

Impact of quark flavor violating SUSY on $h(125)$ decays at future lepton colliders

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Collaboration with

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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]]

PoS(EPS-HEP2021) 594, 2021 [arXiv:2111.02713 [hep-ph]]

PoS(ICHEP2022) 536, 2022 [arXiv:2211.07243 [hep-ph]]

PoS(EPS-HEP2023) 487, 2023

LCWS2024, 8-11 July 2024, University of Tokyo, Japan

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 $h^0(125) \rightarrow c \bar{c}, b \bar{b}, b \bar{s}, \gamma\gamma, gg$ with special emphasis on Supersymmetric Quark Flavor Violation (QFV).*

2. MSSM with general 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*

These QFV parameters are absent in the MSSM with minimal flavor violation (MFV)!

3. Constraints on the MSSM

We respect the following experimental and theoretical constraints:

- (1) The LHC limits on the **SUSY particle masses**.*
- (2) The constraint on $(m_{A/H^+}, \tan\beta)$ from **MSSM Higgs boson search at LHC**.*
- (3) The constraints on the **QFV parameters** from the **B & K meson data**.*

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

- (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) ,
 $0.68 < \kappa_b < 1.11$ (ATLAS), $0.68 < \kappa_b < 1.32$ (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 $T_{D\alpha\beta}$.*

** We also take into account the expected SUSY particle mass limits from the future HL-LHC experiment in our analysis.*

- [1] X. Cid Vidal et al., "Report from Working Group 3: Beyond the Standard Model physics at the HL-LHC and HE-LHC", CERN Yellow Rep: Monogr. 7 (2019) 585-865 [arXiv:1812.07831 [hep-ph]].
- [2] T. Bose et al., "Report of the Topical Group on Physics Beyond the Standard Model at Energy Frontier for Snowmass 2021", arXiv:2209.13128 [hep-ph].
- [3] ATLAS Collaboration, ATLAS Notes ATL-PHYS-PUB-2012-001, ATL-PHYS-PUB2013-002, ATL-PHYS-PUB-2014-010, and ATL-PHYS-PUB-2018-048.
- [4] C. M. Berggren, talk at The European Physical Society Conference on High Energy Physics (EPS-HEP2023), 21-25 August 2023, Hamburg, Germany.
- [5] H. Gilmer, talk at the 40th International Conference on High Energy Physics, virtual conference (ICHEP2020), 28 Jul - 6 Aug 2020, Prague, Czech Republic.
- [6] M. Narain et al., "The Future of US Particle Physics - The Snowmass 2021 Energy Frontier Report", arXiv:2211.11084 [hep-ex].
- [7] H. Bahl, P. Bechtle, S. Heinemeyer, S. Liebler, T. Stefaniak and G. Weiglein, Eur. Phys. J. C 80 (2020) 916 [arXiv:2005.14536 [hep-ph]].

4. Parameter scan

- We compute the $h^0(125)$ decay widths in the *MSSM with general 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 general 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 $T_{D23}, T_{D32}, T_{D33}$

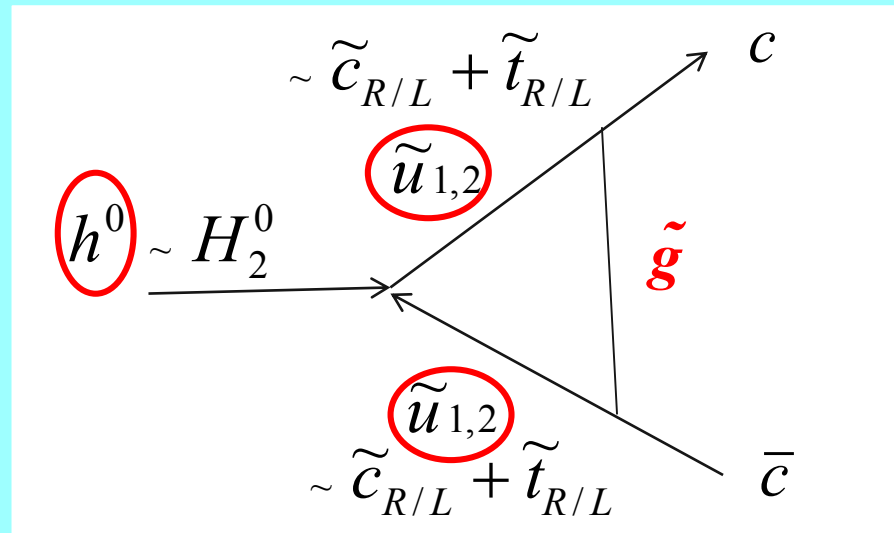
chargino - su loops [su = (\tilde{t} - \tilde{c} mixture)]

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!

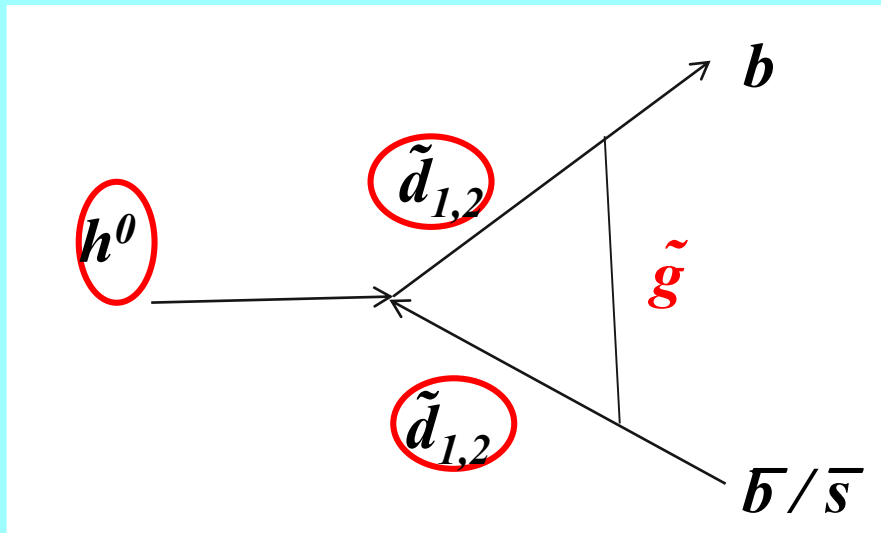
Gluino loop contributions can be large!

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!

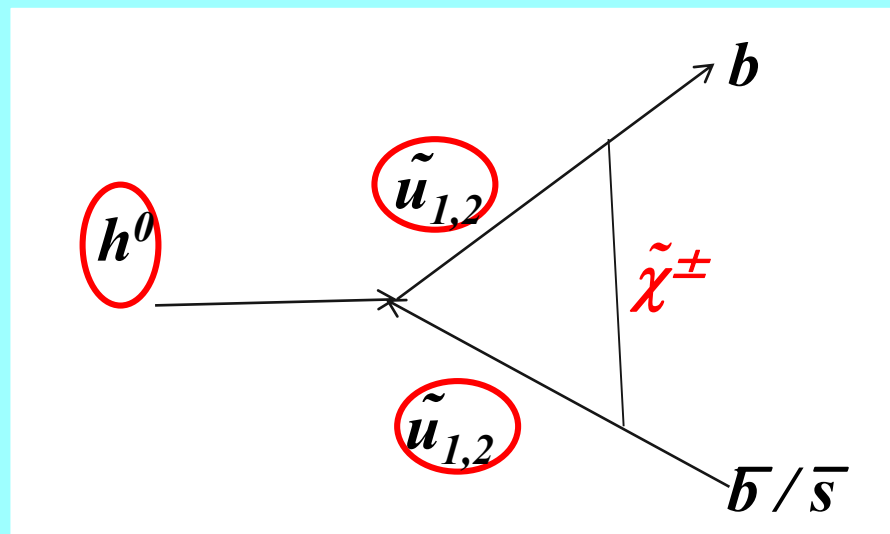
Deviation of $\Gamma(h^0 \rightarrow b \bar{b}/\bar{s})$ from SM width can be large!

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

- *Deviation of the width from the SM prediction:*

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

$$X = c, b$$

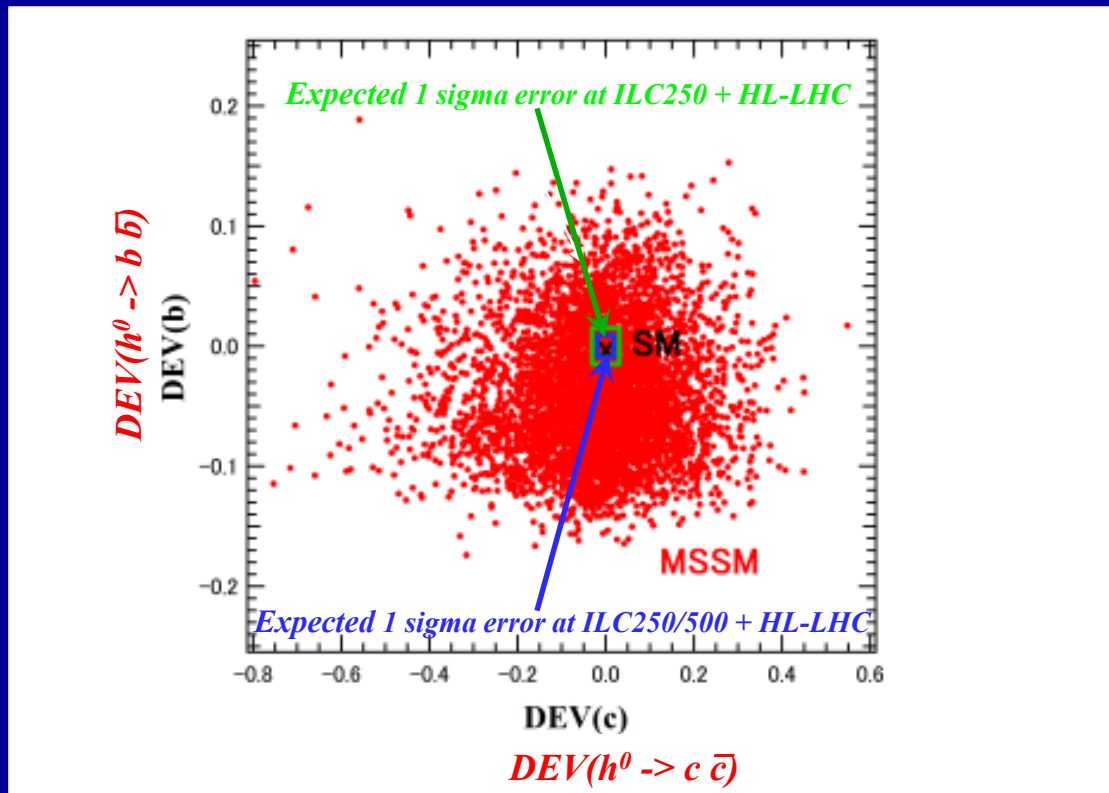
- *Coupling modifier:*

$$\kappa_X = g(h^0 X X) / g(h^0 X X)_{SM}$$

- *DEV - κ_X relation:*

$$DEV(h^0 \rightarrow X X) = \kappa_X^2 - 1$$

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!:

$DEV(h^0 \rightarrow b \bar{b})$ can be as large as $\sim \pm 20\%$
 $DEV(h^0 \rightarrow c \bar{c})$ can be as large as $\sim \pm 60\%$

$DEV(h^0 \rightarrow c \bar{c})$ is very small $< \mathcal{O}(1)\%$ in MSSM with MFV!

