The h(125) decays to $c\,\bar{c}$, $b\,\bar{b}$, $b\,\bar{s}$, $\gamma\,\gamma$, $g\,g$ in the light of the MSSM with quark flavor violation

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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]]

PPP2021, Sep 7, 2021, Kyoto University

$\tilde{u}_{1,2}$

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 $h^0(125) \to c\,\bar{c}, b\,\bar{b}, b\,\bar{s}, \gamma\gamma, g\,g$.***

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} = ($\tilde{c}_L - \tilde{t}_L$ mixing parameter)

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

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

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

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

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

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

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

T_{D33} = ($\tilde{b}_L - \tilde{b}_R$ 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 ($m_{A/H+}$, $\tan\beta$) from recent MSSM Higgs boson search at LHC.*

(3) *The constraints on the QFV parameters from the B & K meson data.*

$B(b \to s\gamma)$ ΔM_{Bs} $B(B_s \to \mu^+\mu^-)$ $B(B_u^+ \to \tau^+\nu)$ *etc.*

(4) *The constraints from the observed Higgs boson mass and couplings at LHC ; e.g.*

121.6 GeV < m_h^0 < 128.6 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*

$\Delta\rho$ (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 $h^0 \to c\bar{c}, b\bar{b}, b\bar{s}$

- We compute the decay widths $\Gamma(h^0 \to c\bar{c})$, $\Gamma(h^0 \to b\bar{b})$, and $\Gamma(h^0 \to b\bar{s})$ at full 1-loop level in the MSSM with QFV.

- We take parameter scan ranges as follows:

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

$10 < \tan\beta < 80$
$2500 < M_3 < 5000\ GeV$
$100 < M_2 < 2500\ GeV$
$100 < M_1 < 2500\ GeV$
$100 < \mu < 2500\ GeV$
$1350 < m_A(pole) < 6000\ GeV$
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 $h^0 \rightarrow b\,\bar{b}$ & $b\,\bar{s}$:*

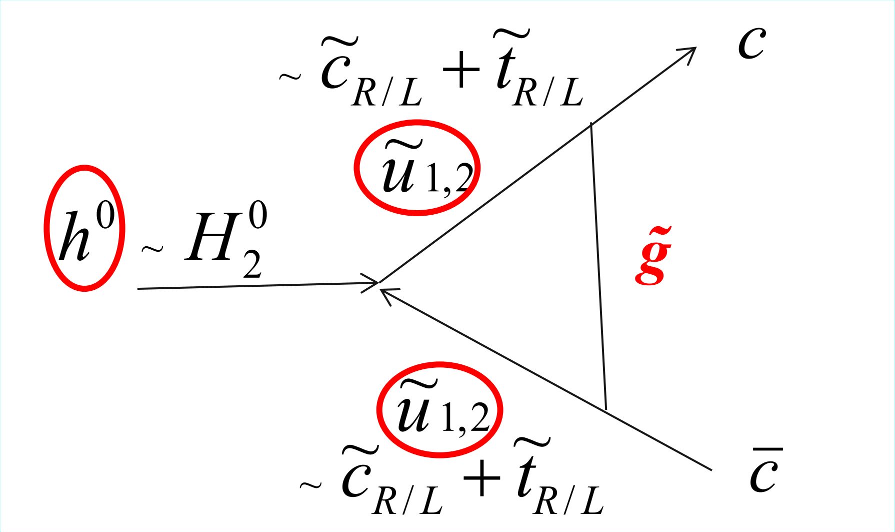
  gluino – sd loops [sd = ($\tilde{b}$ - $\tilde{s}$ mixture)]
  can be enhanced by large trilinear couplings T_{D23}, T_{D32}, T_{D33}

  chargino - su loops [su = ($\tilde{t}$ - $\tilde{c}$ mixture)]
  can be enhanced by large trilinear couplings T_{U23}, T_{U32}, T_{U33}

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

h^0 ~ H_2^0

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



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

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

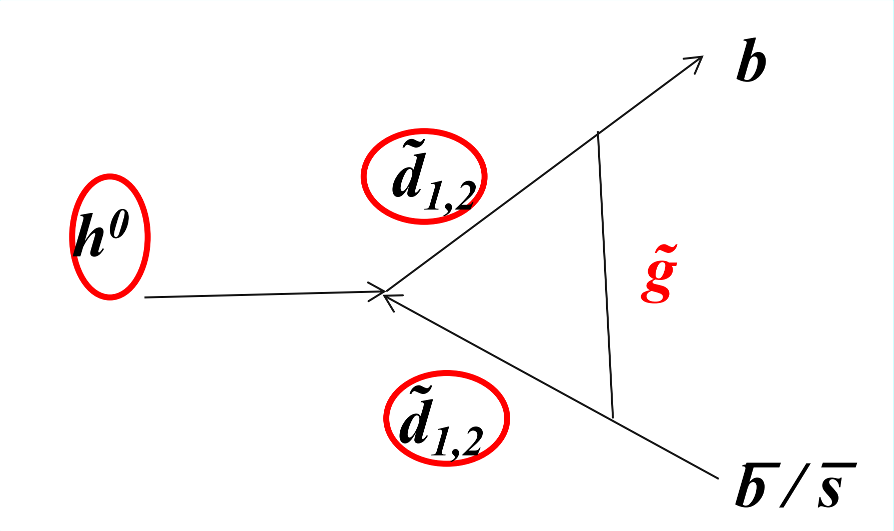
Gluino loop contributions can be large!

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!

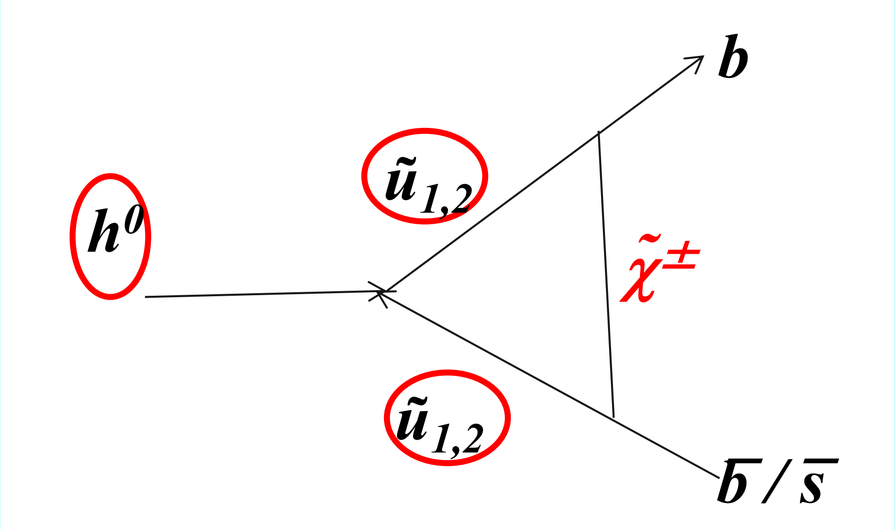
Deviation of $\Gamma(h^0 \rightarrow b\, \bar{b}/\bar{s})$ *from SM width can be large!*

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!

