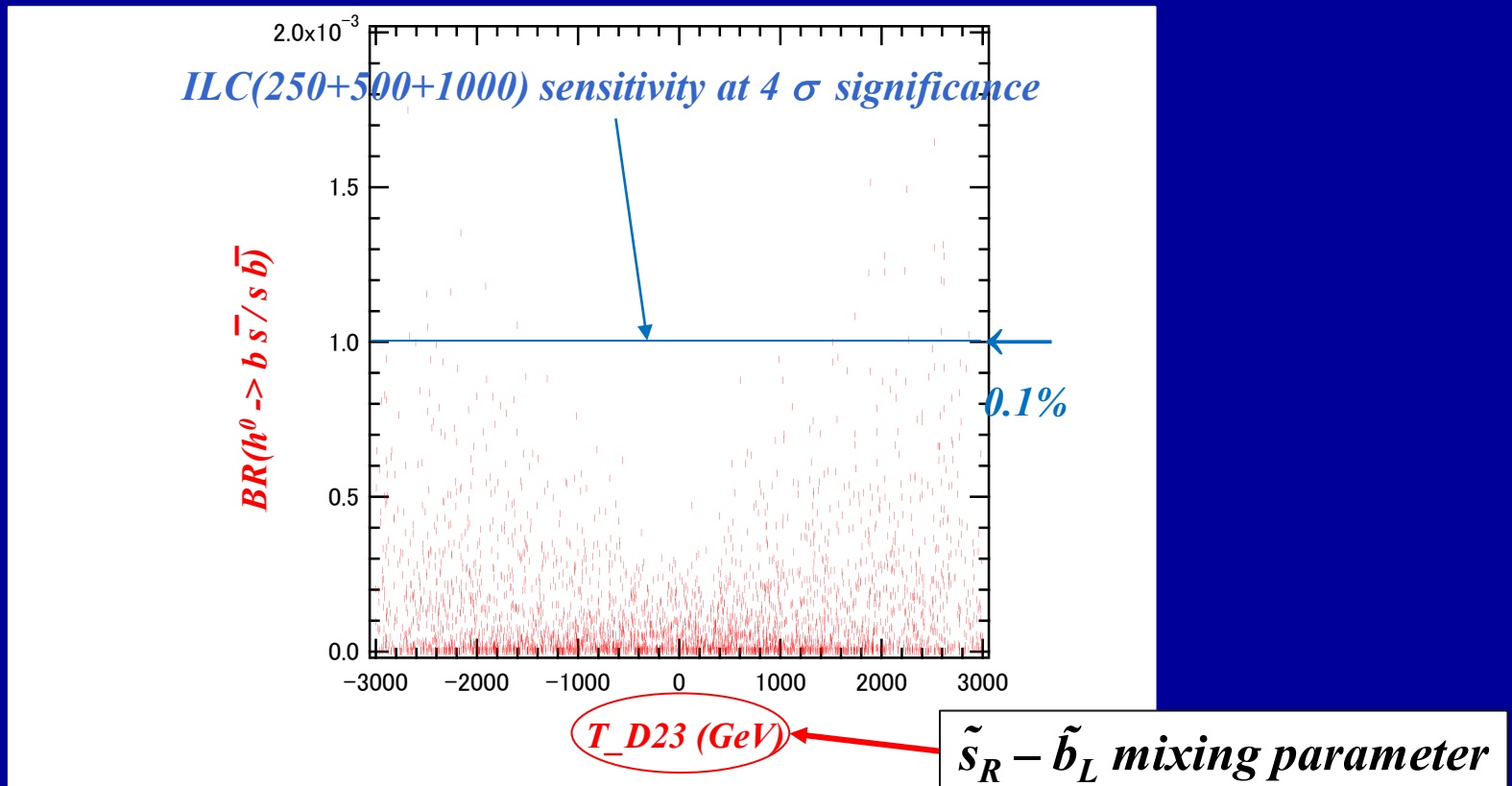
(See also Gomez-Heinemeyer-Rehman, PR D93 (2016) 095021 [arXiv:1511.04342].)

ILC(250+500+1000) sensitivity could be $\sim 0.1\%$ (at 4σ significance)!

Private communication with Junping Tian;

See also Barducci et al., JHEP 12 (2017) 105 [arXiv:1710.06657].

Scatter plot in $T_{D23} - BR(h^0 \rightarrow b \bar{s} / s \bar{b})$ plane



- There is a strong correlation between $T_{D23} - BR(h^0 \rightarrow b \bar{s} / s \bar{b})$!
- $BR(h^0 \rightarrow b \bar{s} / s \bar{b})$ can be as large as **0.17%** for large T_{D23} !
- **ILC(250 + 500 + 1000) sensitivity could be $\sim 0.1\%$ at 4 sigma significance!**

Private communication with Junping Tian;
See also Barducci et al., JHEP 12 (2017) 105 [arXiv:1710.06657].

- LHC & HL-LHC sensitivity should not be so good due to huge QCD BG!

6. $h^0 \rightarrow \gamma\gamma, gg$ in the MSSM

- As the h decays to photon photon and gluon gluon are *loop-induced decays*, these decays are very *sensitive to New Physics!*

- We compute the widths $\Gamma(h^0 \rightarrow \gamma\gamma)$ and $\Gamma(h^0 \rightarrow gg)$ at NLO QCD level in the *MSSM with QFV*.

- Main 1-loop contributions to $h^0 \rightarrow \gamma\gamma$:

[W^+ / top quark / su] - loops [$su = (\tilde{t} - \tilde{c} \text{ mixture})$]

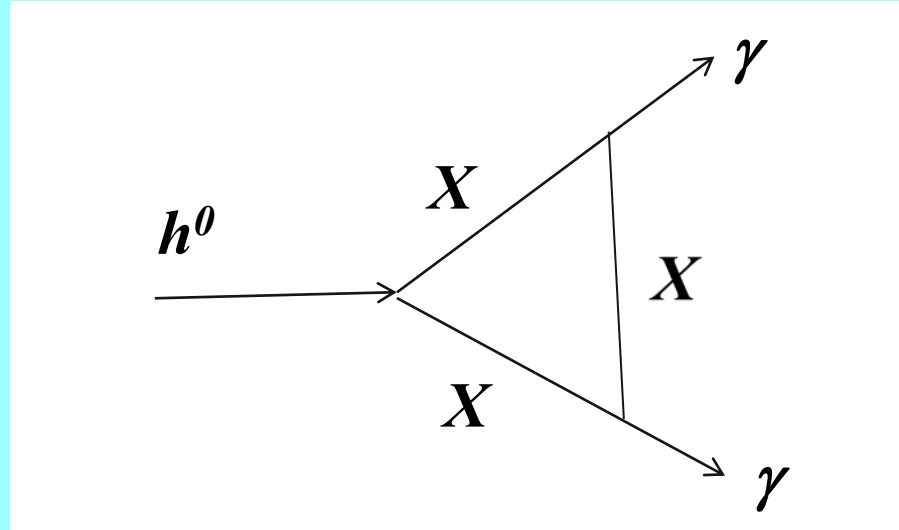
The su -loops can be enhanced by large trilinear couplings $T_{U23}, T_{U32}, T_{U33}$, resulting in sizable deviation of $\Gamma(h^0 \rightarrow \gamma\gamma)$ from the SM width!