- ILC can observe such large deviations from SM at high significance (arXiv:2206.08326)!:

$\Delta DEV(h^0 \rightarrow c \bar{c}) = (3.6\%, 2.4\%, 1.8\%)$ at (ILC250, ILC250/500, ILC250/500/1000)

$\Delta DEV(h^0 \rightarrow b \bar{b}) = (1.7\%, 1.1\%, 0.9\%)$ at (ILC250, ILC250/500, ILC250/500/1000)

Expected absolute 1 sigma errors of the deviations DEVs at future lepton colliders

Table 6: The expected *absolute* 1σ error of the deviations $DEV(X)$ and $DEV(X/Y)$ (denoted by $\Delta DEV(X)$ and $\Delta DEV(X/Y)$) at future lepton colliders: ILC-I = ILC250 + Giga-Z, ILC-II = ILC250+500 + Giga-Z, ILC-III = ILC250+500+1000 + Giga-Z; CLIC-I = CLIC380, CLIC-II = CLIC380+1500, CLIC-III = CLIC380+1500+3000; FCC-ee I = FCC-ee240 + Z/WW, FCC-ee II = FCC-ee240+365 + Z/WW; CEPC-I = CEPC240 + Z/WW, CEPC-II = CEPC240+360 + Z/WW; MuC-I = MuC3TeV, MuC-II = MuC10TeV, MuC-III = MuC10TeV+125GeV. As for ILC the results without Giga-Z run are almost identical to those with Giga-Z one. The Z/WW denote Z-pole and WW threshold runs. All results except for MuC-I and MuC-II are those from the free- Γ_H fit and the results for MuC-I and MuC-II are those from the constrained- Γ_H fit, where Γ_H is the total width of the Higgs boson h^0 . The details of run scenarios of the lepton colliders are explained in Ref. [14]. The HL-LHC and LEP/SLD measurements are combined with all lepton collider run scenarios.

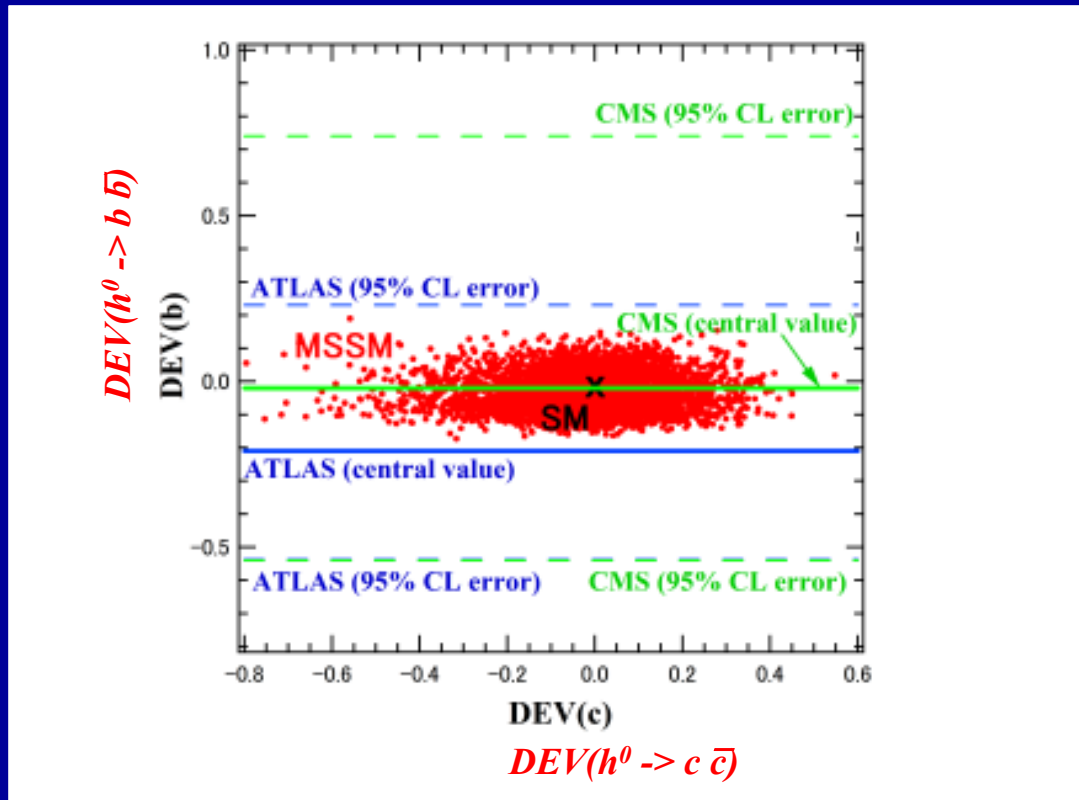
*Jorge de Blas et al., Snowmass2021 Report: arXiv:2206.08326 [hep-ph];
Private communication with Jorge de Blas.*

Expected absolute 1 sigma errors of the deviations DEVs at future lepton colliders

	ILC-I	ILC-II	ILC-III	CLIC-I	CLIC-II	CLIC-III
$\Delta DEV(b)$	1.7%	1.1%	0.9%	2.2%	1.2%	1.1%
$\Delta DEV(c)$	3.6%	2.4%	1.8%	8.6%	3.8%	3.0%
$\Delta DEV(\gamma)$	2.4%	2.2%	2.0%	2.6%	2.4%	2.2%
$\Delta DEV(g)$	1.8%	1.4%	1.1%	2.2%	1.6%	1.4%
$\Delta DEV(b/c)$	3.12%	2.07%	1.3%	8.16%	3.5%	2.54%
$\Delta DEV(\gamma/g)$	3.29%	2.82%	2.3%	3.41%	3.05%	2.61%
$\Delta DEV(g/b)$	1.51%	1.14%	0.85%	1.62%	1.3%	1.1%
$\Delta DEV(g/c)$	3.4%	2.34%	1.52%	8.3%	3.72%	2.75%

	FCC-ee I	FCC-ee II	CEPC-I	CEPC-II	MuC-I	MuC-II	MuC-III
$\Delta DEV(b)$	1.3%	1.2%	0.86%	0.84%	1.8%	0.92%	1.1%
$\Delta DEV(c)$	2.8%	2.6%	2.4%	2.2%	12.4%	3.8%	3.6%
$\Delta DEV(\gamma)$	2.4%	2.2%	1.8%	1.8%	2.4%	1.4%	1.5%
$\Delta DEV(g)$	1.5%	1.4%	0.9%	0.88%	1.7%	0.92%	1.0%
$\Delta DEV(b/c)$	2.22%	2.06%	2.0%	1.94%	11.92%	3.53%	3.37%
$\Delta DEV(\gamma/g)$	3.03%	2.86%	2.07%	2.03%	3.18%	1.55%	1.55%
$\Delta DEV(g/b)$	1.29%	1.16%	0.73%	0.7%	1.69%	0.73%	0.72%
$\Delta DEV(g/c)$	2.54%	2.33%	2.13%	2.06%	12.0%	3.59%	3.43%

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



$$DEV(h^0 \rightarrow XX) = \kappa_X^2 - 1$$

- **Recent LHC data:**

$$DEV(h^0 \rightarrow b \bar{b}) = -0.21 +0.44/-0.33 \text{ (95\% CL) (ATLAS)} \quad (\text{arXiv:2207.00092})$$

$$DEV(h^0 \rightarrow b \bar{b}) = -0.02 +0.76/-0.52 \text{ (95\% CL) (CMS)} \quad (\text{arXiv:2207.00043})$$

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

$BR(h^0 \rightarrow b \bar{s} / s \bar{b}) \cong 0 (< 10^{-7})$ (SM)

$BR(h^0 \rightarrow b \bar{s} / s \bar{b})$ can be as large as $\sim 0.15\%$ (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].

Expected **CEPC** bound is $BR(h^0 \rightarrow b \bar{s} / s \bar{b}) < 2.2 \cdot 10^{-4}$ (at 95% CL)

See H. Liang et al., arXiv:2310.03440.

5.3 Deviation of *width ratio* from the SM prediction

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

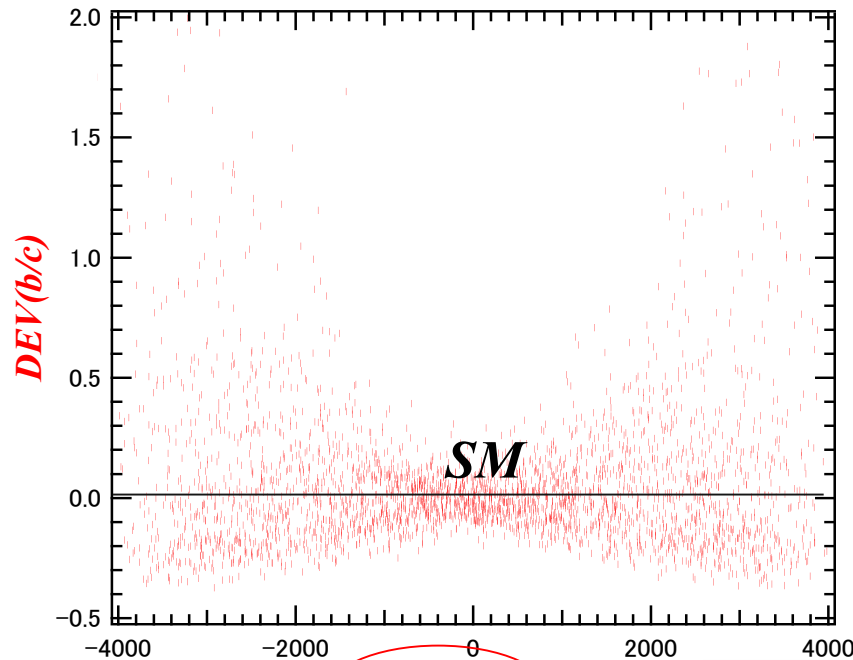
$$DEV(b/c) = [\Gamma(b) / \Gamma(c)]_{MSSM} / [\Gamma(b) / \Gamma(c)]_{SM} - 1$$

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

- *We find;*

the experimental measurement errors as well as the MSSM prediction errors tend to cancel out significantly in the width ratios.