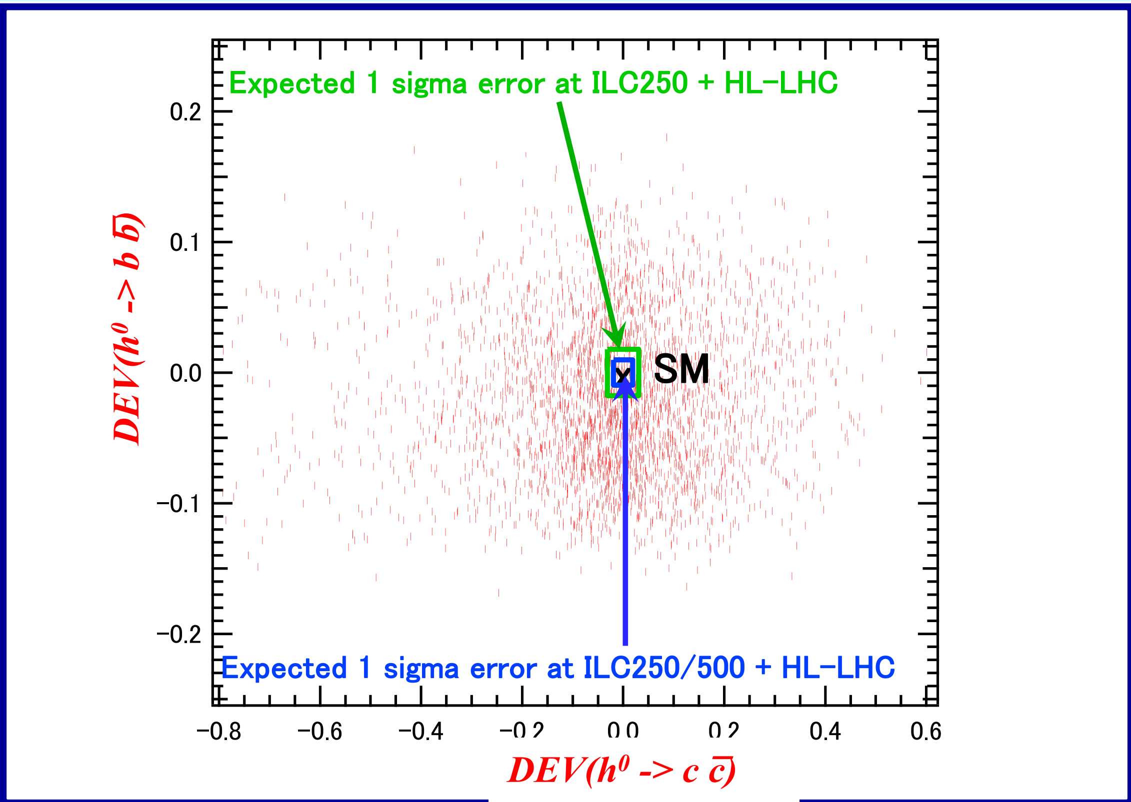
5.1 Deviation of the width from the SM prediction

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

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

$X = c, b$

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



- *DEV($h^0 \to c\bar{c}$) and DEV($h^0 \to b\bar{b}$) can be very large simultaneously!:*
  DEV($h^0 \to c\bar{c}$) can be as large as ~ ±60%.
  DEV($h^0 \to b\bar{b}$) can be as large as ~ ±20%.

- *ILC can observe such large deviations from SM at high significance (arXiv:1908.11299)!:*
  Δ DEV($h^0 \to c\bar{c}$) = (3.60%, 2.40%, 1.58%) at (ILC250, ILC500, ILC1000)
  Δ DEV($h^0 \to b\bar{b}$) = (1.98%, 1.16%, 0.94%) at (ILC250, ILC500, ILC1000)

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

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

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

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

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

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

6. $h^0 \to \gamma\gamma, g\,g$ in the MSSM

[arXiv:1812.08010 [hep-ph]]

- *For the h decays to photon photon and gluon gluon we compute the widths at NLO QCD level. We perform a MSSM parameter scan respecting all the relevant theoretical and experimental constraints.*

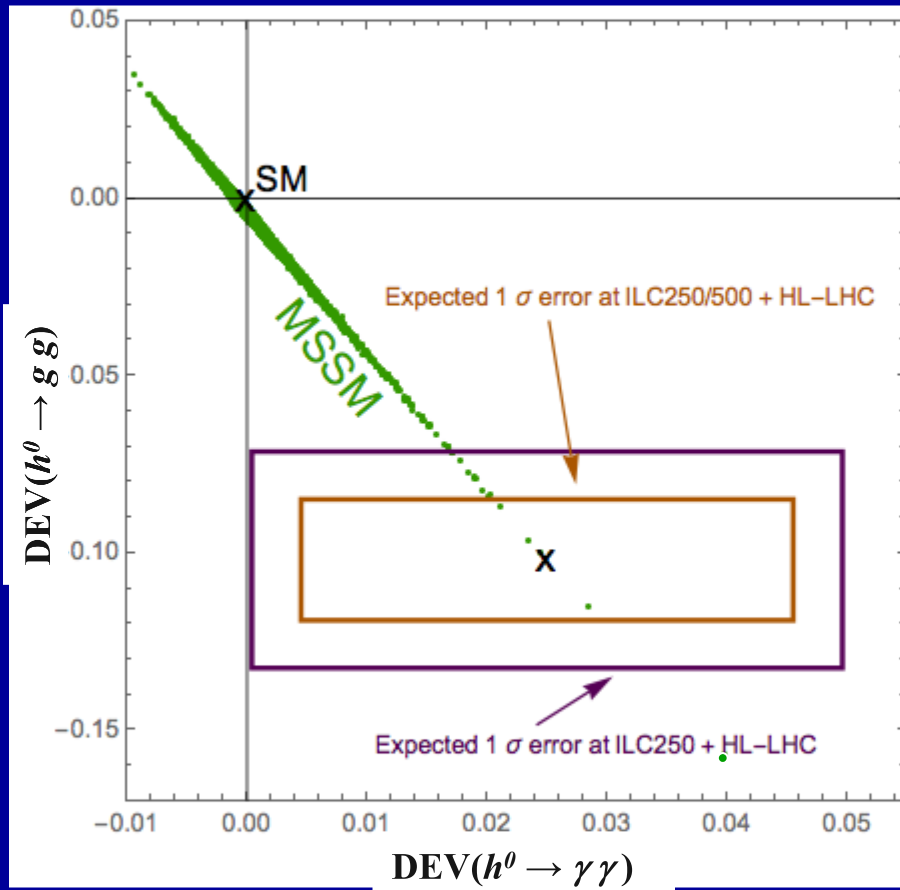
- *From the parameter scan, we find the followings:*

(1) DEV($h^0 \to \gamma\gamma$) and DEV($h^0 \to g\,g$) can be sizable simultaneously:
DEV($h^0 \to \gamma\gamma$) can be as large as ~ + 4%,
DEV($h^0 \to g\,g$) can be as large as ~ -15%.

(2) There is a very strong correlation between DEV($h^0 \to \gamma\gamma$) and DEV($h^0 \to g\,g$). 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 $\Gamma(h^0 \to \gamma\gamma) / \Gamma(h^0 \to g\,g)$ in the MSSM from the SM value can be as large as ~ +20%.

Scatter plot in DEV($h^0 \to \gamma\gamma$) - DEV($h^0 \to g\,g$) *plane*



- DEV($h^0 \to \gamma\gamma$) *and* DEV($h^0 \to g\,g$) *can be sizable simultaneously!*

-*There is a strong correlation between* DEV($h^0 \to \gamma\gamma$) *and* DEV($h^0 \to g\,g$)*!*

- *ILC can observe such large deviations from SM at high significance (arXiv:1908.11299)!*

7. Conclusion

- *We have studied the decays*

  h^0 (125GeV) $\rightarrow$ $c\,\bar{c}$, $b\,\bar{b}$, $b\,\bar{s}$, $\gamma\,\gamma$, $g\,g$ 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 -> $c\,\bar{c}$) and DEV(h^0 -> $b\,\bar{b}$) can be very large simultaneously! :*

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

  DEV(h^0 -> $b\,\bar{b}$) can be as large as ~ $\pm$ 20%.

  ** The deviation of the width ratio Γ(h^0 -> $b\,\bar{b}$) / Γ(h^0 -> $c\,\bar{c}$) from the SM value can be as large as ~ +200%.*

  ** BR(h^0 -> $b\,\bar{s}$ / $s\,\bar{b}$) can be as large as ~ 0.17%!*

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

* *DEV($h^0 \to \gamma\gamma$) and DEV($h^0 \to g\,g$) can be sizable simultaneously! :*
 DEV($h^0 \to \gamma\gamma$) can be as large as ~ +4%,
 DEV($h^0 \to g\,g$) can be as large as ~ -15%.

* *The deviation of the width ratio $\Gamma(h^0 \to \gamma\gamma)/\Gamma(h^0 \to g\,g)$ from the SM value can be as large as ~ +20%.*

* *There is a very strong correlation between DEV($h^0 \to \gamma\gamma$) and DEV($h^0 \to g\,g$). 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 (125GeV) 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 $p\,\bar{p}$ 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:

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

(*at* $Q = 1$ *TeV* scale) ($\alpha,\beta = 1,2,3 =$ *u, c, t 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*
- $M^2_{Q,\alpha\beta}$: *left squark soft mass matrix*
- $M^2_{U\alpha\beta}$: *right up-type squark soft mass matrix*
- $M^2_{D\alpha\beta}$: *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} = ($\tilde{c}_L - \tilde{t}_L$ mixing parameter)

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

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

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

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

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

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

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

T_{D33} = ($\tilde{b}_L - \tilde{b}_R$ 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 GeV^2):*

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

10 < tan β < 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 < μ < 2500
1350 < m_A(pole) < 6000;

$MQ2\_11 = 4500^2$ (fixed)

$2500^2 < MQ2\_22 < 4000^2$

$2500^2 < MQ2\_33 < 4000^2$

$|MQ2\_23| < 1000.^2$ <=== QFV param.