- Main 1-loop contributions to $h^0 \rightarrow gg$:

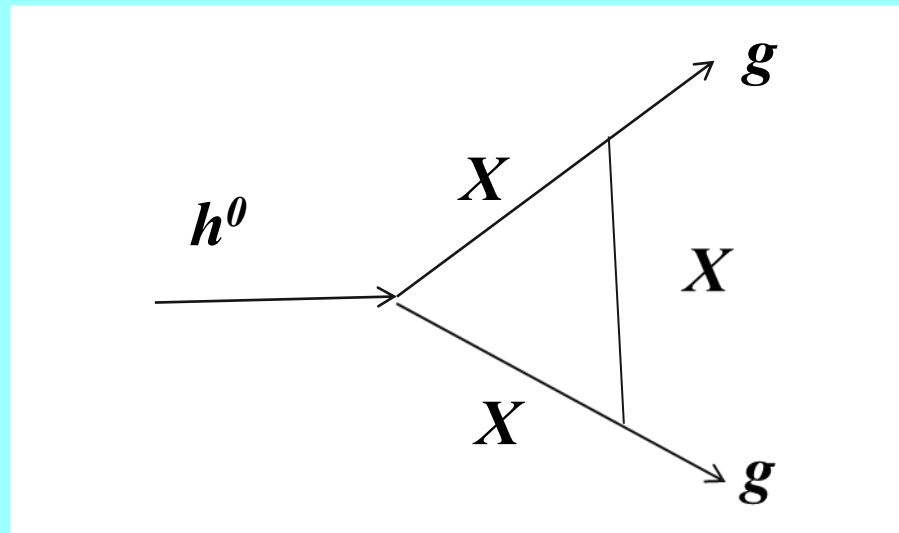
[top quark / su] - loops [$su = (\tilde{t} - \tilde{c} \text{ mixture})$]

The su -loops can be enhanced by large trilinear couplings $T_{U23}, T_{U32}, T_{U33}$, resulting in sizable deviation of $\Gamma(h^0 \rightarrow gg)$ from the SM width!

$$X = W^+ / t / \tilde{u}_{1,2}$$



$$X = t / \tilde{u}_{1,2}$$



- *We perform a MSSM parameter scan respecting all the relevant theoretical and experimental constraints.*

- *From the parameter scan, we find the followings:*

(1) $\text{DEV}(h^0 \rightarrow \gamma\gamma)$ and $\text{DEV}(h^0 \rightarrow g g)$ can be sizable simultaneously:

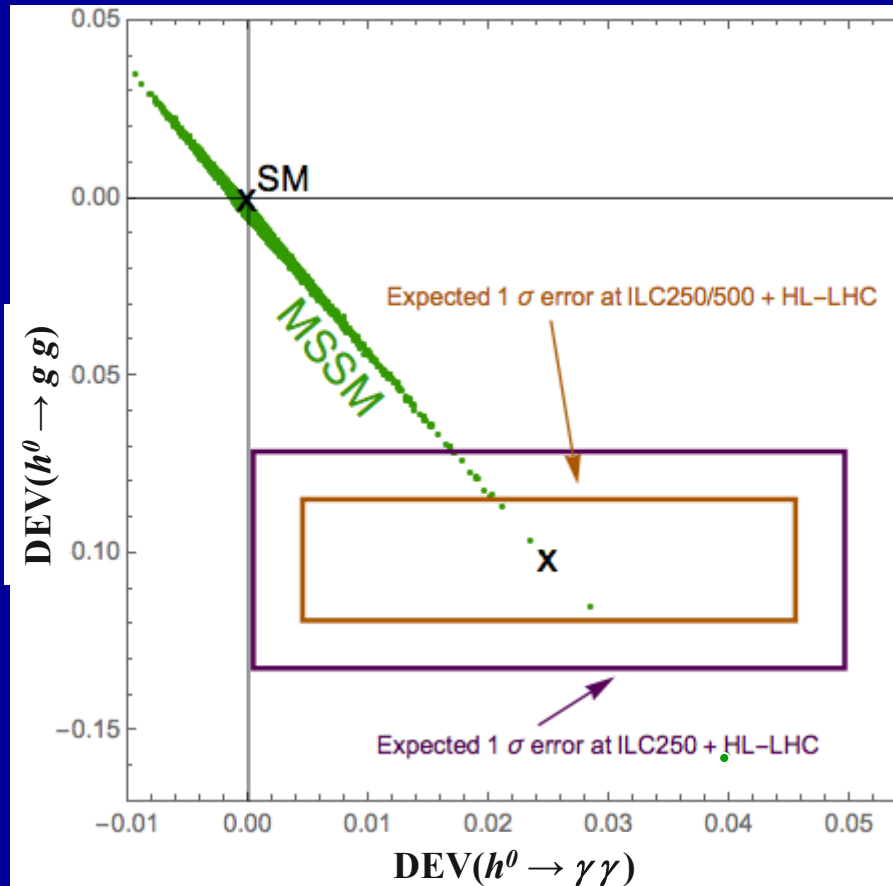
$\text{DEV}(h^0 \rightarrow \gamma\gamma)$ can be as large as $\sim +4\%$,

$\text{DEV}(h^0 \rightarrow g g)$ can be as large as $\sim -15\%$.

(2) There is a very strong correlation between $\text{DEV}(h^0 \rightarrow \gamma\gamma)$ and $\text{DEV}(h^0 \rightarrow g g)$. This correlation is due to the fact that the stop-loop (stop-scharm mixture loop) contributions dominate the two DEVs.

(3) The deviation of the width ratio $\Gamma(h^0 \rightarrow \gamma\gamma) / \Gamma(h^0 \rightarrow g g)$ in the MSSM from the SM value can be as large as $\sim +20\%$.

Scatter plot in $\text{DEV}(h^0 \rightarrow \gamma\gamma) - \text{DEV}(h^0 \rightarrow gg)$ plane



- $\text{DEV}(h^0 \rightarrow \gamma\gamma)$ and $\text{DEV}(h^0 \rightarrow gg)$ can be sizable simultaneously!
- There is a strong correlation between $\text{DEV}(h^0 \rightarrow \gamma\gamma)$ and $\text{DEV}(h^0 \rightarrow gg)$!
- ILC can observe such large deviations from SM at high significance (arXiv:1908.11299)!

7. Conclusion

- *We have studied the decays*

*$h^0 (125\text{GeV}) \rightarrow c \bar{c}, b \bar{b}, b \bar{s}, \gamma\gamma, gg$ in the **MSSM with QFV**.*

- *Performing a systematic MSSM parameter scan respecting all of the relevant theoretical and experimental constraints , we have found the followings:*

** $DEV(h^0 \rightarrow c \bar{c})$ and $DEV(h^0 \rightarrow b \bar{b})$ can be very large simultaneously! :*

$DEV(h^0 \rightarrow c \bar{c})$ can be as large as $\sim \pm 60\%$,

$DEV(h^0 \rightarrow b \bar{b})$ can be as large as $\sim \pm 20\%$.

** The deviation of the width ratio $\Gamma(h^0 \rightarrow b \bar{b}) / \Gamma(h^0 \rightarrow c \bar{c})$ from the SM value can exceed $\sim +100\%$.*

** $BR(h^0 \rightarrow b \bar{s} / s \bar{b})$ can be as large as $\sim 0.17\%$!*

ILC(250 + 500 + 1000) sensitivity could be $\sim 0.1\%$ at 4 sigma signal significance!

- * *$DEV(h^0 \rightarrow \gamma\gamma)$ and $DEV(h^0 \rightarrow gg)$ can be sizable simultaneously! :*
 - $DEV(h^0 \rightarrow \gamma\gamma)$ can be as large as $\sim +4\%$,*
 - $DEV(h^0 \rightarrow gg)$ can be as large as $\sim -15\%$.*
- * *The deviation of the width ratio $\Gamma(h^0 \rightarrow \gamma\gamma)/\Gamma(h^0 \rightarrow gg)$ from the SM value can be as large as $\sim +20\%$.*
- * *There is a very strong correlation between $DEV(h^0 \rightarrow \gamma\gamma)$ and $DEV(h^0 \rightarrow gg)$. This correlation is due to the fact that the stop-loop (stop-scharm mixture loop) contributions dominate the two DEVs.*
- *All of these large deviations in the h^0 (125) decays are due to*
 - large $\tilde{c} - \tilde{t}$ mixing & large \tilde{c} / \tilde{t} involved trilinear couplings $T_{U23}, T_{U32}, T_{U33}$ and*
 - large $\tilde{s} - \tilde{b}$ mixing & large \tilde{s} / \tilde{b} involved trilinear couplings $T_{D23}, T_{D32}, T_{D33}$.*
- *ILC can observe such large deviations from SM at high significance!*
- *In case the deviation pattern shown here is really observed at ILC, then it would strongly suggest the discovery of QFV SUSY (MSSM with QFV)!*
- *See next slide also.*

- *Our analysis suggests the following:*

PETRA/TRISTAN $e^- e^+$ collider discovered virtual Z^0 effect for the first time.

Later, CERN $p p^-$ collider discovered the Z^0 boson.

Similarly, ILC could discover virtual Sparticle effects for the first time in $h^0(125)$ decays!

Later, FCC-hh $p p$ collider could discover the Sparticles!

END

Thank you!