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 exceed $\sim +100\%$ for large T_{U32} !
- Expected absolute 1σ error of $DEV(b/c)$ at ILC:
 $\Delta DEV(b/c) = (3.1\%, 2.1\%, 1.3\%)$ at (ILC250, ILC250+500, ILC250+500+1000).

[Jorge de Blas et al., Snowmass2021 Report: arXiv:2206.08326;
Private communication with Jorge de Blas.]

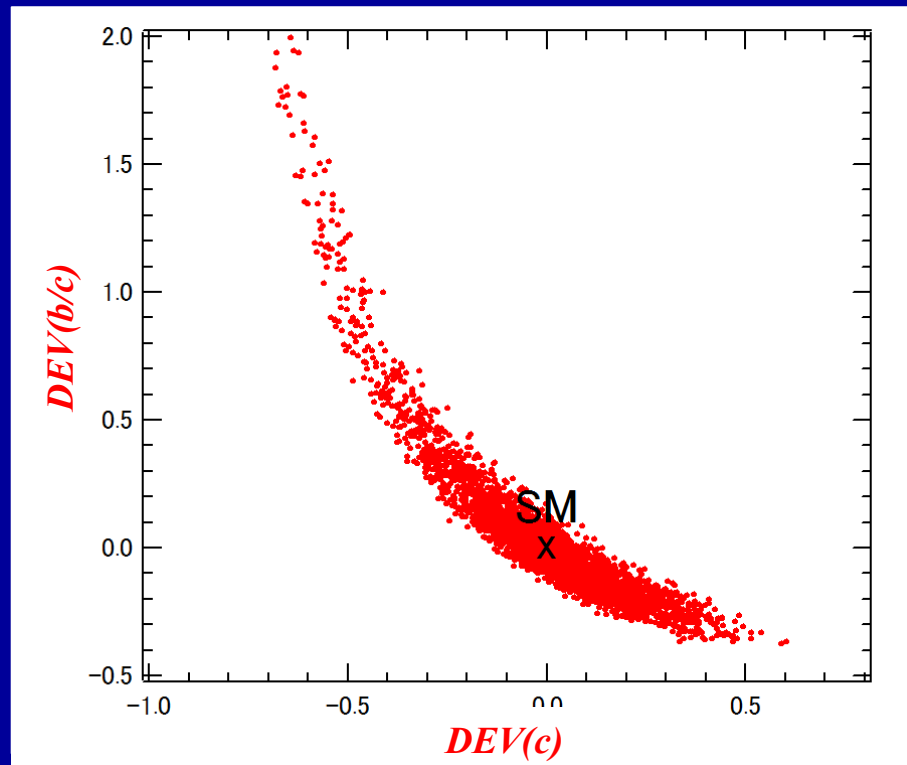
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Expected absolute 1 sigma errors of the deviations DEVs at future lepton colliders

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Scatter plot in $DEV(b/c) - DEV(c)$ plane



- *There is a very strong correlation between $DEV(b/c) - DEV(c)$!*
- *$DEV(b/c)$ and $DEV(c)$ can be very large simultaneously!*
- *Expected absolute 1σ error of $DEV(c)$ and $DEV(b/c)$ at ILC:*
 - $\Delta DEV(c) = (3.6\%, 2.4\%, 1.8\%)$ at (ILC250, ILC250+500, ILC250+500+1000)*
 - $\Delta DEV(b/c) = (3.1\%, 2.1\%, 1.3\%)$ at (ILC250, ILC250+500, ILC250+500+1000).*

[Jorge de Blas et al., Snowmass2021 Report: arXiv:2206.08326;
Private communication with Jorge de Blas.]

- *ILC can observe such large deviation from SM at very high significance!*

Expected absolute 1 sigma errors of the deviations DEVs at future lepton colliders

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$\Delta DEV(g/c)$	2.54%	2.33%	2.13%	2.06%	12.0%	3.59%	3.43%

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

- As the h^0 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 general QFV**.

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

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

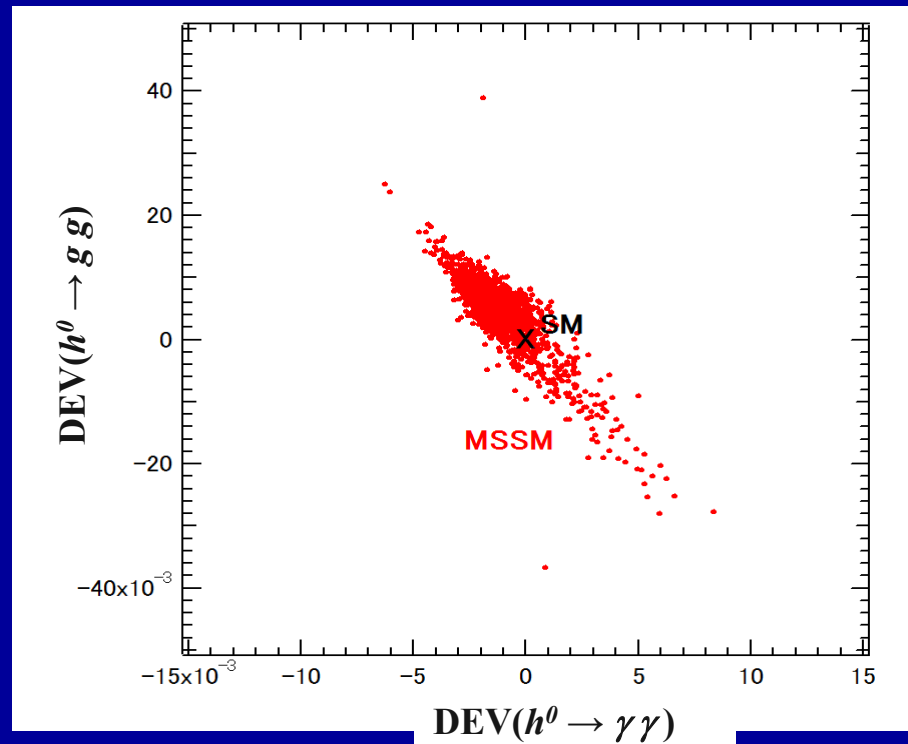
The **su-loops** can be enhanced by large trilinear couplings $T_{U23}, T_{U32}, T_{U33}$, resulting in sizable deviation of $\Gamma(h^0 \rightarrow \gamma\gamma)$ from the SM width!

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

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

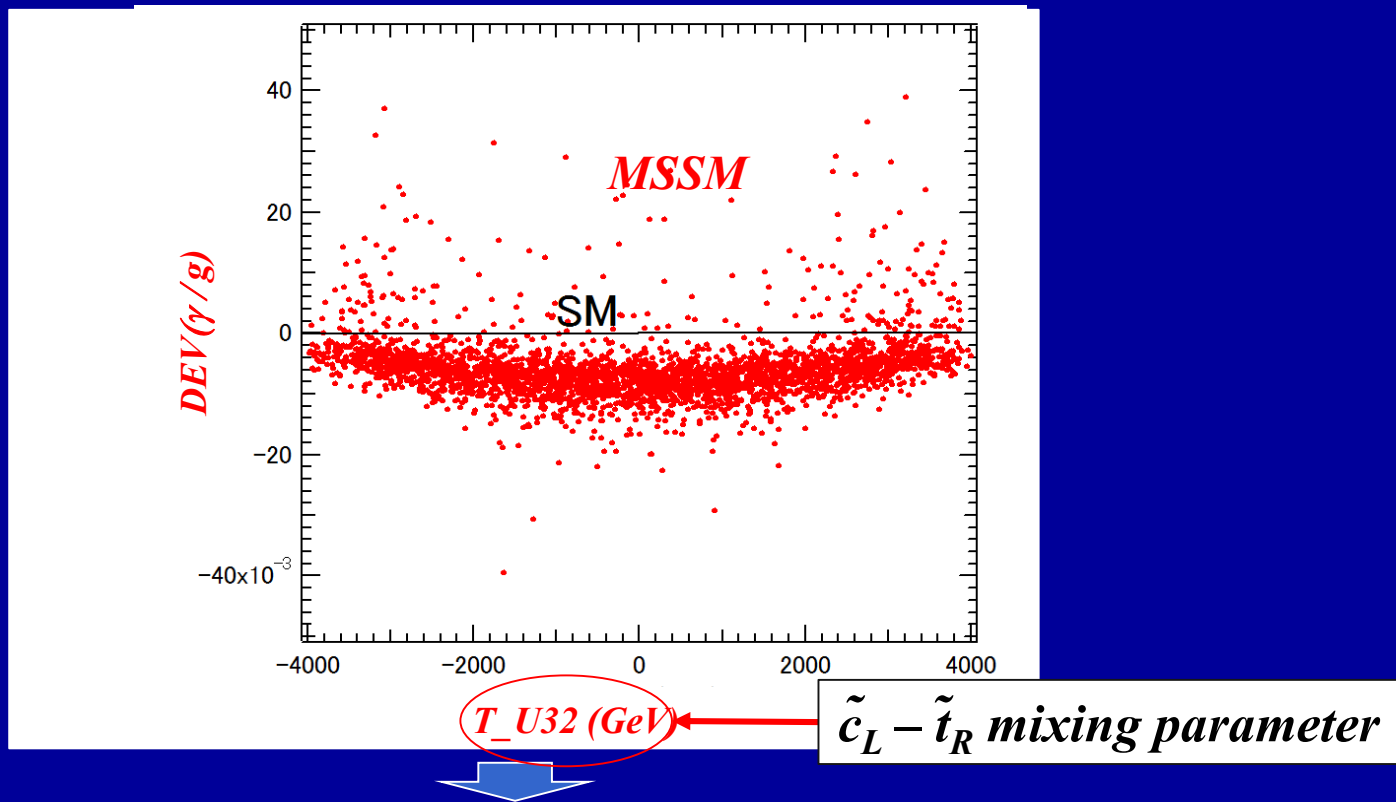
The **su-loops** can be enhanced by large trilinear couplings $T_{U23}, T_{U32}, T_{U33}$, resulting in sizable deviation of $\Gamma(h^0 \rightarrow gg)$ from the SM width!