$MU2\_11 = 4500^2$ (fixed)

$1000.^2 < MU2\_22 < 4000.^2$

$600.^2 < MU2\_33 < 3000.^2$

$|MU2\_23| < 2000.^2$ <=== QFV param.

$MD2\_11 = 4500^2$ (fixed)

$2500.^2 < MD2\_22 < 4000.^2$

$1000.^2 < MD2\_33 < 3000.^2$

$|MD2\_23| < 2000.^2$

$ML2\_11 = 1500^2$ (fixed)

$ML2\_22 = 1500^2$ (fixed)

$ML2\_33 = 1500^2$ (fixed)

$ML2\_23 = 0.$ (fixed)

ME2_11 = 1500^2 (fixed)

ME2_22 = 1500^2 (fixed)

ME2_33 = 1500^2 (fixed)

ME2_23 = 0. (fixed)

|TU_23| < 4000 <=== QFV param

|TU_32| < 4000 <=== QFV param

|TU_33| < 5000 <=== QFC param

|TD_23| < 3000 <=== QFV param

|TD_32| < 3000 <=== QFV param

|TD_33| < 4000 <=== QFC param

TE_23 = 0. (fixed)

TE_32 = 0. (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.*

Table 1: Scanned ranges and fixed values of the MSSM parameters (in units of GeV or GeV^2, except for $\tan\beta$). The parameters that are not shown explicitly are taken to be zero. $M_{1,2,3}$ are the U(1), SU(2), SU(3) gaugino mass parameters.

$\tan\beta$	M_1	M_2	M_3	μ	$m_A(pole)$
$10 \div 80$	$100 \div 2500$	$100 \div 2500$	$2500 \div 5000$	$100 \div 2500$	$1350 \div 6000$
M^2_{Q22}	M^2_{Q33}	$\|M^2_{Q23}\|$	M^2_{U22}	M^2_{U33}	$\|M^2_{U23}\|$
$2500^2 \div 4000^2$	$2500^2 \div 4000^2$	$< 1000^2$	$1000^2 \div 4000^2$	$600^2 \div 3000^2$	$< 2000^2$
M^2_{D22}	M^2_{D33}	$\|M^2_{D23}\|$	$\|T_{U23}\|$	$\|T_{U32}\|$	$\|T_{U33}\|$
$2500^2 \div 4000^2$	$1000^2 \div 3000^2$	$< 2000^2$	< 4000	< 4000	< 5000
$\|T_{D23}\|$	$\|T_{D32}\|$	$\|T_{D33}\|$	$\|T_{E33}\|$		
< 3000	< 3000	< 4000	< 500		

M^2_{Q11}	M^2_{U11}	M^2_{D11}	M^2_{L11}	M^2_{L22}	M^2_{L33}	M^2_{E11}	M^2_{E22}	M^2_{E33}
4500^2	4500^2	4500^2	1500^2	1500^2	1500^2	1500^2	1500^2	1500^2

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 $B(K_L^0 \to \pi^0 \nu\bar{\nu})$, 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
$10^9 \times \mathrm{B}(K_L^0 \to \pi^0 \nu\bar{\nu})$	< 3.0 (90% CL) [21]	± 0.002 (68% CL) [21]	< 3.0 (90% CL)
$10^{10} \times \mathrm{B}(K^+ \to \pi^+ \nu\bar{\nu})$	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
$10^4 \times \mathrm{B}(b \to s\gamma)$	3.32 ± 0.15 (68% CL) [21, 41]	± 0.23 (68% CL) [11]	3.32 ± 0.54
$10^6 \times \mathrm{B}(b \to s\ l^+ l^-)$ ($l = e$ or μ)	$1.60\ ^{+0.48}_{-0.45}$ (68% CL) [43]	± 0.11 (68% CL) [44]	$1.60\ ^{+0.97}_{-0.91}$
$10^9 \times \mathrm{B}(B_s \to \mu^+ \mu^-)$	$2.69\ ^{+0.37}_{-0.35}$ (68%CL) [45]	± 0.23 (68% CL) [46]	$2.69\ ^{+0.85}_{-0.82}$
$10^4 \times \mathrm{B}(B^+ \to \tau^+ \nu)$	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]		$1.06^{+0.37}_{-0.35}$ (ATLAS)
	$1.17^{+0.53}_{-0.61}$ (95% CL) [51]		$1.17^{+0.53}_{-0.61}$ (CMS)
κ_g	$1.03^{+0.14}_{-0.12}$ (95% CL) [50]		$1.03^{+0.14}_{-0.12}$ (ATLAS)
	$1.18^{+0.31}_{-0.27}$ (95% CL) [51]		$1.18^{+0.31}_{-0.27}$ (CMS)
κ_γ	1.00 ± 0.12 (95% CL) [50]		1.00 ± 0.12 (ATLAS)
	$1.07^{+0.27}_{-0.29}$ (95% CL) [51]		$1.07^{+0.27}_{-0.29}$ (CMS)

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

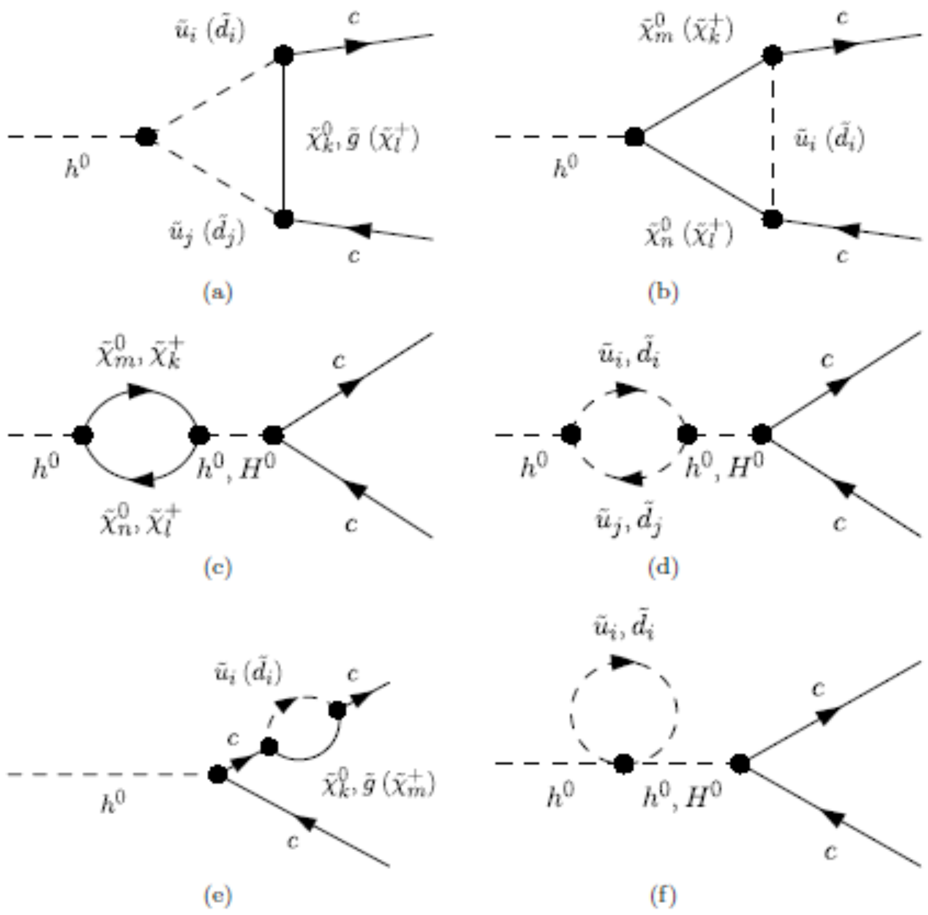
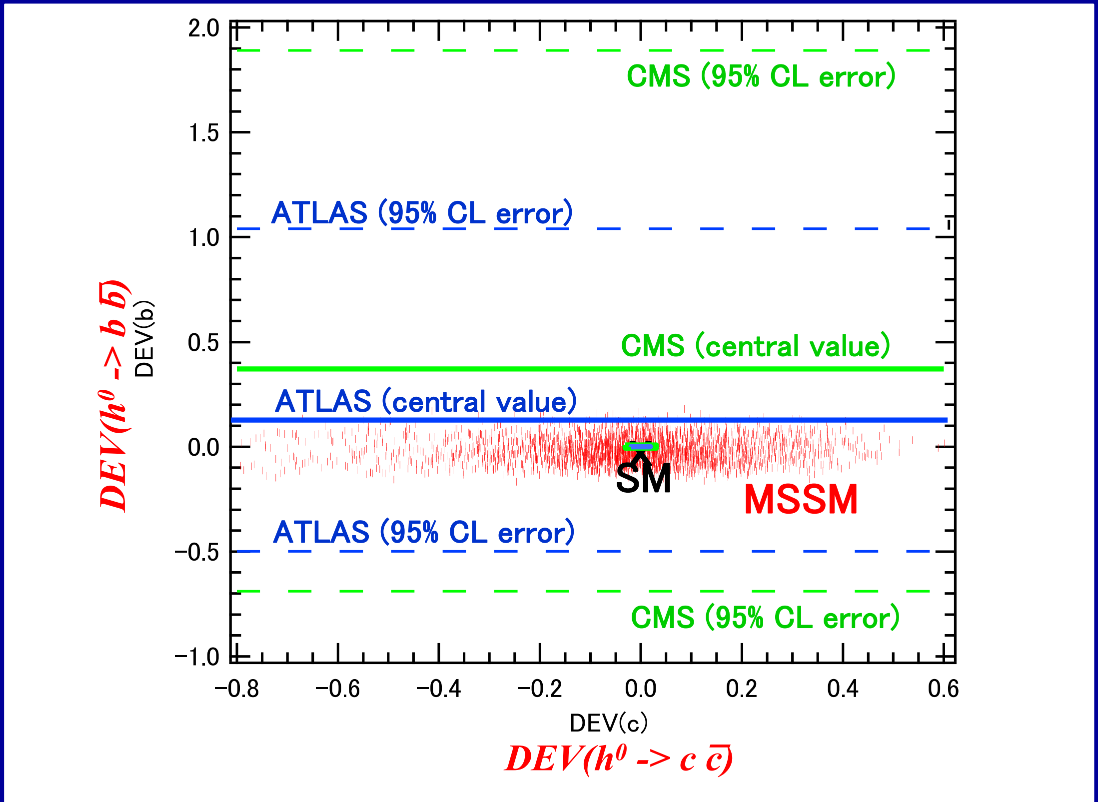