Backup Slides

2. MSSM with QFV

The basic parameters of the MSSM with QFV:

$$\{ \tan\beta, m_A, M_1, M_2, M_3, \mu, M_{Q,\alpha\beta}^2, M_{U,\alpha\beta}^2, M_{D,\alpha\beta}^2, T_{U\alpha\beta}, T_{D\alpha\beta} \}$$

(at $Q = 1 \text{ TeV}$ scale) $(\alpha, \beta = 1, 2, 3 = u, c, t \text{ or } d, s, b)$

$\tan\beta$: ratio of VEV of the two Higgs doublets $\langle H^0_2 \rangle / \langle H^0_1 \rangle$

m_A : CP odd Higgs boson mass (pole mass)

M_1, M_2, M_3 : $U(1), SU(2), SU(3)$ gaugino masses

μ : higgsino mass parameter

$M_{Q,\alpha\beta}^2$: left squark soft mass matrix

$M_{U\alpha\beta}^2$: right up-type squark soft mass matrix

$M_{D\alpha\beta}^2$: right down-type squark soft mass matrix

$T_{U\alpha\beta}$: trilinear coupling matrix of up-type squark and Higgs boson

$T_{D\alpha\beta}$: trilinear coupling matrix of down-type squark and Higgs boson

2. Key parameters of MSSM

Key parameters in this study are:

* *QFV parameters:* $M^2_{Q23}, M^2_{U23}, M^2_{D23}, T_{U23}, T_{U32}, T_{D23}, T_{D32}$

* *QFC parameter:* T_{U33}, T_{D33}

$M^2_{Q23} = (\tilde{c}_L - \tilde{t}_L \text{ mixing parameter})$

$M^2_{U23} = (\tilde{c}_R - \tilde{t}_R \text{ mixing parameter})$

$M^2_{D23} = (\tilde{s}_R - \tilde{b}_R \text{ mixing parameter})$

$T_{U23} = (\tilde{c}_R - \tilde{t}_L \text{ mixing parameter})$

$T_{U32} = (\tilde{c}_L - \tilde{t}_R \text{ mixing parameter})$

$T_{U33} = (\tilde{t}_L - \tilde{t}_R \text{ mixing parameter})$

$T_{D23} = (\tilde{s}_R - \tilde{b}_L \text{ mixing parameter})$

$T_{D32} = (\tilde{s}_L - \tilde{b}_R \text{ mixing parameter})$

$T_{D33} = (\tilde{b}_L - \tilde{b}_R \text{ mixing parameter})$

4. Parameter scan for $h^0 \rightarrow c \bar{c}, b \bar{b}, b \bar{s}$ in the MSSM

- We compute the decay widths $\Gamma(h^0 \rightarrow c \bar{c})$, $\Gamma(h^0 \rightarrow b \bar{b})$, and $\Gamma(h^0 \rightarrow b \bar{s})$ at full 1-loop level in the **MSSM with QFV**.
- Parameter points are generated by using random numbers in the following ranges (in units of GeV or GeV²):

$$1 \text{ TeV} < M_{\text{SUSY}} < 5 \text{ TeV}$$

$$10 < \tan\beta < 80$$

$$2500 < M_3 < 5000$$

$$100 < M_2 < 2500$$

$$100 < M_1 < 2500$$

(without assuming the GUT relation for M_1, M_2, M_3)

$$100 < \mu < 2500$$

$$1350 < m_A(\text{pole}) < 6000;$$

$$MQ2_11 = 4500^2 \text{ (fixed)}$$

$$2500^2 < MQ2_22 < 4000^2$$

$$2500^2 < MQ2_33 < 4000^2$$

$$|MQ2_23| < 1000.^2$$

$\Leftarrow QFV$ param.

$$MU2_11 = 4500^2 \text{ (fixed)}$$

$$1000.^2 < MU2_22 < 4000.^2$$

$$600.^2 < MU2_33 < 3000.^2$$

$$|MU2_23| < 2000.^2$$

$\Leftarrow QFV$ param.

$$MD2_11 = 4500^2 \text{ (fixed)}$$

$$2500.^2 < MD2_22 < 4000.^2$$

$$1000.^2 < MD2_33 < 3000.^2$$

$$|MD2_23| < 2000.^2$$

$$ML2_11 = 1500^2 \text{ (fixed)}$$

$$ML2_22 = 1500^2 \text{ (fixed)}$$

$$ML2_33 = 1500^2 \text{ (fixed)}$$

$$ML2_23 = 0. \text{ (fixed)}$$

$$ME2_{11} = 1500^2 \text{ (fixed)}$$

$$ME2_{22} = 1500^2 \text{ (fixed)}$$

$$ME2_{33} = 1500^2 \text{ (fixed)}$$

$$ME2_{23} = 0. \text{ (fixed)}$$

$$|TU_{23}| < 4000 \quad \Longleftarrow QFV \text{ param}$$

$$|TU_{32}| < 4000 \quad \Longleftarrow QFV \text{ param}$$

$$|TU_{33}| < 5000 \quad \Longleftarrow QFC \text{ param}$$

$$|TD_{23}| < 3000 \quad \Longleftarrow QFV \text{ param}$$

$$|TD_{32}| < 3000 \quad \Longleftarrow QFV \text{ param}$$

$$|TD_{33}| < 4000 \quad \Longleftarrow QFC \text{ param}$$

$$TE_{23} = 0. \text{ (fixed)}$$

$$TE_{32} = 0. \text{ (fixed)}$$

$$|TE_{33}| < 500$$

- *In the parameter scan, all of the relevant experimental and theoretical constraints are imposed.*
- *377180 parameter points are generated and 3208 points survive the constraints.*

Constraints on the MSSM parameters from K & B meson and h^0 data:

Table 5: Constraints on the MSSM parameters from the K - and B -meson data relevant mainly for the mixing between the second and the third generations of squarks and from the data on the h^0 mass and couplings κ_b , κ_g , κ_γ . The fourth column shows constraints at 95% CL obtained by combining the experimental error quadratically with the theoretical uncertainty, except for $B(K_L^0 \rightarrow \pi^0 \nu \bar{\nu})$, m_{h^0} and $\kappa_{b,g,\gamma}$.

Observable	Exp. data	Theor. uncertainty	Constr. (95%CL)
$10^3 \times \epsilon_K $	2.228 ± 0.011 (68% CL) [21]	± 0.28 (68% CL) [40]	2.228 ± 0.549
$10^{15} \times \Delta M_K$ [GeV]	3.484 ± 0.006 (68% CL) [21]	± 1.2 (68% CL) [40]	3.484 ± 2.352
$10^9 \times B(K_L^0 \rightarrow \pi^0 \nu \bar{\nu})$	< 3.0 (90% CL) [21]	± 0.002 (68% CL) [21]	< 3.0 (90% CL)
$10^{10} \times B(K^+ \rightarrow \pi^+ \nu \bar{\nu})$	1.7 ± 1.1 (68% CL) [21]	± 0.04 (68% CL) [21]	$1.7^{+2.16}_{-1.70}$
ΔM_{B_s} [ps $^{-1}$]	17.757 ± 0.021 (68% CL) [21, 41]	± 2.7 (68% CL) [42]	17.757 ± 5.29
$10^4 \times B(b \rightarrow s \gamma)$	3.32 ± 0.15 (68% CL) [21, 41]	± 0.23 (68% CL) [11]	3.32 ± 0.54
$10^6 \times B(b \rightarrow s l^+ l^-)$ ($l = e$ or μ)	$1.60^{+0.48}_{-0.45}$ (68% CL) [43]	± 0.11 (68% CL) [44]	$1.60^{+0.97}_{-0.91}$
$10^9 \times B(B_s \rightarrow \mu^+ \mu^-)$	$2.69^{+0.37}_{-0.35}$ (68%CL) [45]	± 0.23 (68% CL) [46]	$2.69^{+0.85}_{-0.82}$
$10^4 \times B(B^+ \rightarrow \tau^+ \nu)$	1.06 ± 0.19 (68%CL) [41]	± 0.29 (68% CL) [47]	1.06 ± 0.69
m_{h^0} [GeV]	125.09 ± 0.24 (68% CL) [48]	± 3 [49]	125.09 ± 3.48
κ_b	$1.06^{+0.37}_{-0.35}$ (95% CL) [50] $1.17^{+0.53}_{-0.61}$ (95% CL) [51]		$1.06^{+0.37}_{-0.35}$ (ATLAS) $1.17^{+0.53}_{-0.61}$ (CMS)
κ_g	$1.03^{+0.14}_{-0.12}$ (95% CL) [50] $1.18^{+0.31}_{-0.27}$ (95% CL) [51]		$1.03^{+0.14}_{-0.12}$ (ATLAS) $1.18^{+0.31}_{-0.27}$ (CMS)
κ_γ	1.00 ± 0.12 (95% CL) [50] $1.07^{+0.27}_{-0.29}$ (95% CL) [51]		1.00 ± 0.12 (ATLAS) $1.07^{+0.27}_{-0.29}$ (CMS)