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



- There is a strong correlation between $\text{DEV}(h^0 \rightarrow \gamma\gamma)$ and $\text{DEV}(h^0 \rightarrow g g)$!
 - $\text{DEV}(h^0 \rightarrow \gamma\gamma)$ and $\text{DEV}(h^0 \rightarrow g g)$ can be sizable simultaneously!:
 - $\text{DEV}(h^0 \rightarrow \gamma\gamma)$ can be as large as $\sim \pm 1\%$
 - $\text{DEV}(h^0 \rightarrow g g)$ can be as large as $\sim \pm 4\%$.
 - Expected absolute 1σ errors at (ILC250, ILC250+500, ILC250+500+1000):
 - $\Delta \text{DEV}(h^0 \rightarrow \gamma\gamma) = (2.4\%, 2.2\%, 2.0\%)$
 - $\Delta \text{DEV}(h^0 \rightarrow g g) = (1.8\%, 1.4\%, 1.1\%)$
- [Jorge de Blas et al., Snowmass2021 Report: arXiv:2206.08326;
Private communication with Jorge de Blas.] (See Backup slides)
- ILC can observe such sizable deviation $\text{DEV}(h^0 \rightarrow g g)$ at high significance!

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



- *There is a strong correlation between $T_{U32} - DEV(\gamma/g)$!*
- *$DEV(\gamma/g)$ can be as large as $\sim +4\%$ for large T_{U32} ! (from scatter plot analysis)
 $\sim +8\%$ for large T_{U32} ! (from contour plot analysis)*
- *Expected absolute 1 sigma error of $DEV(\gamma/g)$ at ILC:*
 $\Delta DEV(\gamma/g) = (3.3\%, 2.8\%, 2.3\%)$ at (ILC250, ILC250+500, ILC250+500+1000).

[Jorge de Blas et al., Snowmass2021 Report: arXiv:2206.08326;
 Private communication with Jorge de Blas.] (See Backup slides)

- *ILC can observe such sizable deviation from SM at high significance.*

Expected absolute 1 sigma errors of the deviations DEVs at future lepton colliders

	ILC-I	ILC-II	ILC-III	CLIC-I	CLIC-II	CLIC-III
$\Delta DEV(b)$	1.7%	1.1%	0.9%	2.2%	1.2%	1.1%
$\Delta DEV(c)$	3.6%	2.4%	1.8%	8.6%	3.8%	3.0%
$\Delta DEV(\gamma)$	2.4%	2.2%	2.0%	2.6%	2.4%	2.2%
$\Delta DEV(g)$	1.8%	1.4%	1.1%	2.2%	1.6%	1.4%
$\Delta DEV(b/c)$	3.12%	2.07%	1.3%	8.16%	3.5%	2.54%
$\Delta DEV(\gamma/g)$	3.29%	2.82%	2.3%	3.41%	3.05%	2.61%
$\Delta DEV(g/b)$	1.51%	1.14%	0.85%	1.62%	1.3%	1.1%
$\Delta DEV(g/c)$	3.4%	2.34%	1.52%	8.3%	3.72%	2.75%

	FCC-ee I	FCC-ee II	CEPC-I	CEPC-II	MuC-I	MuC-II	MuC-III
$\Delta DEV(b)$	1.3%	1.2%	0.86%	0.84%	1.8%	0.92%	1.1%
$\Delta DEV(c)$	2.8%	2.6%	2.4%	2.2%	12.4%	3.8%	3.6%
$\Delta DEV(\gamma)$	2.4%	2.2%	1.8%	1.8%	2.4%	1.4%	1.5%
$\Delta DEV(g)$	1.5%	1.4%	0.9%	0.88%	1.7%	0.92%	1.0%
$\Delta DEV(b/c)$	2.22%	2.06%	2.0%	1.94%	11.92%	3.53%	3.37%
$\Delta DEV(\gamma/g)$	3.03%	2.86%	2.07%	2.03%	3.18%	1.55%	1.55%
$\Delta DEV(g/b)$	1.29%	1.16%	0.73%	0.7%	1.69%	0.73%	0.72%
$\Delta DEV(g/c)$	2.54%	2.33%	2.13%	2.06%	12.0%	3.59%	3.43%

7. Benchmark scenario

- *In our analysis we also take into account the expected sparticle mass limits from the future HL-LHC experiment .*
- *From the allowed MSSM parameter points in the scan, we have selected a benchmark point P1 shown in Table 2 .*
- *This benchmark scenario P1 satisfies also all the expected sparticle mass limits [including $(m_{A/H^+}, \tan\beta)$ limits] from future HL-LHC experiment .*
[see CERN Yellow Rep., arXiv:1812.07831;
Snowmass Rep. of EF, arXiv:2209.13128; ...]
- *The resulting physical masses of the particles are shown in Table 3.*

Physical masses for Benchmark scenario P1

Table 3: Physical masses in GeV of the particles for the scenario of Table 2.

$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{\chi}_3^0}$	$m_{\tilde{\chi}_4^0}$	$m_{\tilde{\chi}_1^+}$	$m_{\tilde{\chi}_2^+}$
781	882	911	1669	782	914

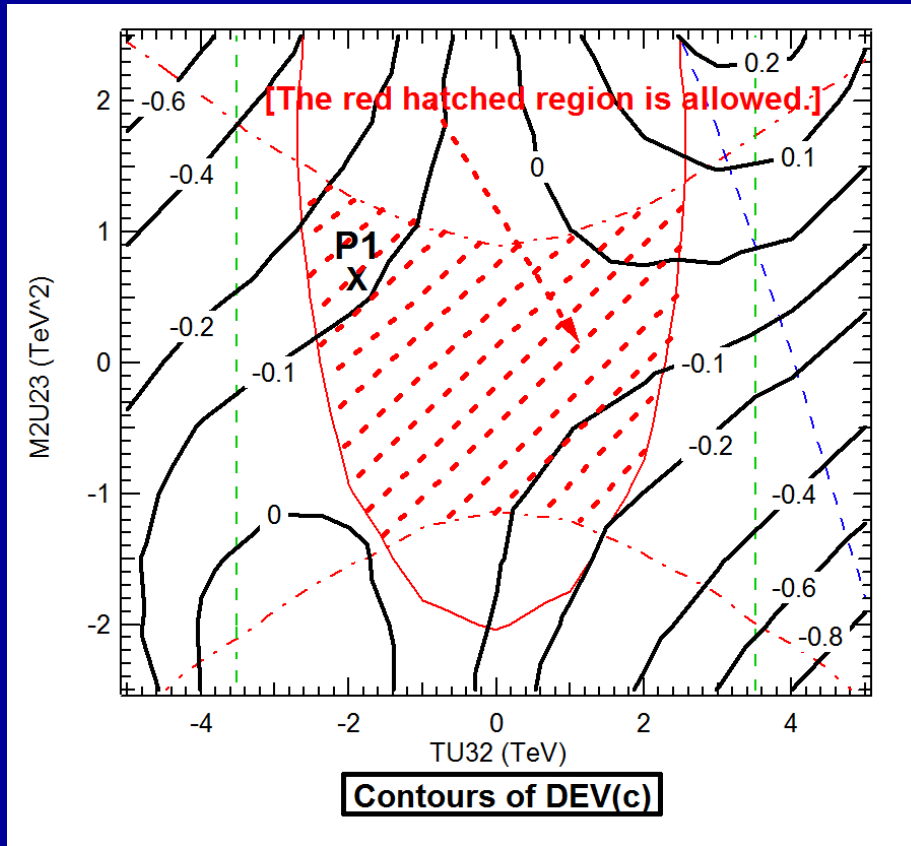
m_{h^0}	m_{H^0}	m_{A^0}	m_{H^\pm}
124	5325	5325	5359

$m_{\tilde{g}}$	$m_{\tilde{u}_1}$	$m_{\tilde{u}_2}$	$m_{\tilde{u}_3}$	$m_{\tilde{u}_4}$	$m_{\tilde{u}_5}$	$m_{\tilde{u}_6}$
4424	868	3011	3331	3877	4402	4402

$m_{\tilde{d}_1}$	$m_{\tilde{d}_2}$	$m_{\tilde{d}_3}$	$m_{\tilde{d}_4}$	$m_{\tilde{d}_5}$	$m_{\tilde{d}_6}$
1705	2833	3010	3877	4397	4403

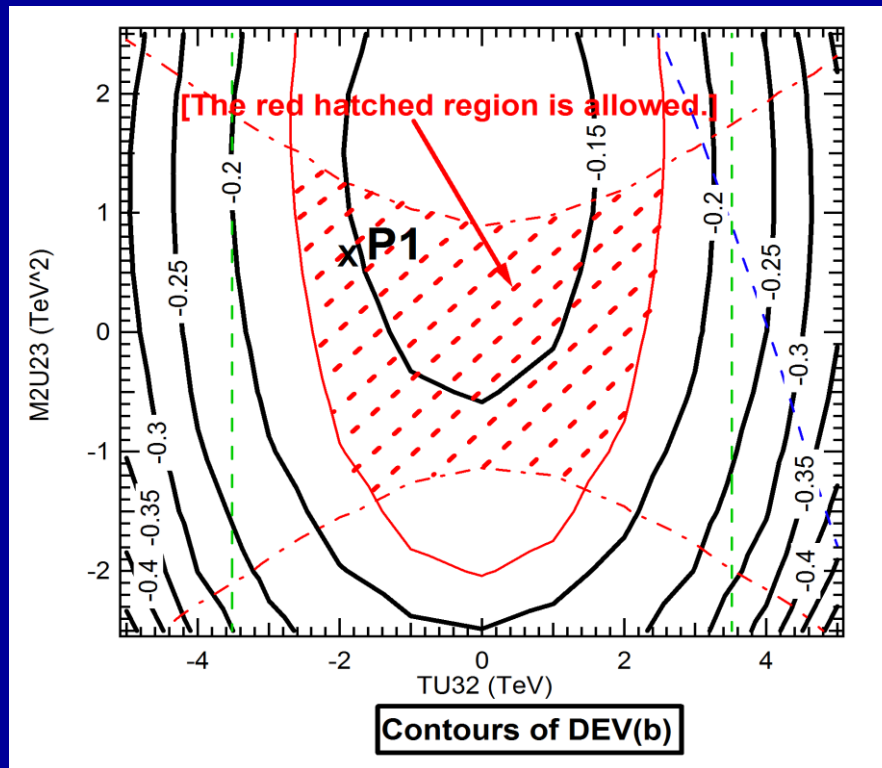
$m_{\tilde{\nu}_1}$	$m_{\tilde{\nu}_2}$	$m_{\tilde{\nu}_3}$	$m_{\tilde{l}_1}$	$m_{\tilde{l}_2}$	$m_{\tilde{l}_3}$	$m_{\tilde{l}_4}$	$m_{\tilde{l}_5}$	$m_{\tilde{l}_6}$
1509	1509	1528	1489	1489	1509	1512	1512	1545