Figure 2: The main one-loop contributions with SUSY particles in $h^0 \to c\bar{c}$. The corresponding diagram to (e) with the self-energy contribution to the other charm quark is not shown explicitly.

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



- *Recent LHC data:*

  DEV($h^0 \to b\,\bar{b}$) = 0.12 +0.92/-0.62 = [-0.50, 1.04] (ATLA S) (arXiv:1909.02845)
  DEV($h^0 \to b\,\bar{b}$) = 0.37 +1.52/-1.06 = [-0.69, 1.89] (CMS) (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!

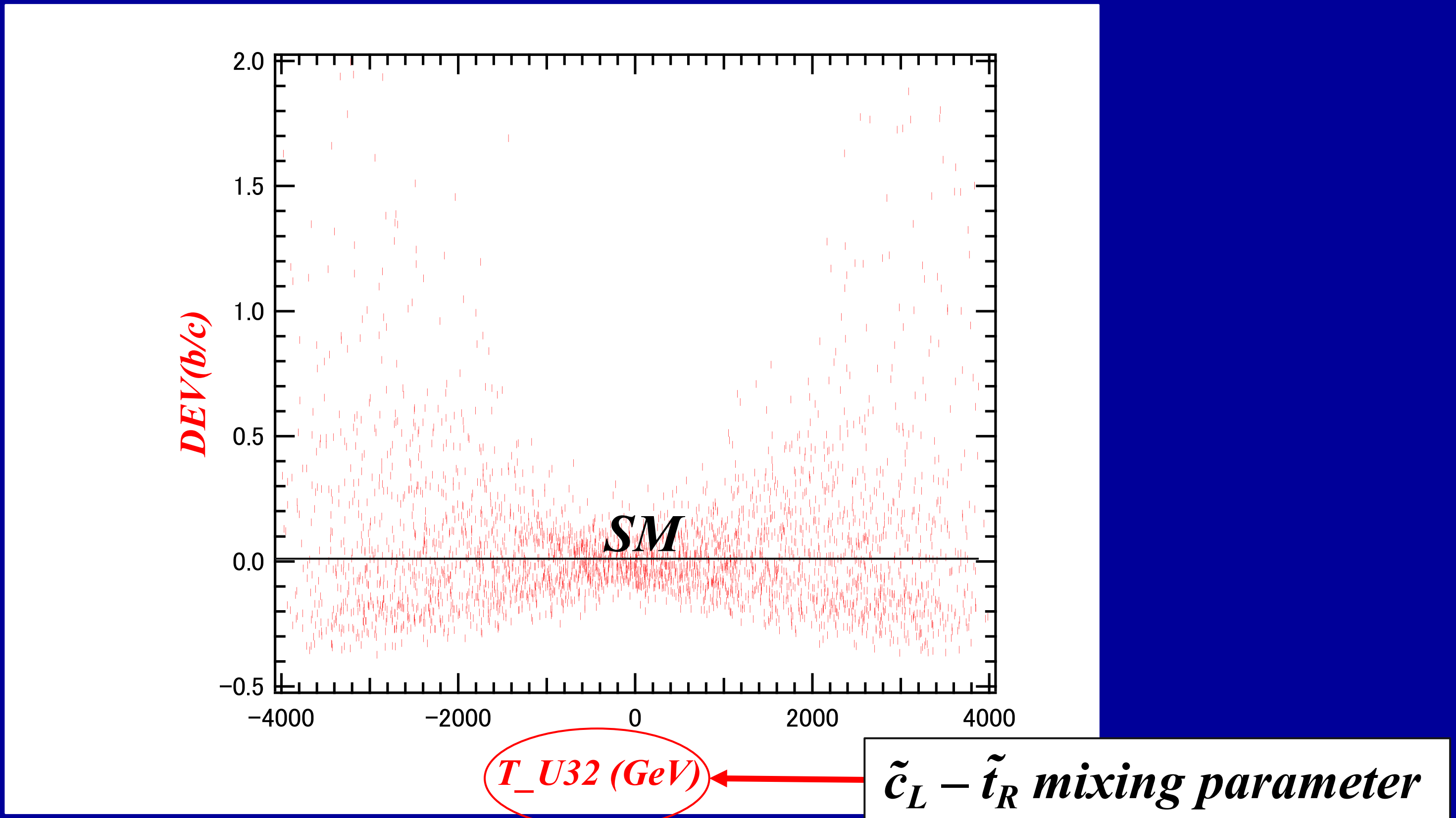
5.2 Deviation of width ratio from the SM prediction

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

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

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

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



-There is a strong correlation between $T_{U32} - DEV(b/c)$!

- DEV(b/c) can be as large as ~ +200% for large T_{U32} !