Main SUSY one-loop contributions to $h^0 \rightarrow c \bar{c}$

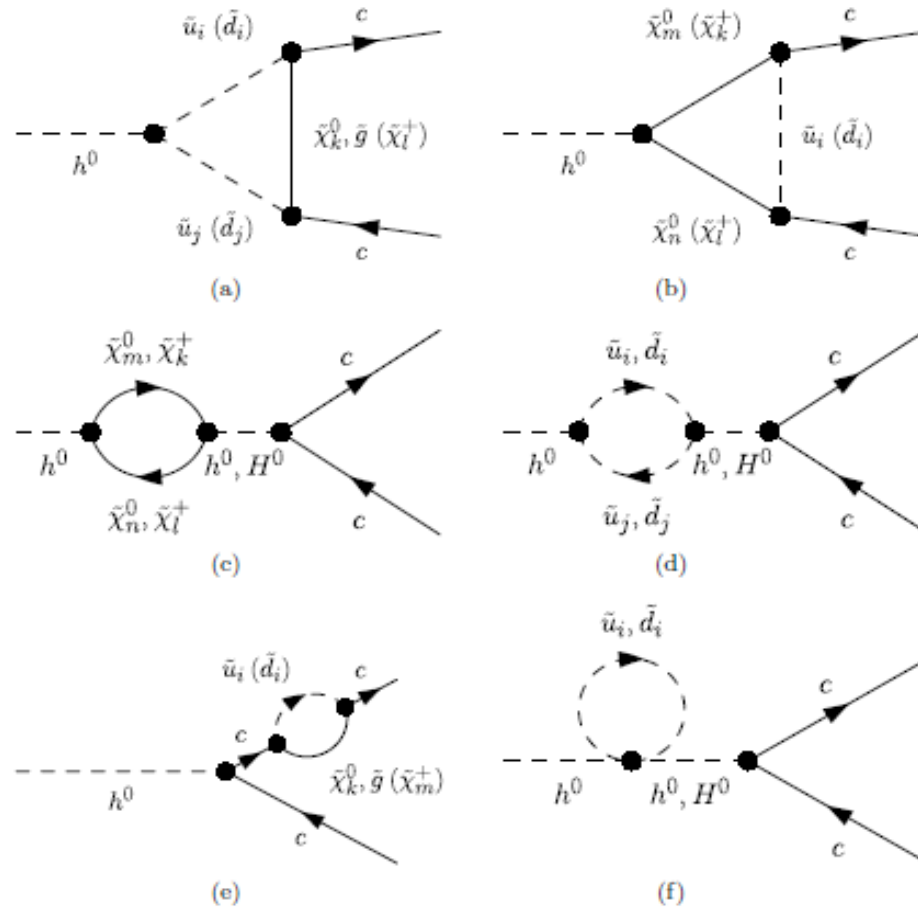
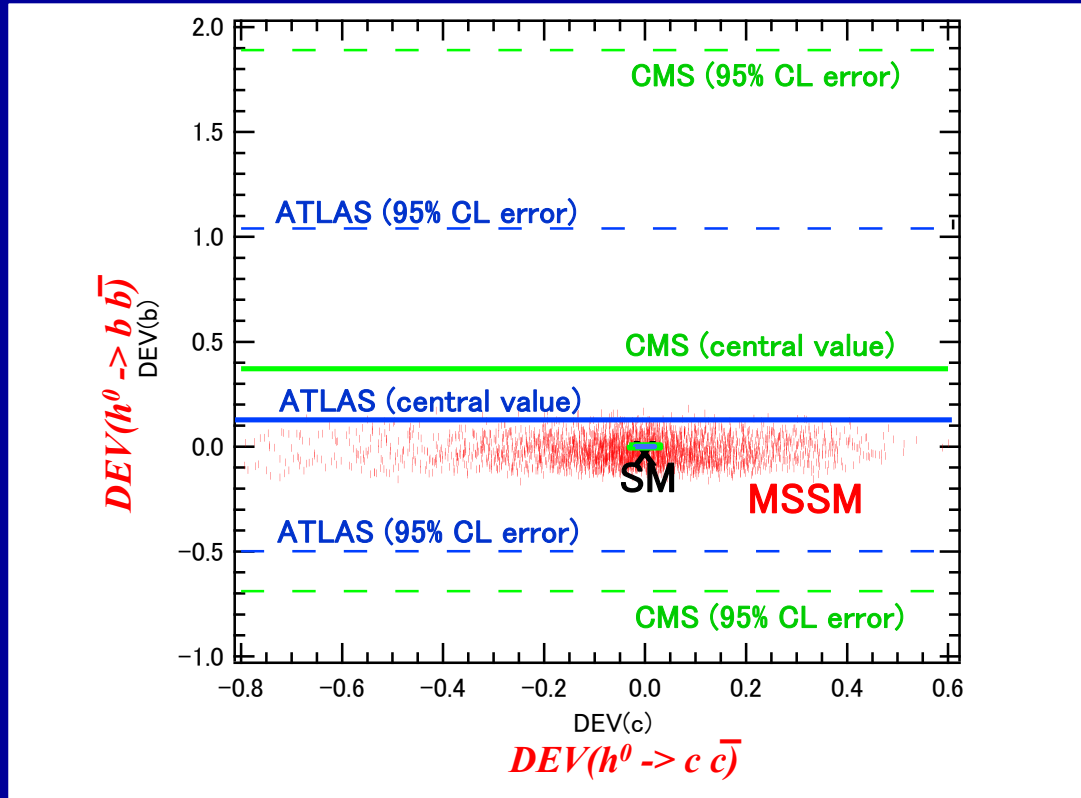


Figure 2: The main one-loop contributions with SUSY particles in $h^0 \rightarrow c \bar{c}$. The corresponding diagram to (e) with the self-energy contribution to the other charm quark is not shown explicitly.

Scatter plot in $DEV(h^0 \rightarrow c \bar{c}) - DEV(h^0 \rightarrow b \bar{b})$ plane



- Recent LHC data:

$$DEV(h^0 \rightarrow b \bar{b}) = 0.12 + 0.92/-0.62 = [-0.50, 1.04] \text{ (ATLAS)} \text{ (arXiv:1909.02845)}$$

$$DEV(h^0 \rightarrow b \bar{b}) = 0.37 + 1.52/-1.06 = [-0.69, 1.89] \text{ (CMS)} \text{ (arXiv:1809.10733)}$$

- Both SM and MSSM are consistent with the recent ATLAS/CMS data!
The errors of the recent ATLAS/CMS data are too large!

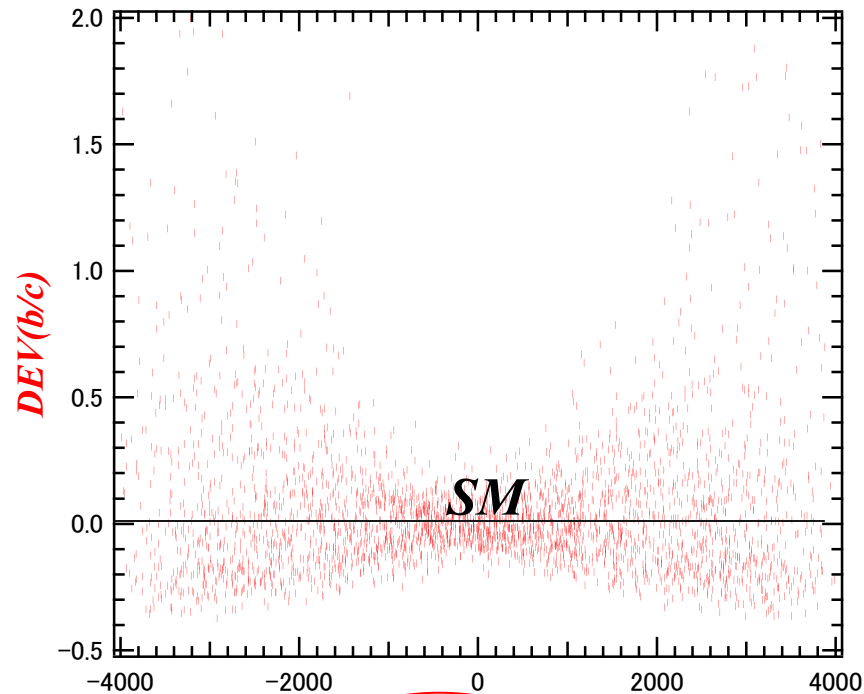
5.2 Deviation of width ratio from the SM prediction

- The deviation of the width ratio from the SM prediction:

$$DEV(b/c) = [\Gamma(b) / \Gamma(c)]_{MSSM} / [\Gamma(b) / \Gamma(c)]_{SM} - 1$$

$$\Gamma(X) = \Gamma(h^0 \rightarrow X \bar{X})$$

Scatter plot in $T_{U32} - DEV(b/c)$ plane



$T_{U32} (GeV)$

$\tilde{c}_L - \tilde{t}_R$ mixing parameter



- There is a strong correlation between $T_{U32} - DEV(b/c)$!
- $DEV(b/c)$ can be as large as $\sim +200\%$ for large T_{U32} !