Contours of $DEV(h^0 \rightarrow c \bar{c})$ in $T_{U32} - M_{U23}^2$ plane around P1



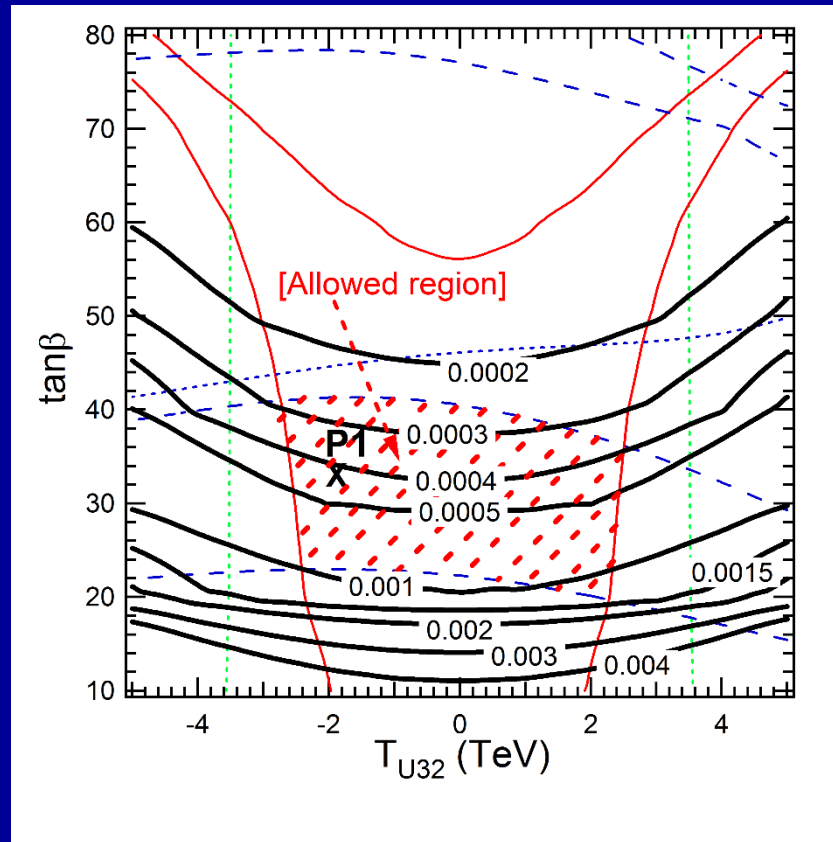
We find that $DEV(c)$ can be very large (about -30% to 10%) in a sizable region allowed by all the constraints including the expected sparticle mass limits from the future HL-LHC experiment!

Contours of $DEV(h^0 \rightarrow b \bar{b})$ in $T_{U32} - M^2_{U23}$ plane around $P1$



- We find that $DEV(b)$ can be very large (about -10% to -18%) in a sizable region allowed by all the constraints including the expected sparticle mass limits from the future HL-LHC experiment!
- For $DEV(g)$, $DEV(\gamma)$, $DEV(\gamma/g)$ and $DEV(b/c)$ we have obtained similar results to those for $DEV(c)$ and $DEV(b)$.

Contours of $B(h^0 \rightarrow b \bar{s} / s \bar{b})$ in $T_{U32} - \tan\beta$ plane around P1



- $B(h^0 \rightarrow b \bar{s} / s \bar{b})$ can be as large as $\sim 0.15\%$ in a sizable region allowed by all the constraints including the expected sparticle mass limits from the future HL-LHC!
- 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].

8. 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 general QFV.

- *For the first time, we have performed a systematic MSSM parameter scan respecting all of the relevant theoretical and experimental constraints.*

- *In strong contrast to the usual studies in the MSSM with minimal flavor violation (MFV), we have found that the deviations of these MSSM decay widths and width ratios from the SM values can be quite sizable in the MSSM with general QFV.*

- *All of these large deviations in the $h (125)$ 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 $T_{D23}, T_{D32}, T_{D33}$.

- *Future lepton colliders such as ILC, CLIC, CEPC, FCC-ee and MuC can observe such sizable deviations from the SM at high signal significance even after the failure of SUSY particle discovery at the HL-LHC.*

- *In case the deviation pattern shown here is really observed at the lepton colliders, then it would strongly suggest the discovery of QFV SUSY (the MSSM with general QFV).*

- *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, lepton colliders, such as 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!

Impact of quark flavor violating SUSY on $h(125)$ decays at future lepton colliders

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]]

PoS(EPS-HEP2021) 594, 2021 [arXiv:2111.02713 [hep-ph]]

PoS(ICHEP2022) 536, 2022 [arXiv:2211.07243 [hep-ph]]

PoS(EPS-HEP2023) 487, 2023

LCWS2024, 8-11 July 2024, University of Tokyo, Japan

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 $h^0(125) \rightarrow c \bar{c}, b \bar{b}, b \bar{s}, \gamma\gamma, gg$ with special emphasis on Supersymmetric Quark Flavor Violation (QFV).*

2. MSSM with general 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*

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

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

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

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

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

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

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

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

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

2. MSSM with general 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*

These QFV parameters are absent in the MSSM with minimal flavor violation (MFV)!

3. Constraints on the MSSM

We respect the following experimental and theoretical constraints:

- (1) The LHC limits on the **SUSY particle masses**.*
- (2) The constraint on $(m_{A/H^+}, \tan\beta)$ from **MSSM Higgs boson search at LHC**.*
- (3) The constraints on the **QFV parameters** from the **B & K meson data**.*

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

- (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) ,
 $0.68 < \kappa_b < 1.11$ (ATLAS), $0.68 < \kappa_b < 1.32$ (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 $T_{D\alpha\beta}$.*

** We also take into account the expected SUSY particle mass limits from the future HL-LHC experiment in our analysis.*

- [1] X. Cid Vidal et al., "Report from Working Group 3: Beyond the Standard Model physics at the HL-LHC and HE-LHC", CERN Yellow Rep: Monogr. 7 (2019) 585-865 [arXiv:1812.07831 [hep-ph]].
- [2] T. Bose et al., "Report of the Topical Group on Physics Beyond the Standard Model at Energy Frontier for Snowmass 2021", arXiv:2209.13128 [hep-ph].
- [3] ATLAS Collaboration, ATLAS Notes ATL-PHYS-PUB-2012-001, ATL-PHYS-PUB2013-002, ATL-PHYS-PUB-2014-010, and ATL-PHYS-PUB-2018-048.
- [4] C. M. Berggren, talk at The European Physical Society Conference on High Energy Physics (EPS-HEP2023), 21-25 August 2023, Hamburg, Germany.
- [5] H. Gilmer, talk at the 40th International Conference on High Energy Physics, virtual conference (ICHEP2020), 28 Jul - 6 Aug 2020, Prague, Czech Republic.
- [6] M. Narain et al., "The Future of US Particle Physics - The Snowmass 2021 Energy Frontier Report", arXiv:2211.11084 [hep-ex].
- [7] H. Bahl, P. Bechtle, S. Heinemeyer, S. Liebler, T. Stefaniak and G. Weiglein, Eur. Phys. J. C 80 (2020) 916 [arXiv:2005.14536 [hep-ph]].

** Constraints from W boson mass data:*

The recent m_W data from CDF II [1] disagrees significantly with the previous world average. (-> See backup slides.)

[1] CDF Collaboration, Science 376, 170–176 (2022)

This issue of the m_W data is not yet settled.

Hence, we do not take into account this m_W constraint on the MSSM parameters in our analysis.

* *Constraint from muon $g-2$:*

- *Tension btw the new Fermilab muon $g-2$ data [1] and the SM prediction is ~ 5 sigma..*
- *In our scenario with heavy sleptons/sneutrinos with masses of about 1.5 TeV the MSSM loop contributions to muon $g-2$ are too small to explain this tension.*

However;

- *The tension btw the muon $g-2$ data and the SM prediction with lattice QCD [2] is only ~ 1.6 sigma!*
- *Moreover, the SM prediction in the data-driven approach using the recent CMD-3 data [3] supports the SM prediction with the lattice QCD [2]!*

[1] Muon $g-2$ Collaboration, arXiv:2308.06230 [hep-ex].

[2] BMW Collaboration, Nature 593 (2021) 51 [arXiv:2002.12347[hep-lat]].

[3] CMD-3 Collaboration, arXiv:2302.08834 [hep-ex].

** Constraint on the MSSM QFV parameters from $B(Z \rightarrow b s)$:*

*The current best experimental upper limit on $B(Z \rightarrow b s)$ can not give any significant constraint on the s -strange- s -bottom and s -charm- s -stop mixings.
(see D. Atwood et al., Phys. Rev. D66(2002) 093005 [arXiv:hep-ph/0203200])*

Note that no experimental upper limit on $B(Z \rightarrow b s)$ is listed in PDG2022 !