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

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

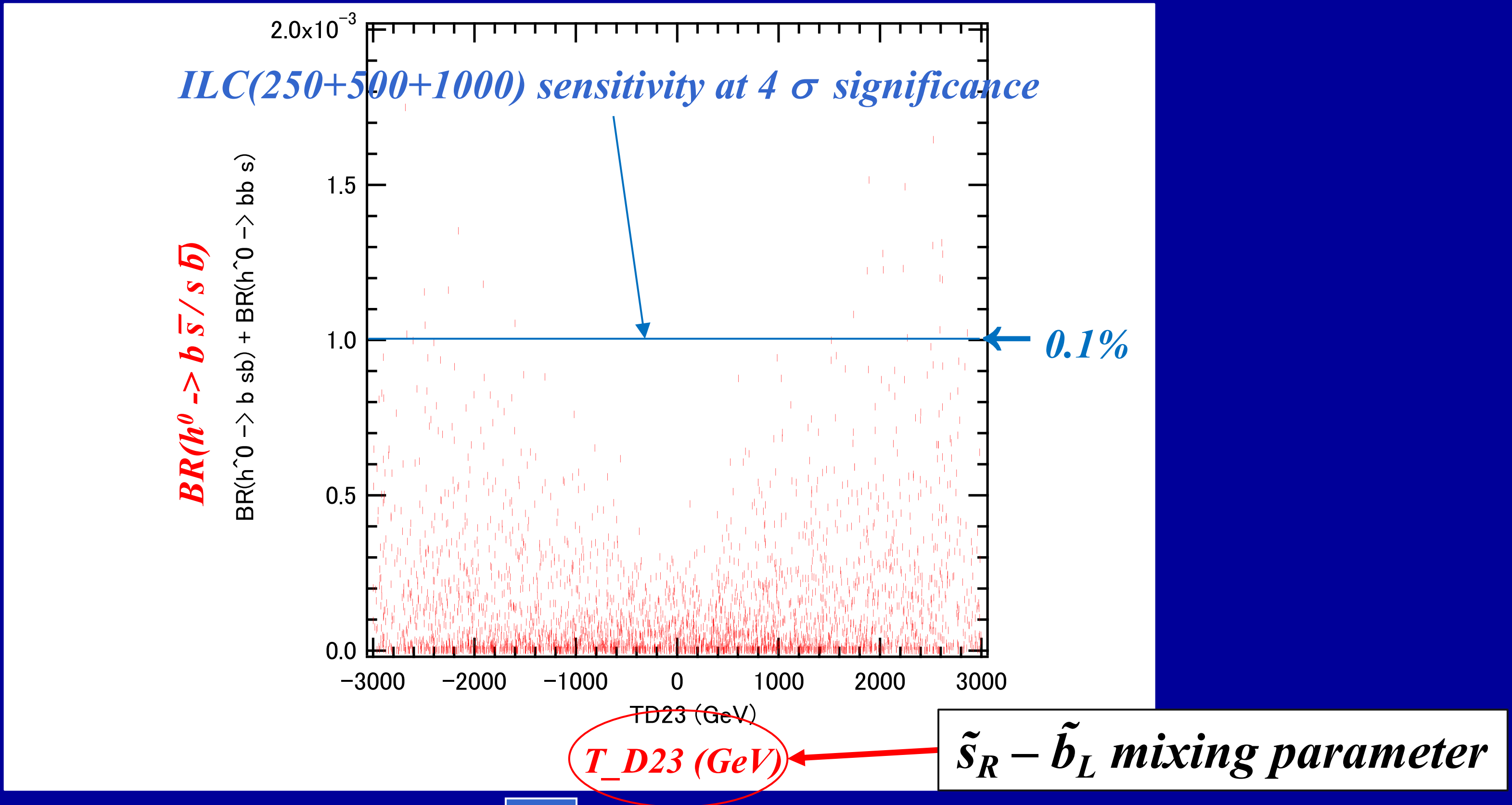
$BR(h^0 \to b\,\bar{s}\,/\,s\,\bar{b})$ can be as large as ~ 0.17% (MSSM with QFV)!

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

ILC(250+500+1000) sensitivity could be ~ 0.1% (at 4 σ 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 -> b $\bar{s}$ / s $\bar{b}$) plane

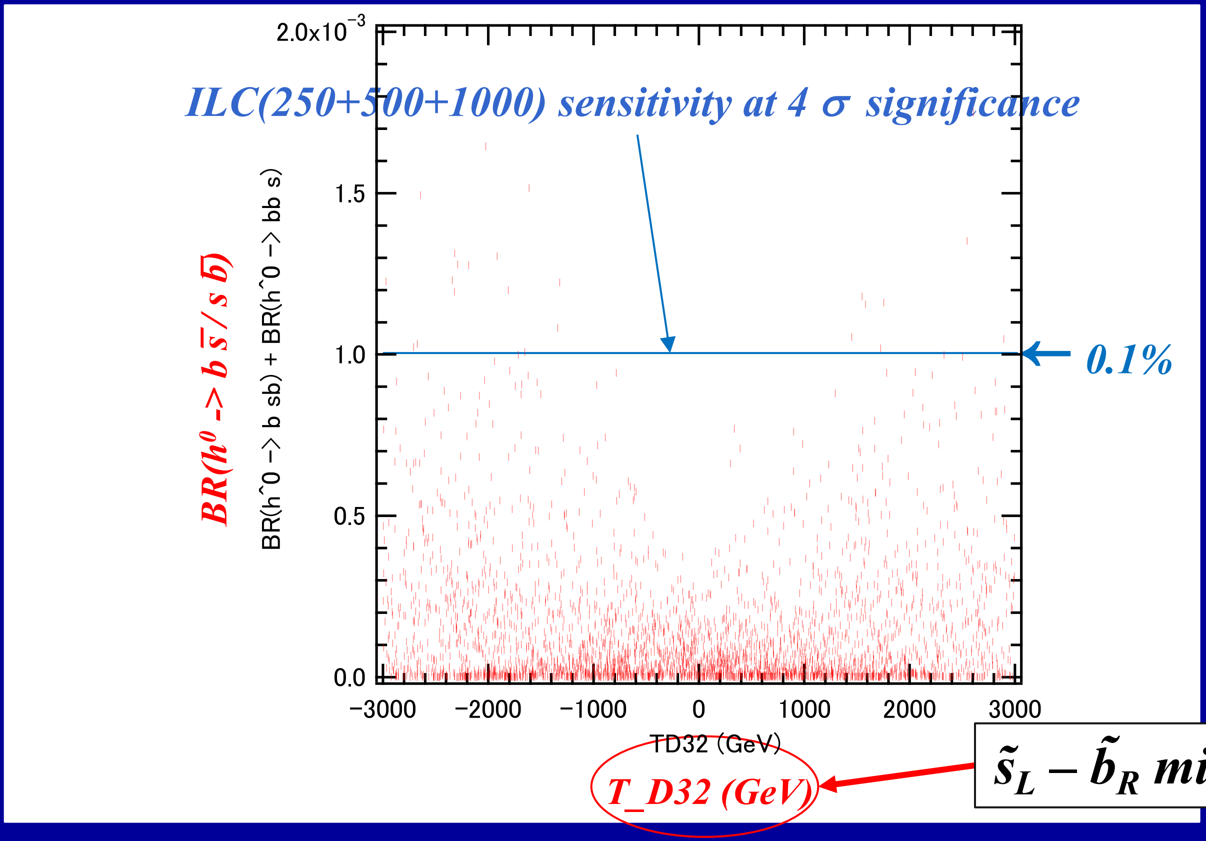


- *There is a strong correlation between T_{D23} - BR(h^0 -> b $\bar{s}$ / s $\bar{b}$)!*
- *BR(h^0 -> b $\bar{s}$ / s $\bar{b}$) can be as large as 0.17% for large T_{D23} !*
- *ILC(250 + 500 + 1000) sensitivity could be ~ 0.1% at 4 sigma significance!*