5.2 $BR(h^0 \rightarrow b \bar{s} / s \bar{b})$

$BR(h^0 \rightarrow b \bar{s} / s \bar{b}) \cong 0$ (SM)

$BR(h^0 \rightarrow b \bar{s} / s \bar{b})$ can be as large as $\sim 0.17\%$ (MSSM with QFV)!

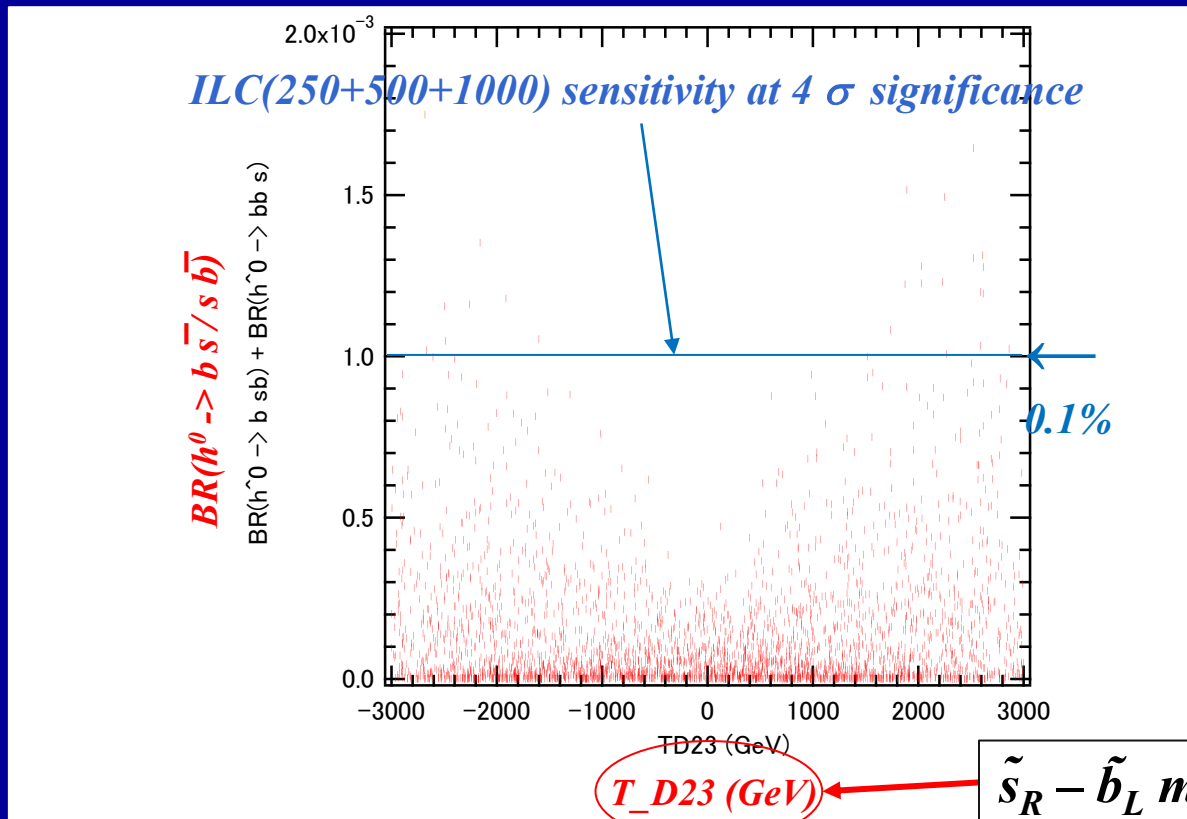
(See also Gomez-Heinemeyer-Rehman, PR D93 (2016) 095021 [arXiv:1511.04342].)

ILC(250+500+1000) sensitivity could be $\sim 0.1\%$ (at 4σ significance)!

Private communication with Junping Tian;

See also Barducci et al., JHEP 12 (2017) 105 [arXiv:1710.06657]

Scatter plot in $T_{D23} - BR(h^0 \rightarrow b \bar{s} / s \bar{b})$ plane

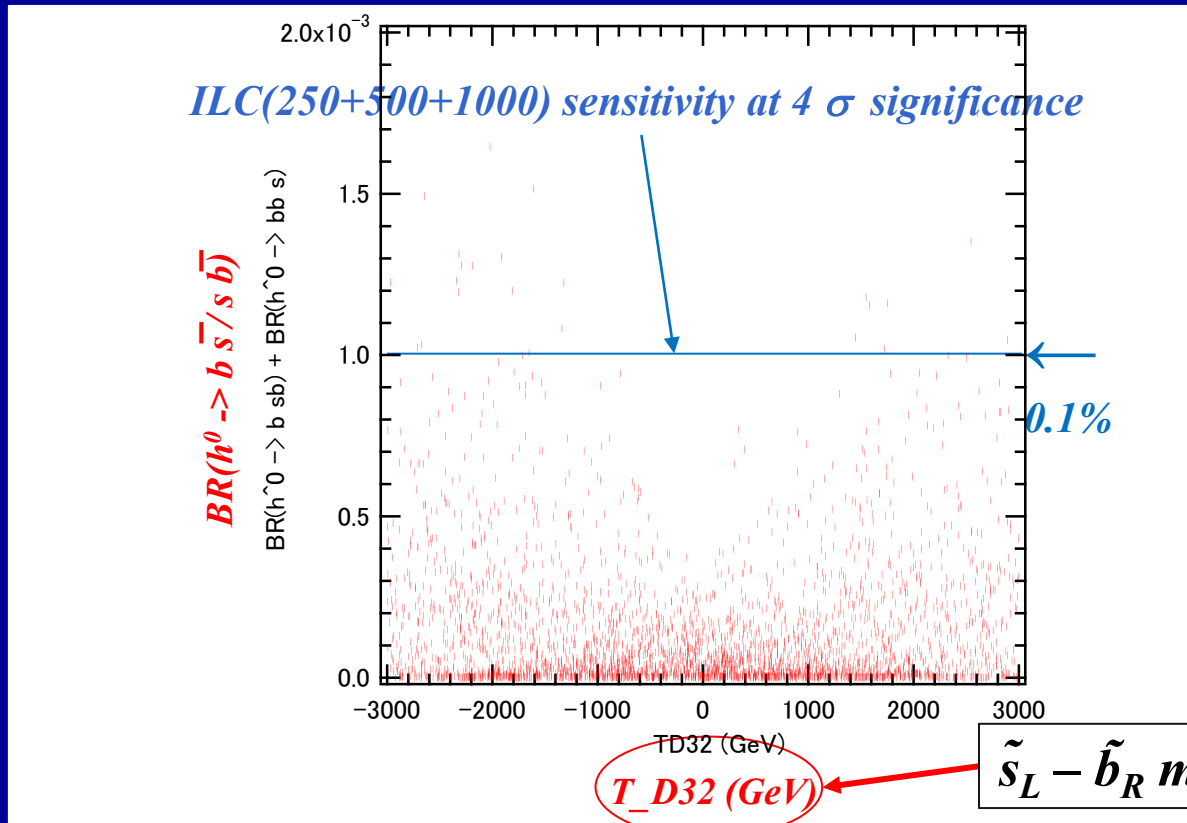


- There is a strong correlation between $T_{D23} - BR(h^0 \rightarrow b \bar{s} / s \bar{b})$!
- $BR(h^0 \rightarrow b \bar{s} / s \bar{b})$ can be as large as **0.17%** for large T_{D23} !
- **ILC(250 + 500 + 1000) sensitivity could be $\sim 0.1\%$ at 4 sigma significance!**

Private communication with Junping Tian;
See also Barducci et al., JHEP 12 (2017) 105 [arXiv:1710.06657].