4. Parameter scan

- We compute the $h^0(125)$ decay widths in the *MSSM with general 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 general 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 $T_{D23}, T_{D32}, T_{D33}$

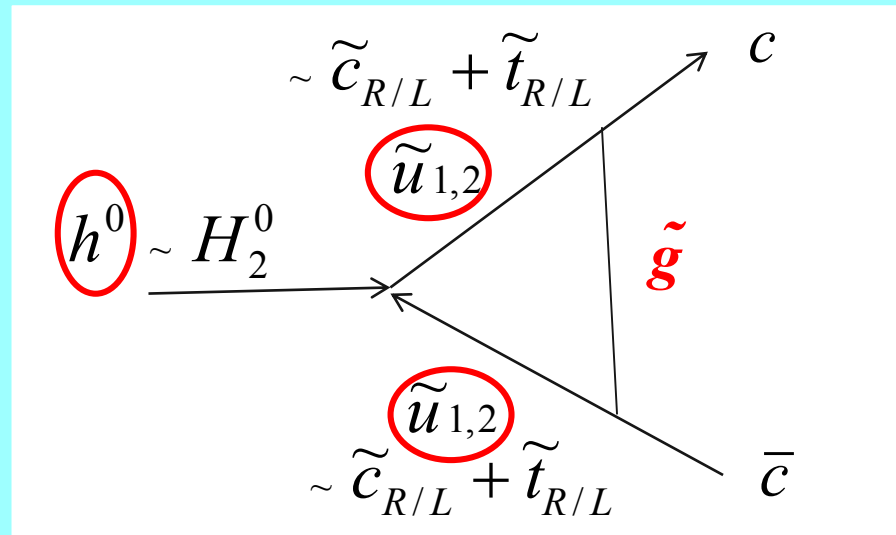
chargino - su loops [su = (\tilde{t} - \tilde{c} mixture)]

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!

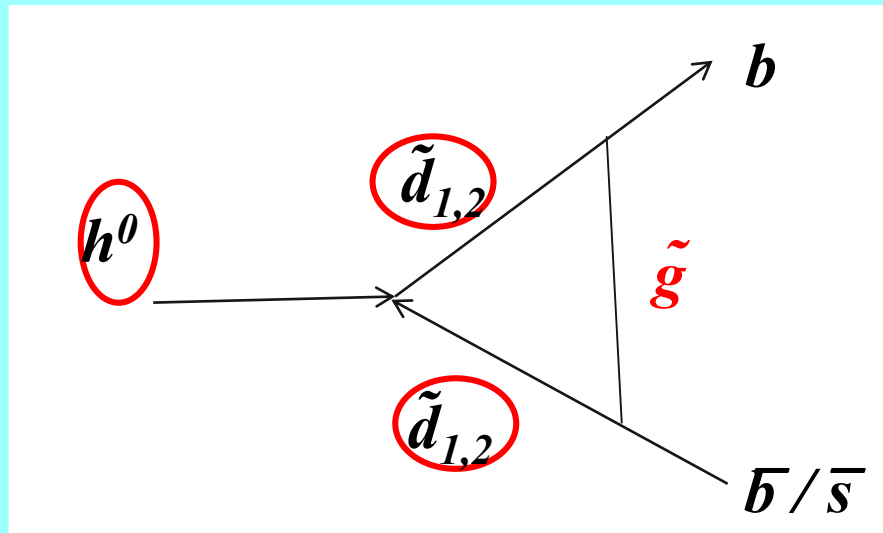
Gluino loop contributions can be large!

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!

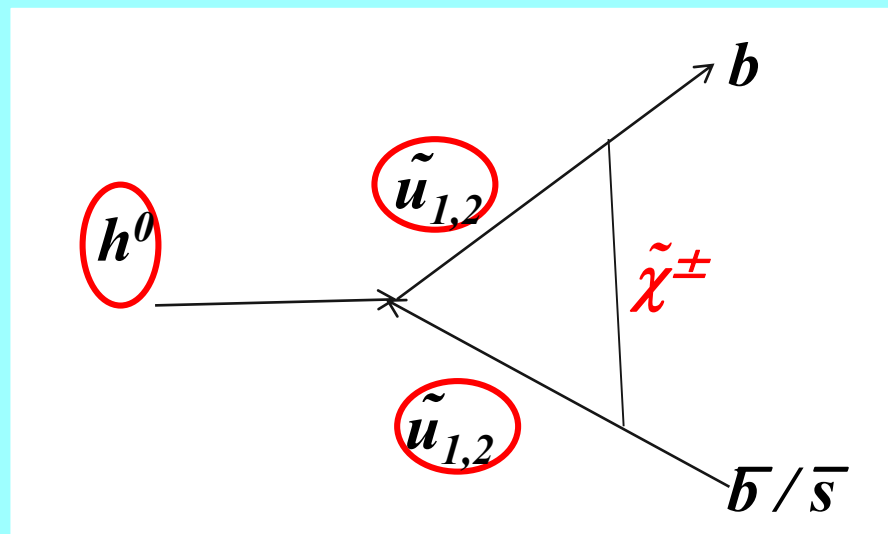
Deviation of $\Gamma(h^0 \rightarrow b \bar{b}/\bar{s})$ from SM width can be large!

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

- *Deviation of the width from the SM prediction:*

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

$$X = c, b$$

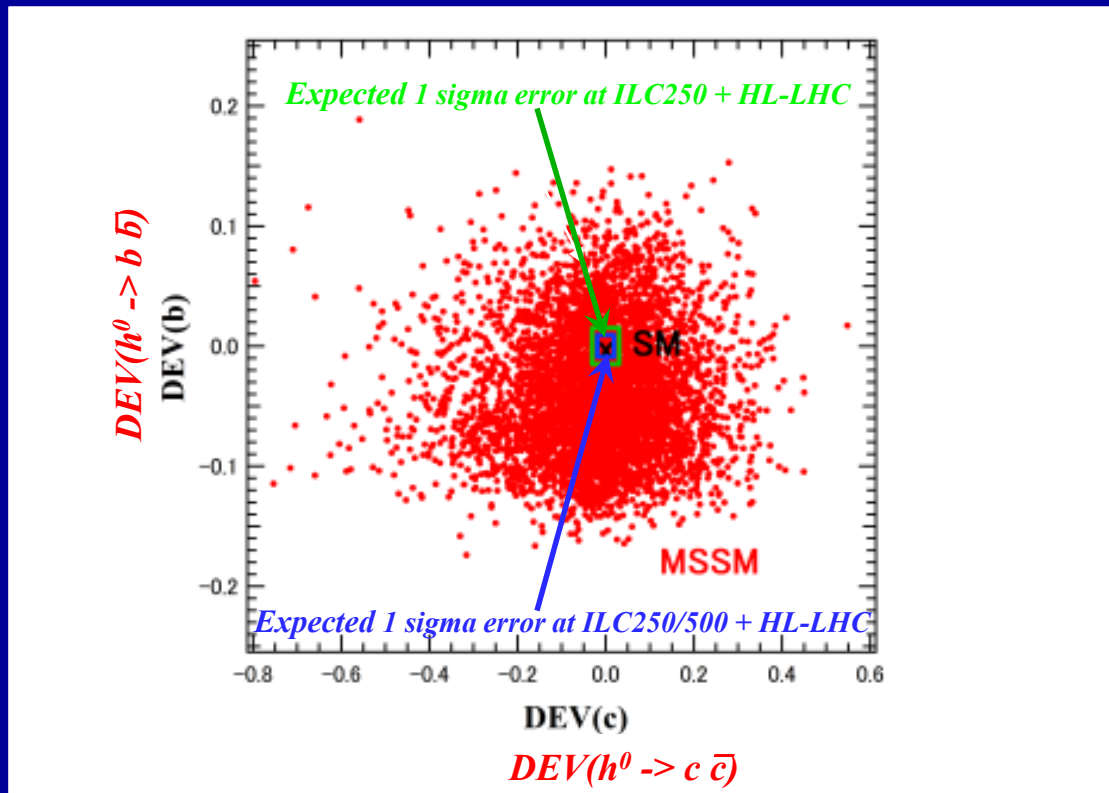
- *Coupling modifier:*

$$\kappa_X = g(h^0 X X) / g(h^0 X X)_{SM}$$

- *DEV - κ_X relation:*

$$DEV(h^0 \rightarrow X X) = \kappa_X^2 - 1$$

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:2206.08326)!:

$\Delta DEV(h^0 \rightarrow c \bar{c}) = (3.6\%, 2.4\%, 1.8\%)$ at (ILC250, ILC250/500, ILC250/500/1000)

$\Delta DEV(h^0 \rightarrow b \bar{b}) = (1.7\%, 1.1\%, 0.9\%)$ at (ILC250, ILC250/500, ILC250/500/1000)

Expected absolute 1 sigma errors of the deviations DEVs at future lepton colliders

Table 6: The expected *absolute* 1σ error of the deviations $DEV(X)$ and $DEV(X/Y)$ (denoted by $\Delta DEV(X)$ and $\Delta DEV(X/Y)$) at future lepton colliders: ILC-I = ILC250 + Giga-Z, ILC-II = ILC250+500 + Giga-Z, ILC-III = ILC250+500+1000 + Giga-Z; CLIC-I = CLIC380, CLIC-II = CLIC380+1500, CLIC-III = CLIC380+1500+3000; FCC-ee I = FCC-ee240 + Z/WW, FCC-ee II = FCC-ee240+365 + Z/WW; CEPC-I = CEPC240 + Z/WW, CEPC-II = CEPC240+360 + Z/WW; MuC-I = MuC3TeV, MuC-II = MuC10TeV, MuC-III = MuC10TeV+125GeV. As for ILC the results without Giga-Z run are almost identical to those with Giga-Z one. The Z/WW denote Z-pole and WW threshold runs. All results except for MuC-I and MuC-II are those from the free- Γ_H fit and the results for MuC-I and MuC-II are those from the constrained- Γ_H fit, where Γ_H is the total width of the Higgs boson h^0 . The details of run scenarios of the lepton colliders are explained in Ref. [14]. The HL-LHC and LEP/SLD measurements are combined with all lepton collider run scenarios.