  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!*

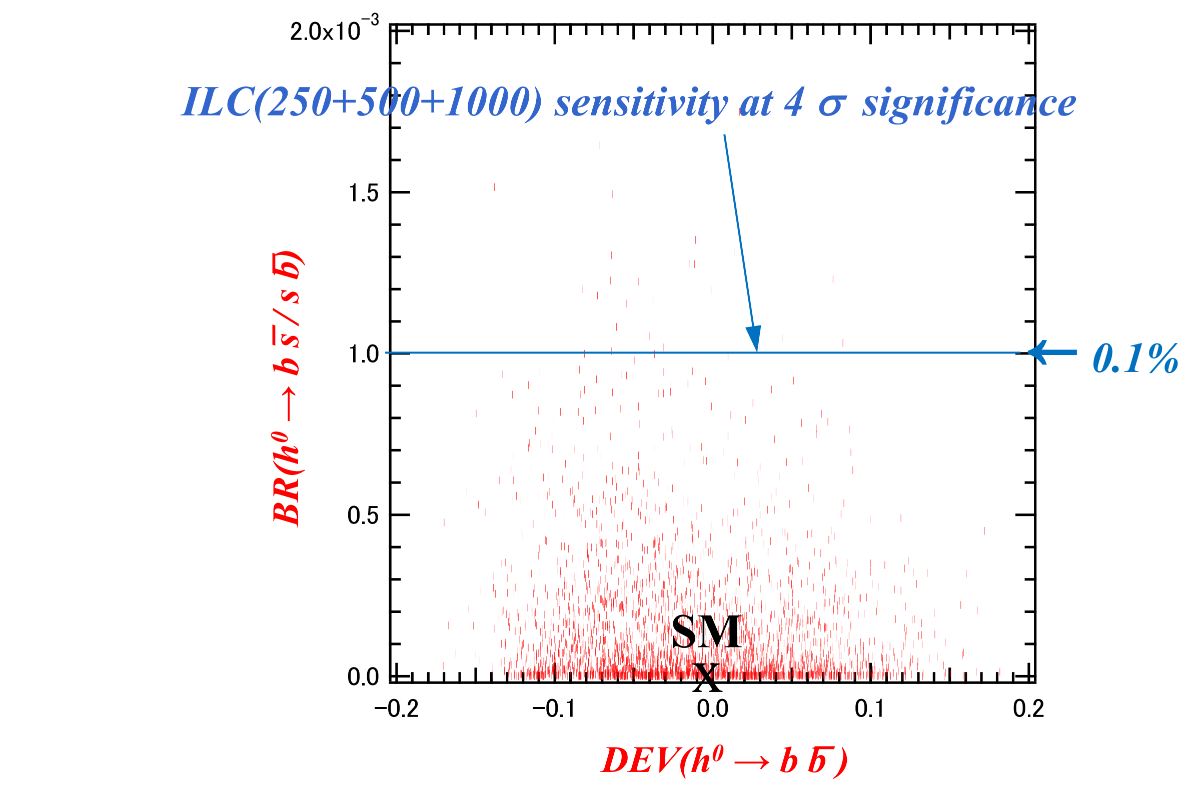
Scatter plot in T_{D32} - BR(h^0 -> b $\bar{s}$ / s $\bar{b}$) plane



$\tilde{s}_L - \tilde{b}_R$ mixing parameter

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

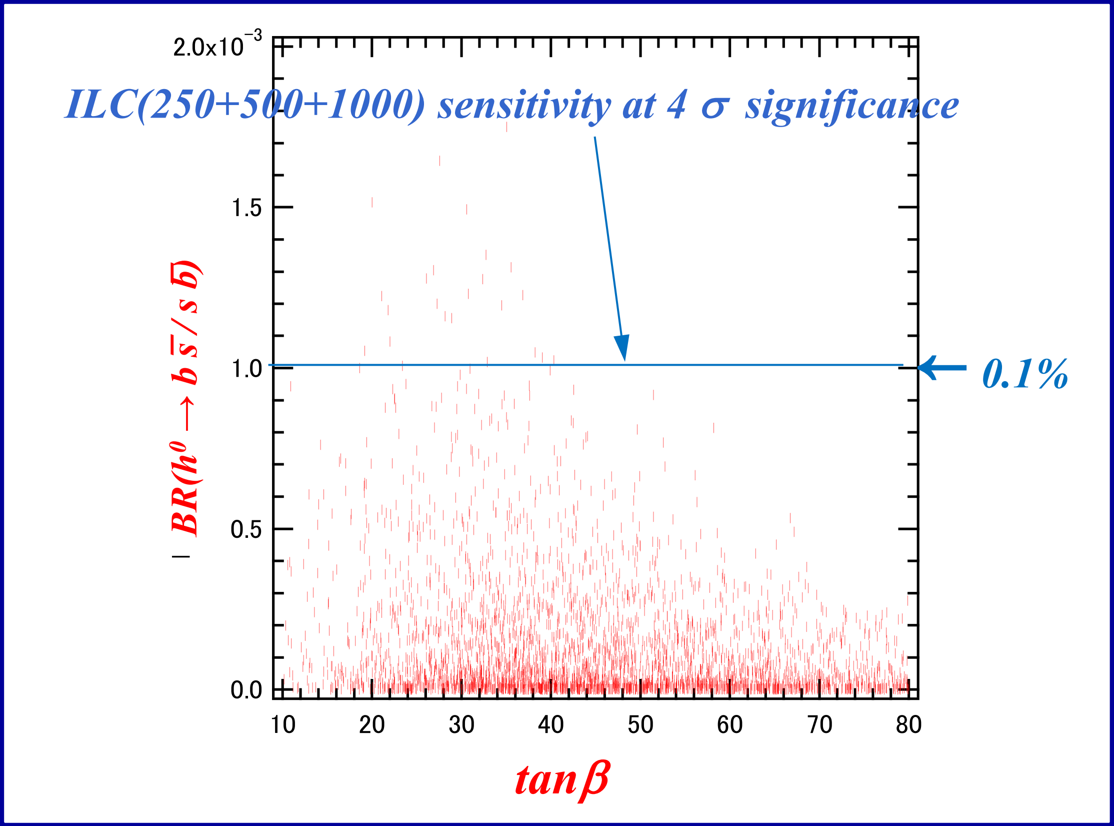
Scatter plot in $BR(h^0 \to b\bar{s}/s\bar{b})$ - $DEV(h^0 \to b\bar{b})$ plane



- *There is a strong correlation between $DEV(h^0 \to b\bar{b})$ & $BR(h^0 \to b\bar{s}/s\bar{b})$!*

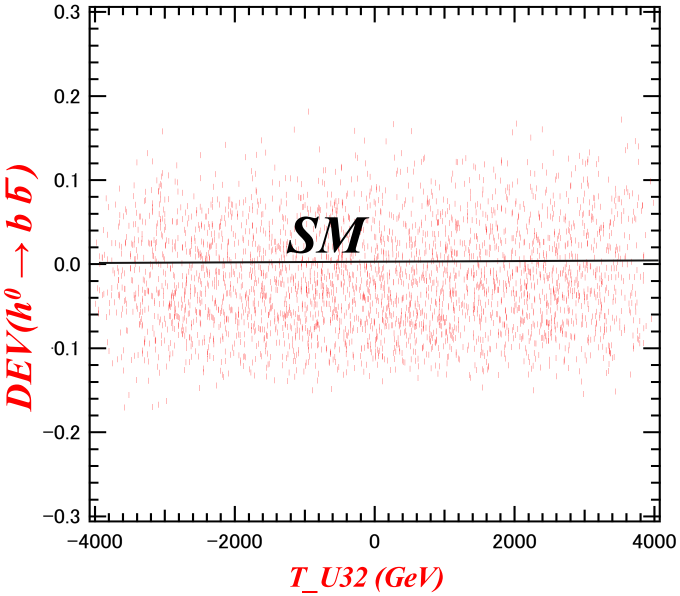
- *This is due to the fact that $DEV(h^0 \to b\bar{b})$ & $BR(h^0 \to b\bar{s}/s\bar{b})$ have a common origin of enhancement effect, i.e. large trilinear couplings $T_{D23,32,33}$ & $T_{U23,32,33}$.*

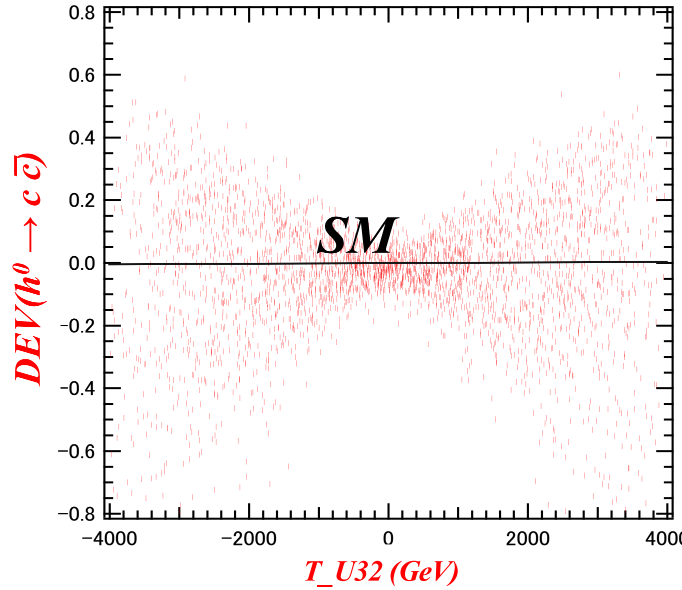
Scatter plot in $BR(h^0 \to b\bar{s}/s\bar{b})$ - $\tan\beta$ plane