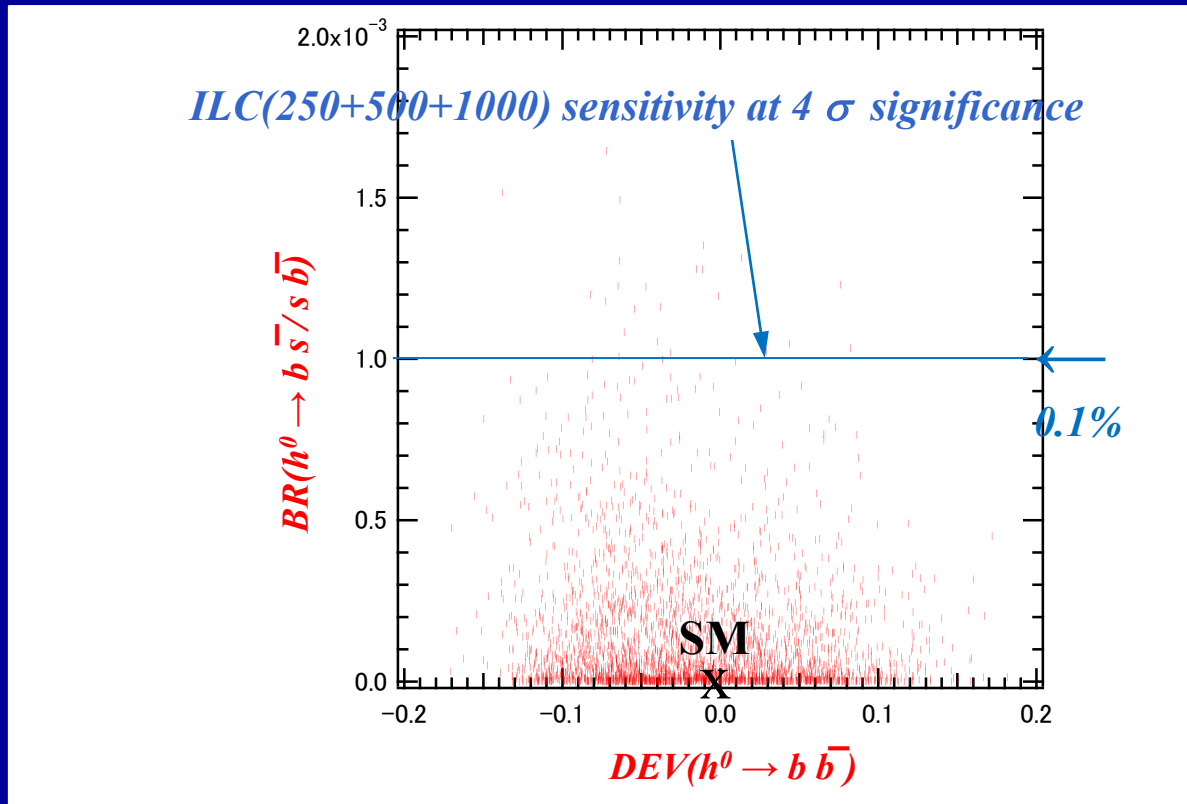
- LHC & HL-LHC sensitivity should not be so good due to huge QCD BG!

Scatter plot in $T_{D32} - BR(h^0 \rightarrow b \bar{s} / s \bar{b})$ plane



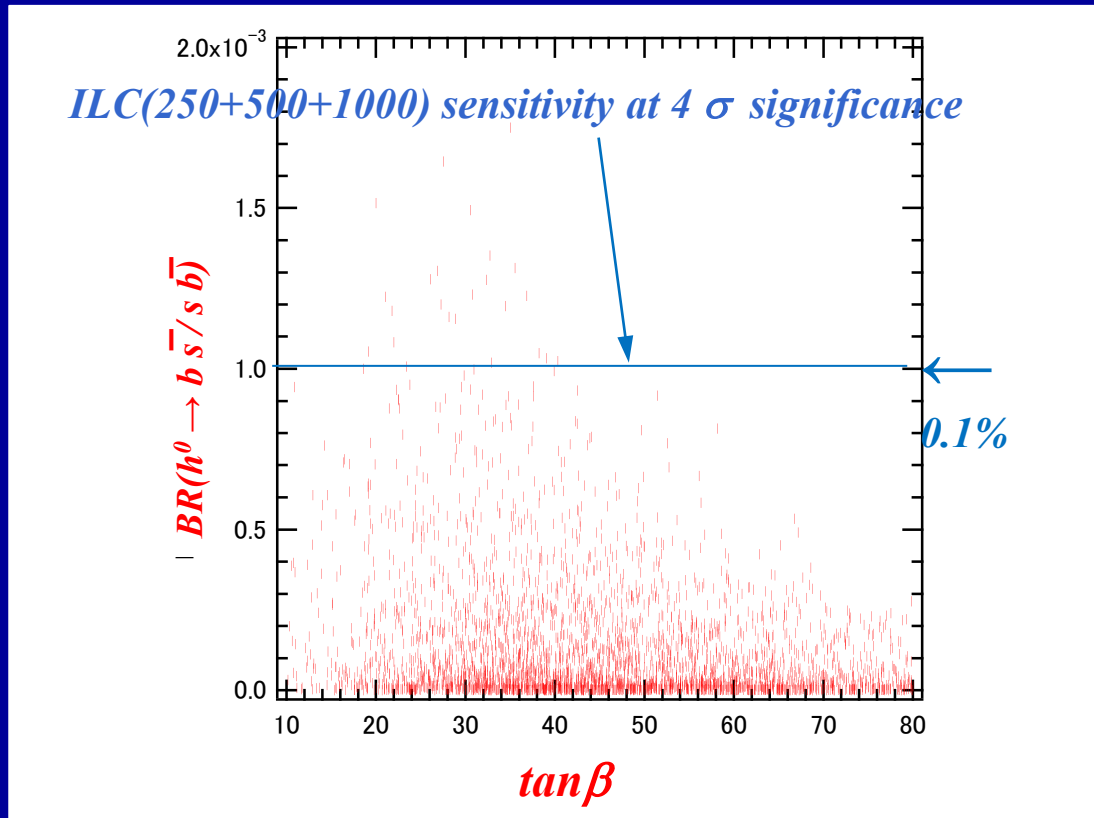
- There is also a strong correlation between $T_{D32} - BR(h^0 \rightarrow b \bar{s} / s \bar{b})$!
- $BR(h^0 \rightarrow b \bar{s} / s \bar{b})$ can be as large as 0.17% for large T_{D32} !

Scatter plot in $BR(h^0 \rightarrow b \bar{s}/s \bar{b}) - DEV(h^0 \rightarrow b \bar{b})$ plane