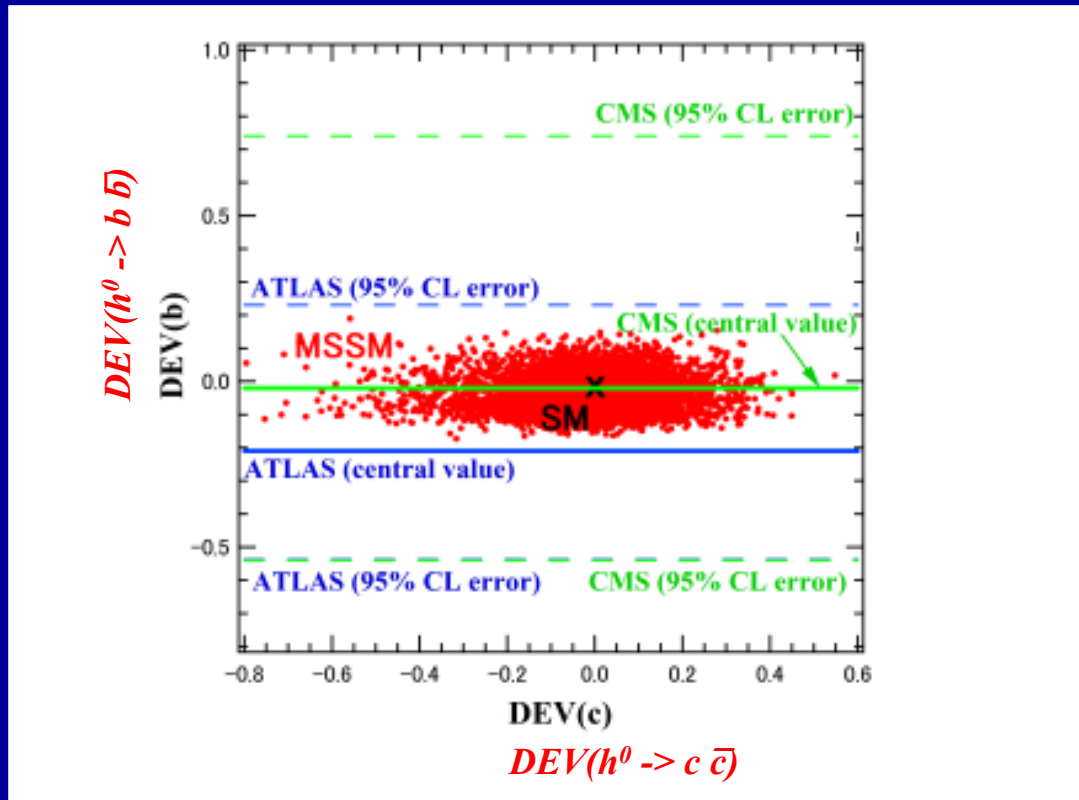
*Jorge de Blas et al., Snowmass2021 Report: arXiv:2206.08326 [hep-ph];
Private communication with Jorge de Blas.*

Expected absolute 1 sigma errors of the deviations DEVs at future lepton colliders

	ILC-I	ILC-II	ILC-III	CLIC-I	CLIC-II	CLIC-III
$\Delta DEV(b)$	1.7%	1.1%	0.9%	2.2%	1.2%	1.1%
$\Delta DEV(c)$	3.6%	2.4%	1.8%	8.6%	3.8%	3.0%
$\Delta DEV(\gamma)$	2.4%	2.2%	2.0%	2.6%	2.4%	2.2%
$\Delta DEV(g)$	1.8%	1.4%	1.1%	2.2%	1.6%	1.4%
$\Delta DEV(b/c)$	3.12%	2.07%	1.3%	8.16%	3.5%	2.54%
$\Delta DEV(\gamma/g)$	3.29%	2.82%	2.3%	3.41%	3.05%	2.61%
$\Delta DEV(g/b)$	1.51%	1.14%	0.85%	1.62%	1.3%	1.1%
$\Delta DEV(g/c)$	3.4%	2.34%	1.52%	8.3%	3.72%	2.75%

	FCC-ee I	FCC-ee II	CEPC-I	CEPC-II	MuC-I	MuC-II	MuC-III
$\Delta DEV(b)$	1.3%	1.2%	0.86%	0.84%	1.8%	0.92%	1.1%
$\Delta DEV(c)$	2.8%	2.6%	2.4%	2.2%	12.4%	3.8%	3.6%
$\Delta DEV(\gamma)$	2.4%	2.2%	1.8%	1.8%	2.4%	1.4%	1.5%
$\Delta DEV(g)$	1.5%	1.4%	0.9%	0.88%	1.7%	0.92%	1.0%
$\Delta DEV(b/c)$	2.22%	2.06%	2.0%	1.94%	11.92%	3.53%	3.37%
$\Delta DEV(\gamma/g)$	3.03%	2.86%	2.07%	2.03%	3.18%	1.55%	1.55%
$\Delta DEV(g/b)$	1.29%	1.16%	0.73%	0.7%	1.69%	0.73%	0.72%
$\Delta DEV(g/c)$	2.54%	2.33%	2.13%	2.06%	12.0%	3.59%	3.43%

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



$$DEV(h^0 \rightarrow X X) = \kappa_X^2 - 1$$

- **Recent LHC data:**

$$DEV(h^0 \rightarrow b \bar{b}) = -0.21 +0.44/-0.33 \text{ (95\% CL) (ATLAS) (arXiv:2207.00092)}$$

$$DEV(h^0 \rightarrow b \bar{b}) = -0.02 +0.76/-0.52 \text{ (95\% CL) (CMS) (arXiv:2207.00043)}$$

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

$BR(h^0 \rightarrow b \bar{s} / s \bar{b}) \cong 0 (< 10^{-7})$ (SM)

$BR(h^0 \rightarrow b \bar{s} / s \bar{b})$ can be as large as $\sim 0.15\%$ (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)!

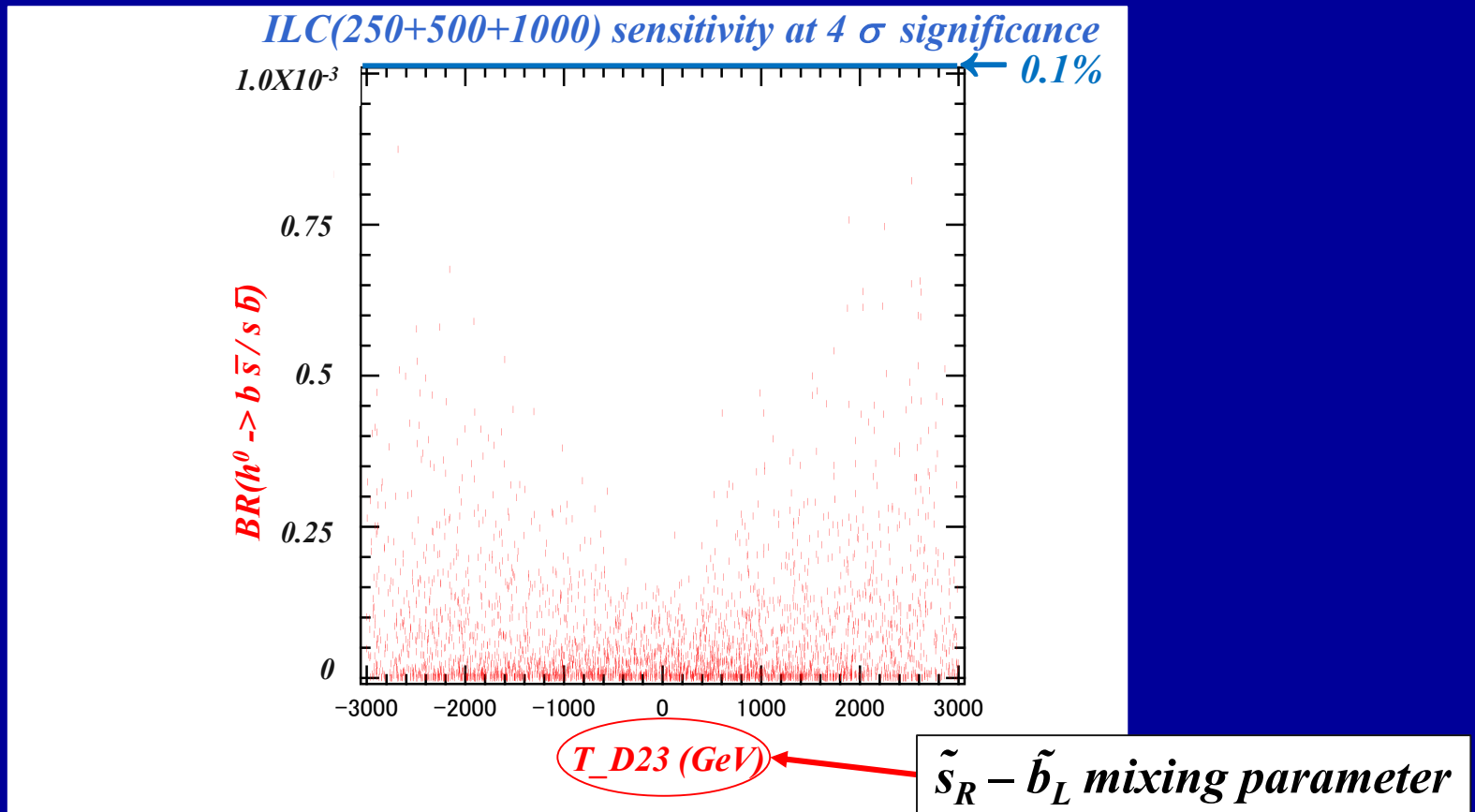
Private communication with Junping Tian;

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

Expected **CEPC** bound is $BR(h^0 \rightarrow b \bar{s} / s \bar{b}) < 2.2 \cdot 10^{-4}$ (at 95% CL)

See H. Liang et al., arXiv:2310.03440.

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 **0.1%** 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!**

5.3 Deviation of *width ratio* from the SM prediction

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

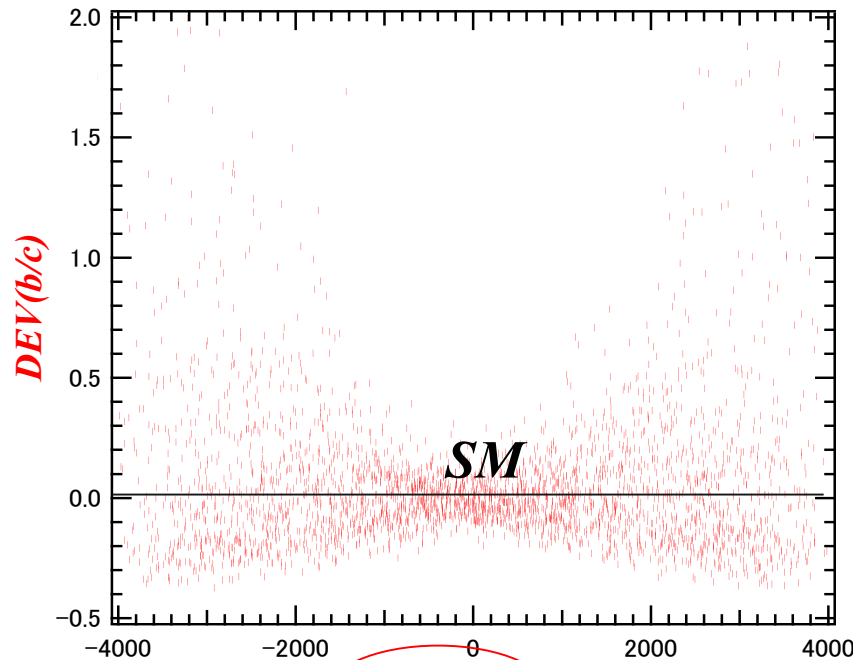
$$DEV(b/c) = [\Gamma(b) / \Gamma(c)]_{MSSM} / [\Gamma(b) / \Gamma(c)]_{SM} - 1$$

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

- *We find;*

the experimental measurement errors as well as the MSSM prediction errors tend to cancel out significantly in the width ratios.