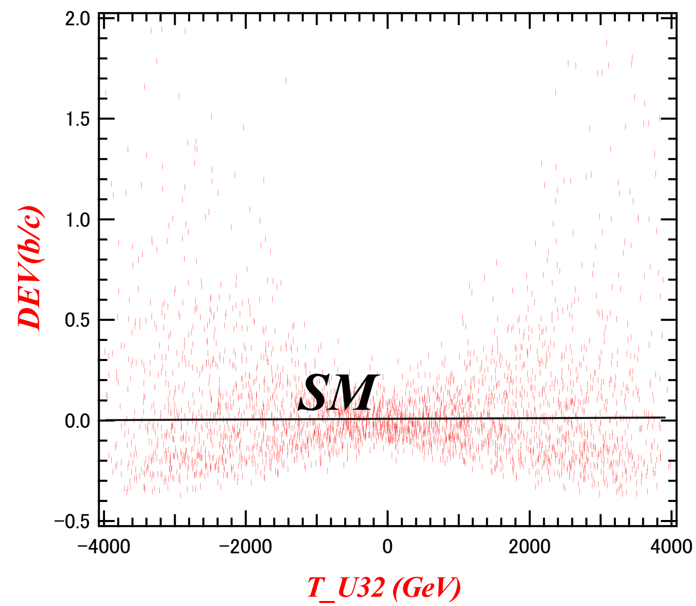


- *There is a strong correlation between $BR(h^0 \to b\bar{s}/s\bar{b})$ & $\tan\beta$!*
- *$BR(h^0 \to b\bar{s}/s\bar{b})$ can be as large as 0.17% for $\tan\beta \sim 30$!*

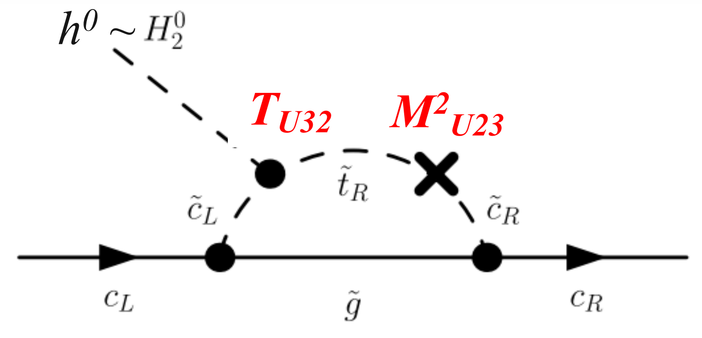
Caveat for very large DEV(h^0 -> c $\bar{c}$) & DEV(b/c)







Caveat for very large DEV(h^0 -> 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^2_{U23}**!*

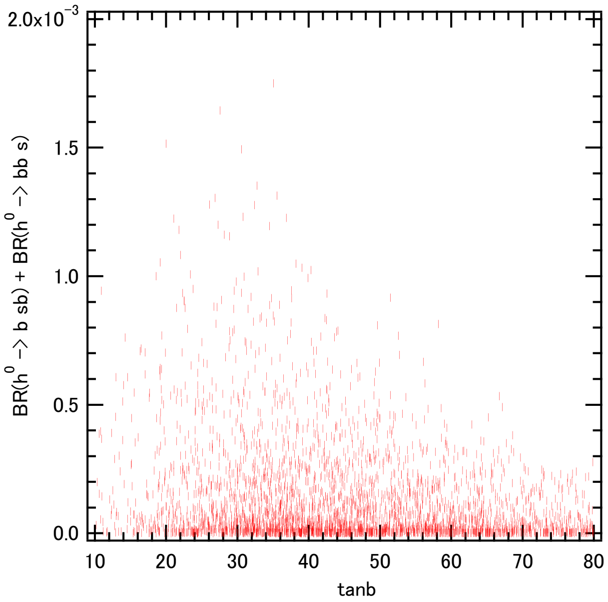
*The **interference term** between the tree diagram and the gluino one-loop diagram can be **very large** (positive and negative) **for large T_{U32}*M^2_{U23}**, which can lead to even **NEGATIVE width** $\Gamma(h^0 \rightarrow c\,\bar{c})$ at one-loop level !*

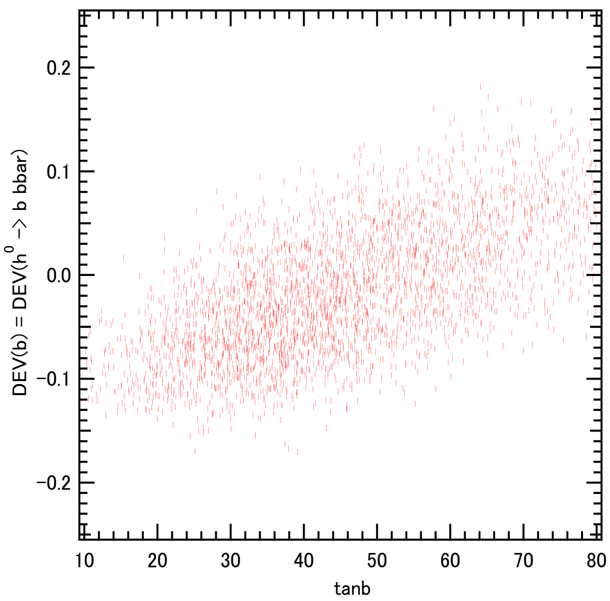
*In this case **perturbation theory breaks down!***

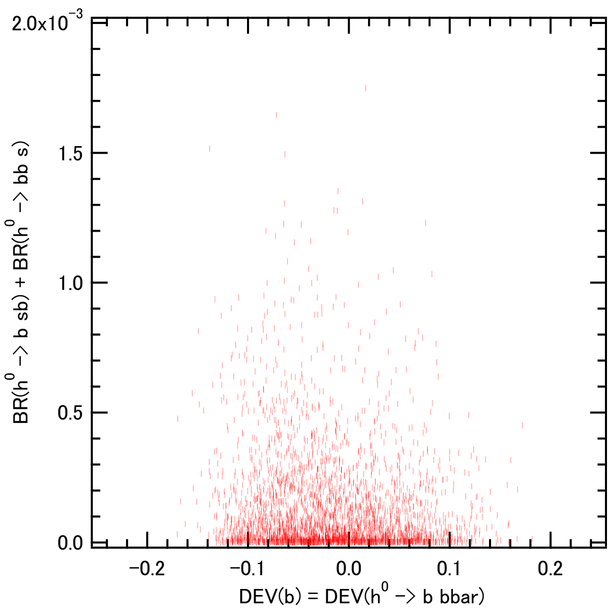
*A large deviation of $\Gamma(h^0 \rightarrow c\,\bar{c})$ from the SM value is in principle possible due to large values of the product T_{U32}*M^2_{U23} .*

*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 ~ +/-60%.*

Correlations among DEV(h^0 -> b $\bar{b}$), BR(h^0 -> b $\bar{s}$ / s $\bar{b}$), tanβ