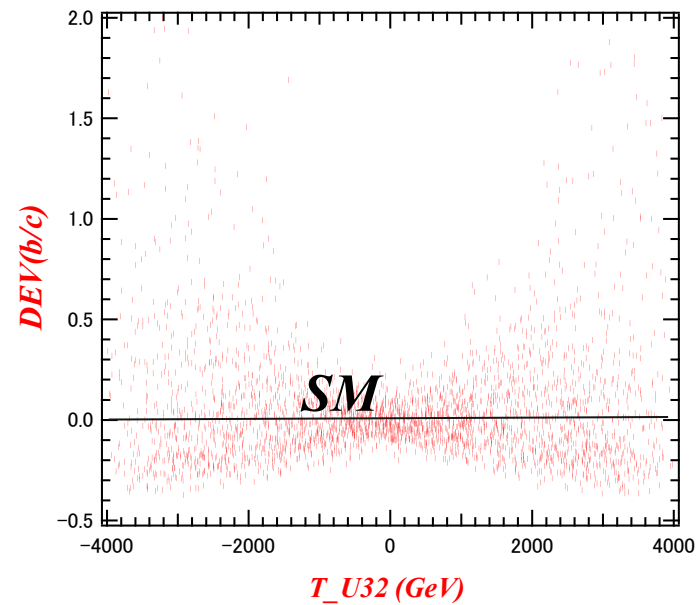
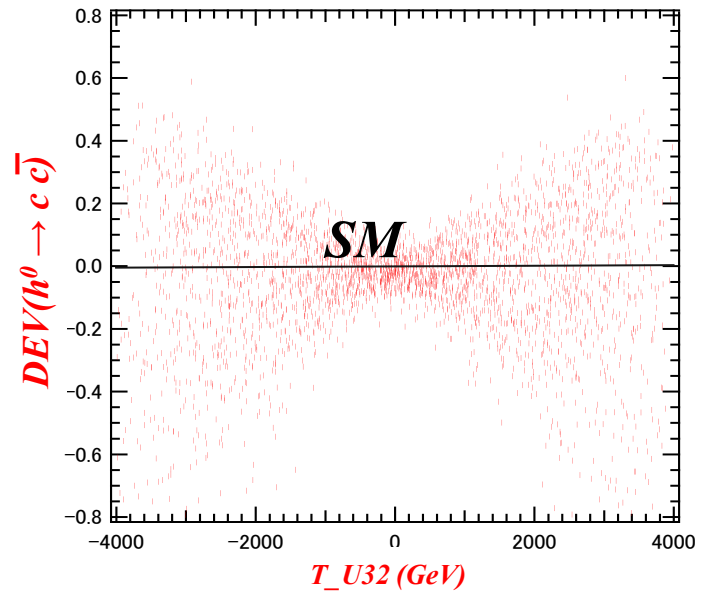
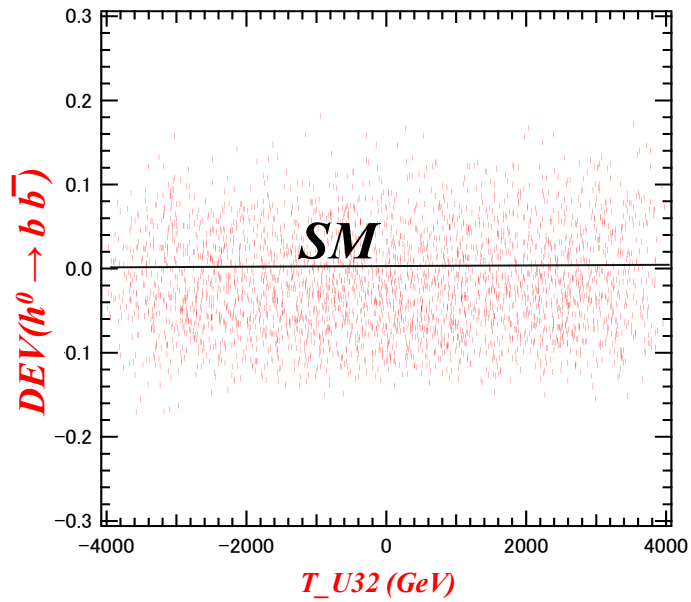
- There is a strong correlation between $DEV(h^0 \rightarrow b \bar{b})$ & $BR(h^0 \rightarrow b \bar{s}/s \bar{b})$!
- This is due to the fact that $DEV(h^0 \rightarrow b \bar{b})$ & $BR(h^0 \rightarrow b \bar{s}/s \bar{b})$ have a common origin of enhancement effect, i.e. large trilinear couplings $T_{D23,32,33}$ & $T_{U23,32,33}$.

Scatter plot in $BR(h^0 \rightarrow b \bar{s} / s \bar{b}) - \tan\beta$ plane



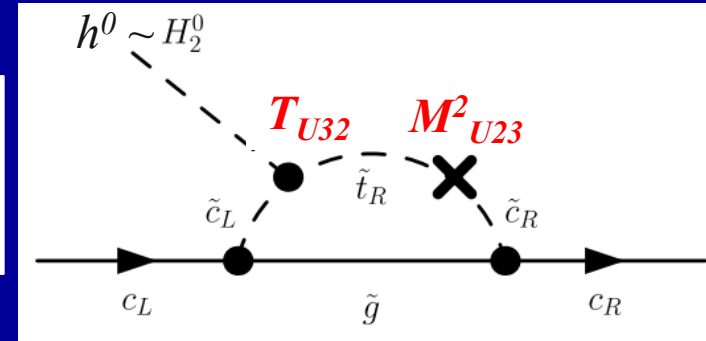
- There is a strong correlation between $BR(h^0 \rightarrow b \bar{s} / s \bar{b})$ & $\tan\beta$!
- $BR(h^0 \rightarrow b \bar{s} / s \bar{b})$ can be as large as 0.17% for $\tan\beta \sim 30$!

Caveat for very large $DEV(h^0 \rightarrow c \bar{c})$ & $DEV(b/c)$



Caveat for very large $DEV(h^0 \rightarrow c \bar{c})$ & $DEV(b/c)$

Gluino loop contribution to $h^0 \rightarrow c \bar{c}$ can be **very large** (positive and negative) **for large $T_{U32} * M_{U23}^2$!**



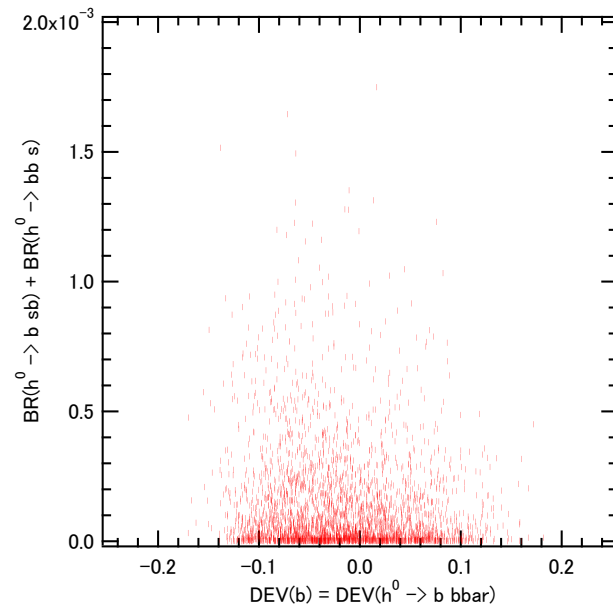
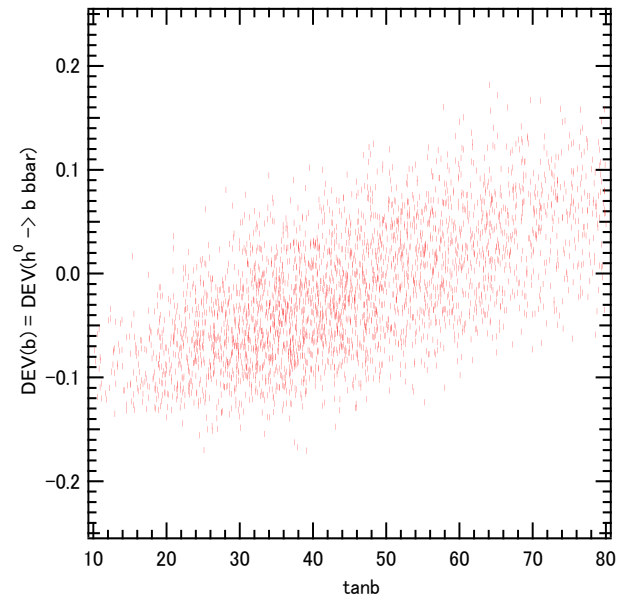
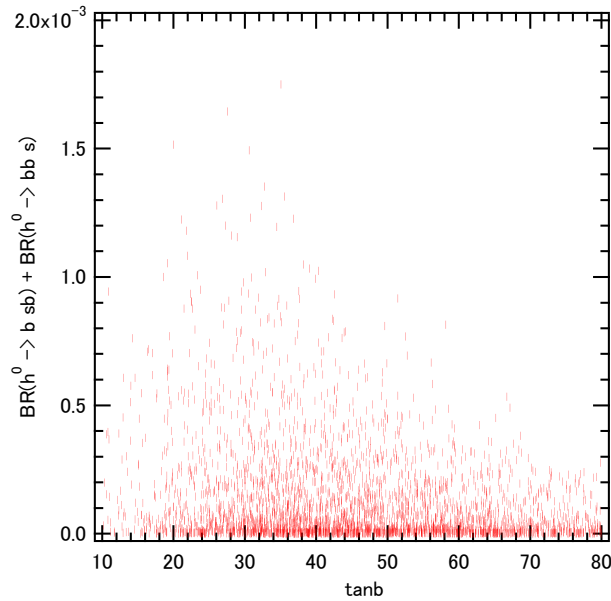
The **interference term** between the tree diagram and the gluino one-loop diagram can be **very large** (positive and negative) **for large $T_{U32} * M_{U23}^2$** , which can lead to even **NEGATIVE width** $\Gamma(h^0 \rightarrow c \bar{c})$ at one-loop level !

In this case **perturbation theory breaks down!**

A large deviation of $\Gamma(h^0 \rightarrow c \bar{c})$ from the SM value is in principle possible due to large values of the product **$T_{U32} * M_{U23}^2$** .

Since **there exists no physical constraint on this product**, the deviation $DEV(h^0 \rightarrow c \bar{c})$ can be unnaturally large. So, we show only the results with a deviation from the SM up to $\sim \pm 60\%$.