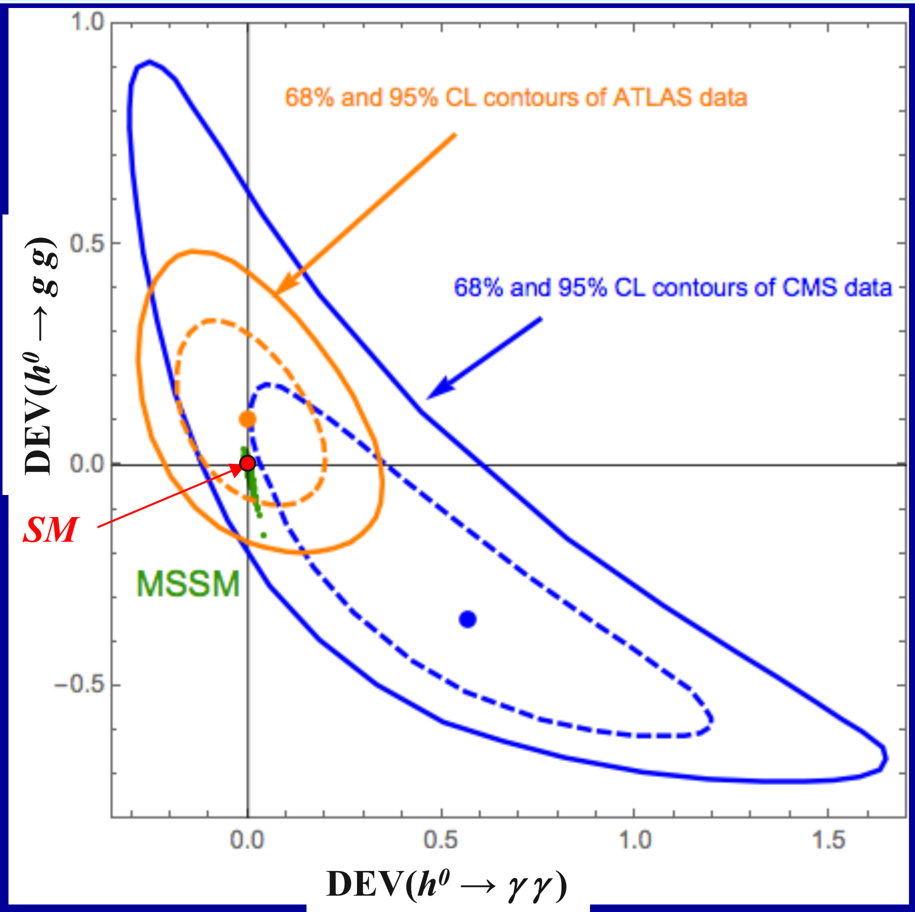


Effect of Resummation of the bottom Yukawa coupling at large tanβ

As for $\Gamma(h^0 \to b\,\bar{b})$ & $\Gamma(h^0 \to b\,\bar{s}\,/\,s\,\bar{b})$, we have considered the large tanβ 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 **DEV($h^0 \to \gamma\gamma$) - DEV($h^0 \to g\,g$)** *plane*



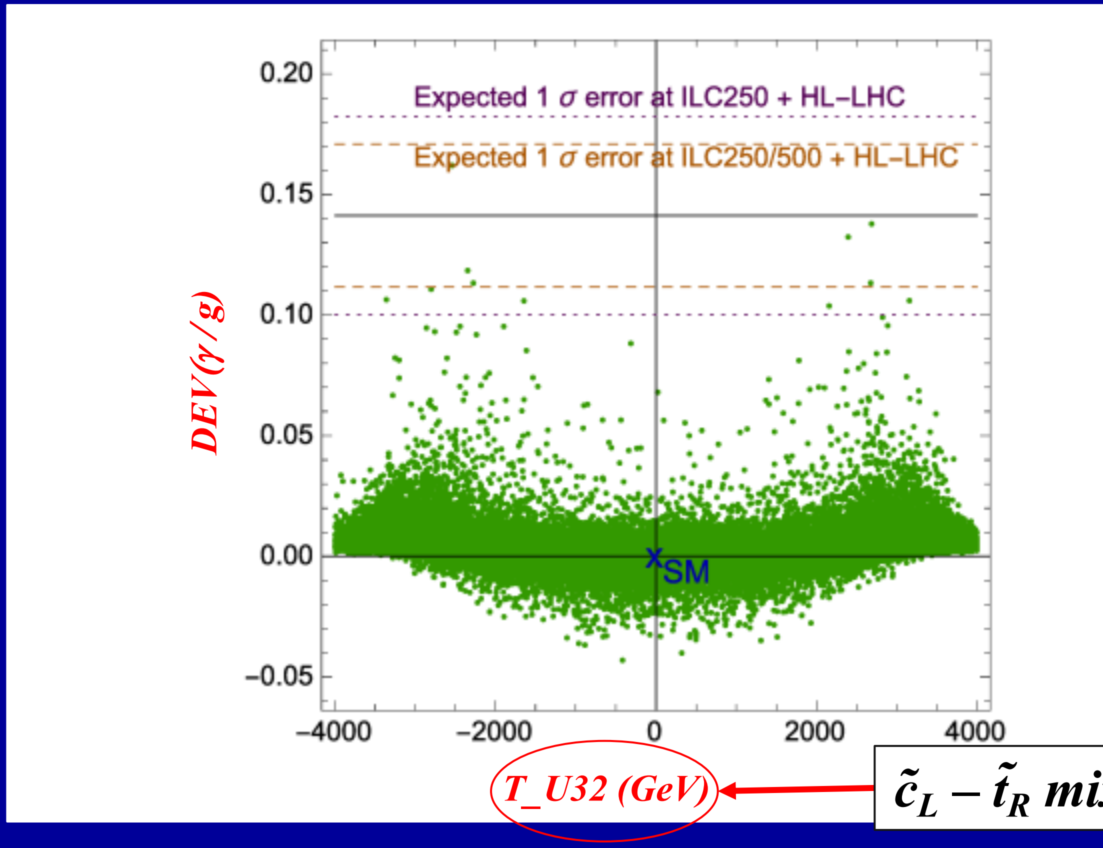
- *Both SM and MSSM are consistent with the recent ATLAS/CMS data!:*

  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

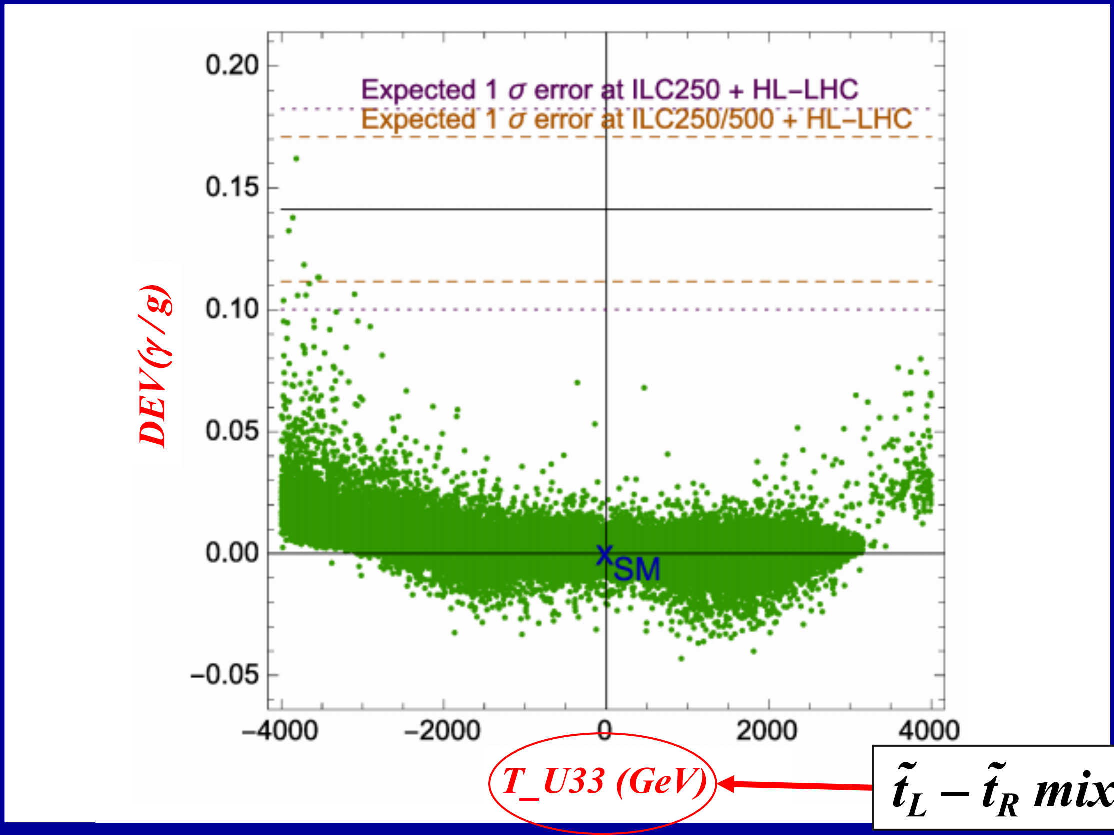


$\tilde{c}_L - \tilde{t}_R$ mixing parameter

-There is a strong correlation between $T_{U32} - DEV(\gamma/g)$!

- $DEV(\gamma/g)$ can be as large as ~ +15% for large T_{U32} !

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



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

-There is a strong correlation between $T_{U33} - DEV(\gamma/g)$!

- $DEV(\gamma/g)$ can be as large as ~ +16% for large T_{U33} !