Correlations among $DEV(h^0 \rightarrow b \bar{b})$, $BR(h^0 \rightarrow b \bar{s} / s \bar{b})$, $\tan\beta$

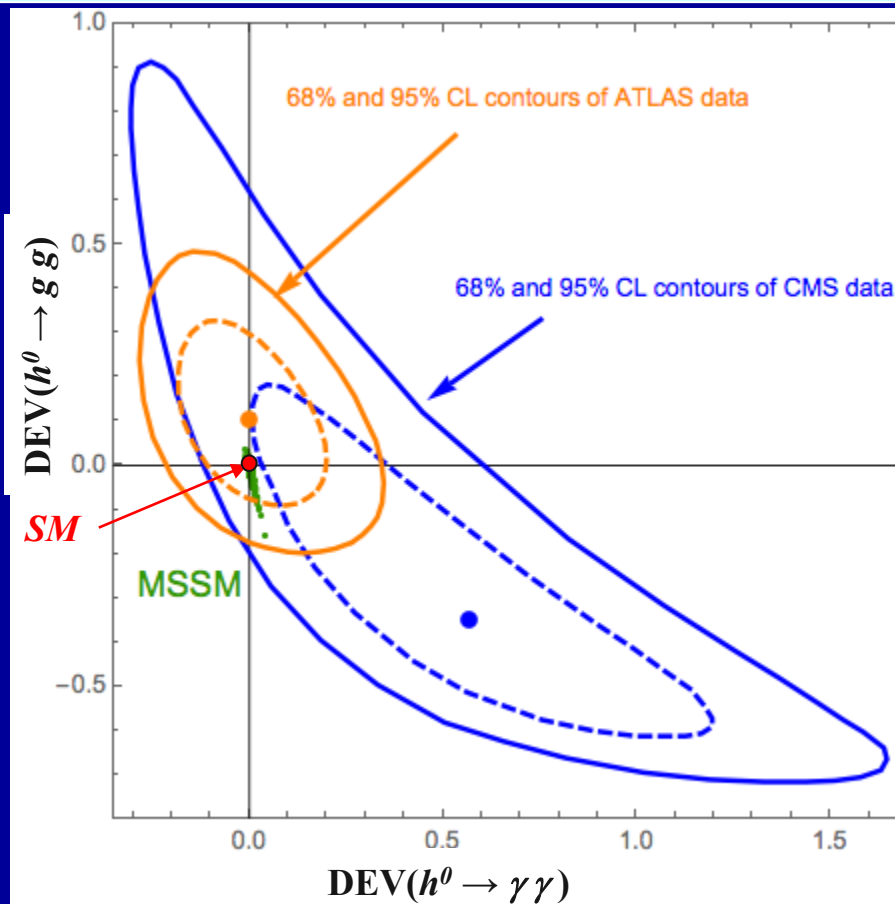


Effect of Resummation of the bottom Yukawa coupling at large $\tan\beta$

*As for $\Gamma(h^0 \rightarrow b \bar{b})$ & $\Gamma(h^0 \rightarrow b \bar{s}/s \bar{b})$, we have considered the large $\tan\beta$ enhancement and the resummation of the bottom Yukawa coupling [1]. It turns out, however, that in our case with large m_A close to the decoupling Higgs limit, the **resummation effect (Δ_b effect) is very small ($< 0.1\%$).***

[1] *M. Carena et al., Nucl. Phys. B 577 (2000) 88 [hep-ph/9912516].*

Scatter plot in $\text{DEV}(h^0 \rightarrow \gamma\gamma) - \text{DEV}(h^0 \rightarrow gg)$ plane



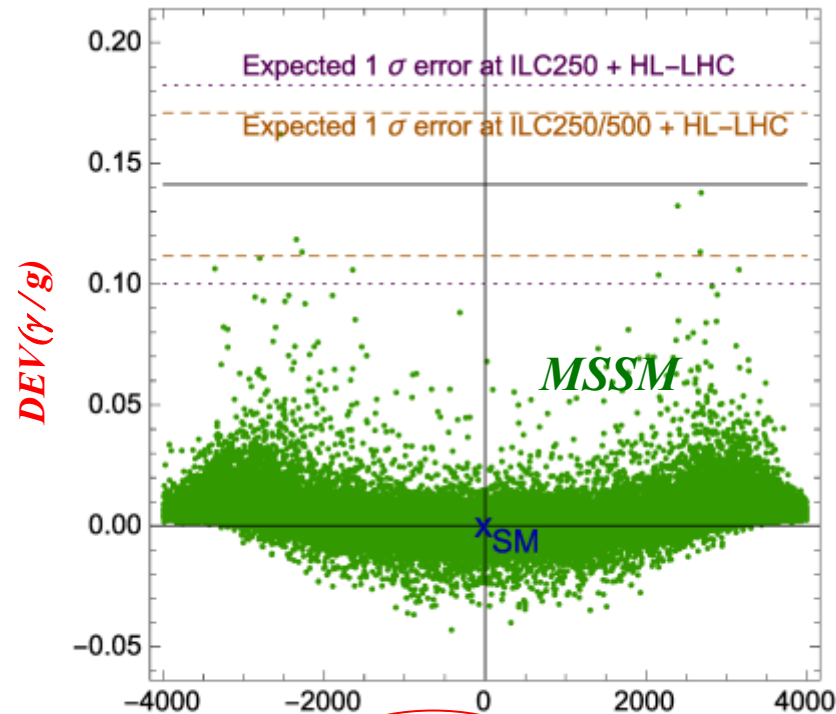
- **Both SM and MSSM are consistent with the recent ATLAS/CMS data!:**

ATLAS: *arXiv:1909.02845 (Phys.Rev.D 101 (2020) 012002)*

CMS: *arXiv:1804.02716 (JHEP 11 (2018) 185)*

- **The errors of the recent ATLAS/CMS data are too large!**

Scatter plot in $T_{U32} - DEV(\gamma/g)$ plane



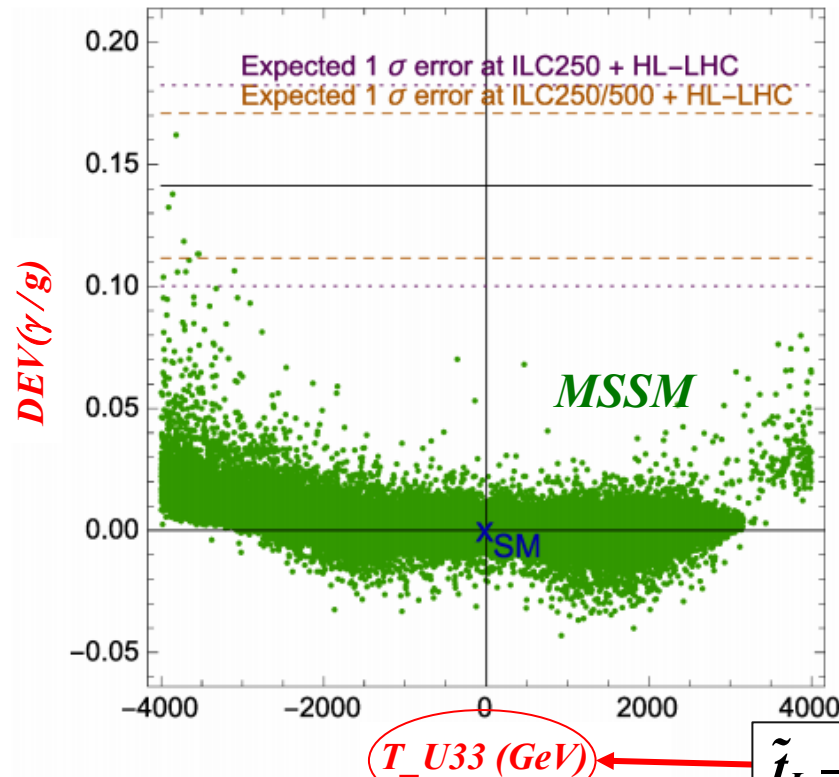
T_{U32} (GeV)

$\tilde{c}_L - \tilde{t}_R$ mixing parameter



- There is a strong correlation between $T_{U32} - DEV(\gamma/g)$!
- $DEV(\gamma/g)$ can be as large as $\sim +15\%$ for large T_{U32} !

Scatter plot in $T_{U33} - DEV(\gamma/g)$ plane



- There is a strong correlation between $T_{U33} - DEV(\gamma/g)$!
- $DEV(\gamma/g)$ can be as large as $\sim +16\%$ for large T_{U33} !