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 exceed $\sim +100\%$ for large T_{U32} !
- Expected absolute 1σ error of $DEV(b/c)$ at ILC:
 $\Delta DEV(b/c) = (3.1\%, 2.1\%, 1.3\%)$ at (ILC250, ILC250+500, ILC250+500+1000).

[Jorge de Blas et al., Snowmass2021 Report: arXiv:2206.08326;
Private communication with Jorge de Blas.]

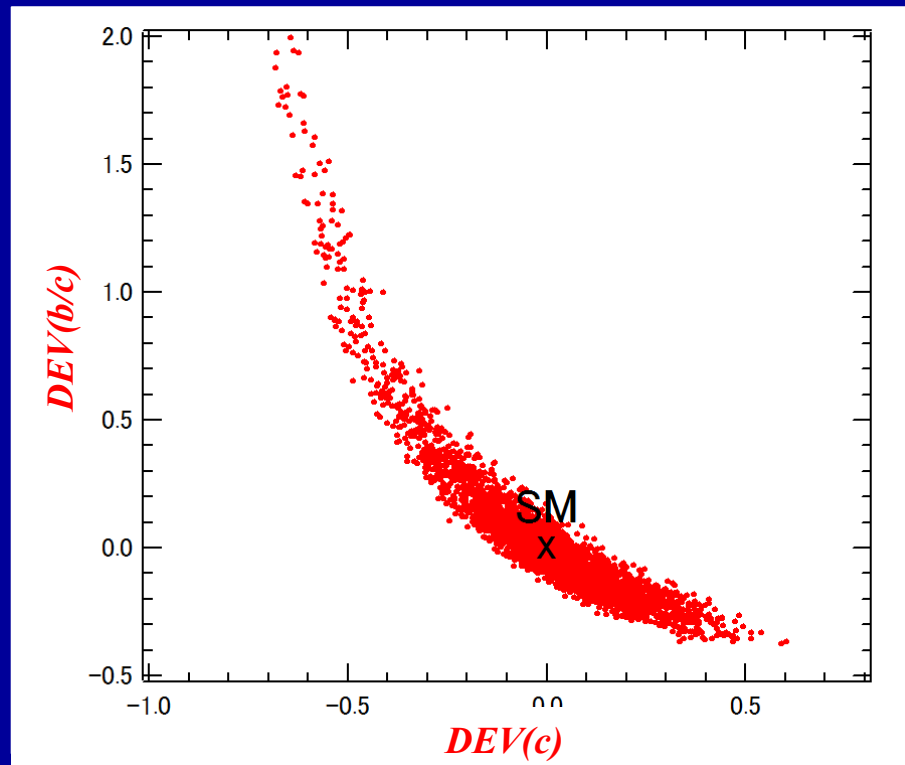
- ILC can observe such large deviation from SM at very high significance!

Expected absolute 1 sigma errors of the deviations DEVs at future lepton colliders

	ILC-I	ILC-II	ILC-III	CLIC-I	CLIC-II	CLIC-III
$\Delta DEV(b)$	1.7%	1.1%	0.9%	2.2%	1.2%	1.1%
$\Delta DEV(c)$	3.6%	2.4%	1.8%	8.6%	3.8%	3.0%
$\Delta DEV(\gamma)$	2.4%	2.2%	2.0%	2.6%	2.4%	2.2%
$\Delta DEV(g)$	1.8%	1.4%	1.1%	2.2%	1.6%	1.4%
$\Delta DEV(b/c)$	3.12%	2.07%	1.3%	8.16%	3.5%	2.54%
$\Delta DEV(\gamma/g)$	3.29%	2.82%	2.3%	3.41%	3.05%	2.61%
$\Delta DEV(g/b)$	1.51%	1.14%	0.85%	1.62%	1.3%	1.1%
$\Delta DEV(g/c)$	3.4%	2.34%	1.52%	8.3%	3.72%	2.75%

	FCC-ee I	FCC-ee II	CEPC-I	CEPC-II	MuC-I	MuC-II	MuC-III
$\Delta DEV(b)$	1.3%	1.2%	0.86%	0.84%	1.8%	0.92%	1.1%
$\Delta DEV(c)$	2.8%	2.6%	2.4%	2.2%	12.4%	3.8%	3.6%
$\Delta DEV(\gamma)$	2.4%	2.2%	1.8%	1.8%	2.4%	1.4%	1.5%
$\Delta DEV(g)$	1.5%	1.4%	0.9%	0.88%	1.7%	0.92%	1.0%
$\Delta DEV(b/c)$	2.22%	2.06%	2.0%	1.94%	11.92%	3.53%	3.37%
$\Delta DEV(\gamma/g)$	3.03%	2.86%	2.07%	2.03%	3.18%	1.55%	1.55%
$\Delta DEV(g/b)$	1.29%	1.16%	0.73%	0.7%	1.69%	0.73%	0.72%
$\Delta DEV(g/c)$	2.54%	2.33%	2.13%	2.06%	12.0%	3.59%	3.43%

Scatter plot in $DEV(b/c) - DEV(c)$ plane



- *There is a very strong correlation between $DEV(b/c) - DEV(c)$!*
- *$DEV(b/c)$ and $DEV(c)$ can be very large simultaneously!*
- *Expected absolute 1σ error of $DEV(c)$ and $DEV(b/c)$ at ILC:*
 - $\Delta DEV(c) = (3.6\%, 2.4\%, 1.8\%)$ at (ILC250, ILC250+500, ILC250+500+1000)*
 - $\Delta DEV(b/c) = (3.1\%, 2.1\%, 1.3\%)$ at (ILC250, ILC250+500, ILC250+500+1000).*

*[Jorge de Blas et al., Snowmass2021 Report: arXiv:2206.08326;
Private communication with Jorge de Blas.]*

- *ILC can observe such large deviation from SM at very high significance!*

Expected absolute 1 sigma errors of the deviations DEVs at future lepton colliders

	ILC-I	ILC-II	ILC-III	CLIC-I	CLIC-II	CLIC-III
$\Delta DEV(b)$	1.7%	1.1%	0.9%	2.2%	1.2%	1.1%
$\Delta DEV(c)$	3.6%	2.4%	1.8%	8.6%	3.8%	3.0%
$\Delta DEV(\gamma)$	2.4%	2.2%	2.0%	2.6%	2.4%	2.2%
$\Delta DEV(g)$	1.8%	1.4%	1.1%	2.2%	1.6%	1.4%
$\Delta DEV(b/c)$	3.12%	2.07%	1.3%	8.16%	3.5%	2.54%
$\Delta DEV(\gamma/g)$	3.29%	2.82%	2.3%	3.41%	3.05%	2.61%
$\Delta DEV(g/b)$	1.51%	1.14%	0.85%	1.62%	1.3%	1.1%
$\Delta DEV(g/c)$	3.4%	2.34%	1.52%	8.3%	3.72%	2.75%

	FCC-ee I	FCC-ee II	CEPC-I	CEPC-II	MuC-I	MuC-II	MuC-III
$\Delta DEV(b)$	1.3%	1.2%	0.86%	0.84%	1.8%	0.92%	1.1%
$\Delta DEV(c)$	2.8%	2.6%	2.4%	2.2%	12.4%	3.8%	3.6%
$\Delta DEV(\gamma)$	2.4%	2.2%	1.8%	1.8%	2.4%	1.4%	1.5%
$\Delta DEV(g)$	1.5%	1.4%	0.9%	0.88%	1.7%	0.92%	1.0%
$\Delta DEV(b/c)$	2.22%	2.06%	2.0%	1.94%	11.92%	3.53%	3.37%
$\Delta DEV(\gamma/g)$	3.03%	2.86%	2.07%	2.03%	3.18%	1.55%	1.55%
$\Delta DEV(g/b)$	1.29%	1.16%	0.73%	0.7%	1.69%	0.73%	0.72%
$\Delta DEV(g/c)$	2.54%	2.33%	2.13%	2.06%	12.0%	3.59%	3.43%

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

- As the h^0 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 general QFV**.

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

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

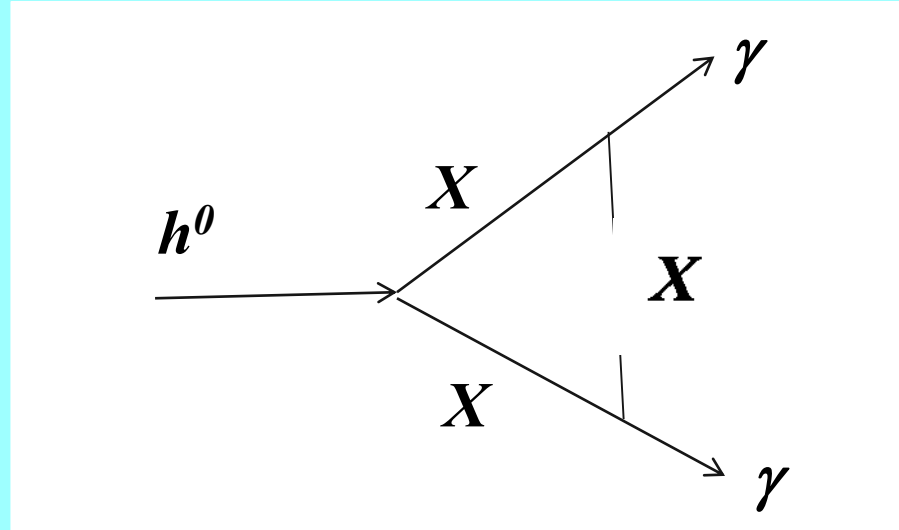
The **su-loops** can be enhanced by large trilinear couplings $T_{U23}, T_{U32}, T_{U33}$, resulting in sizable deviation of $\Gamma(h^0 \rightarrow \gamma\gamma)$ from the SM width!

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

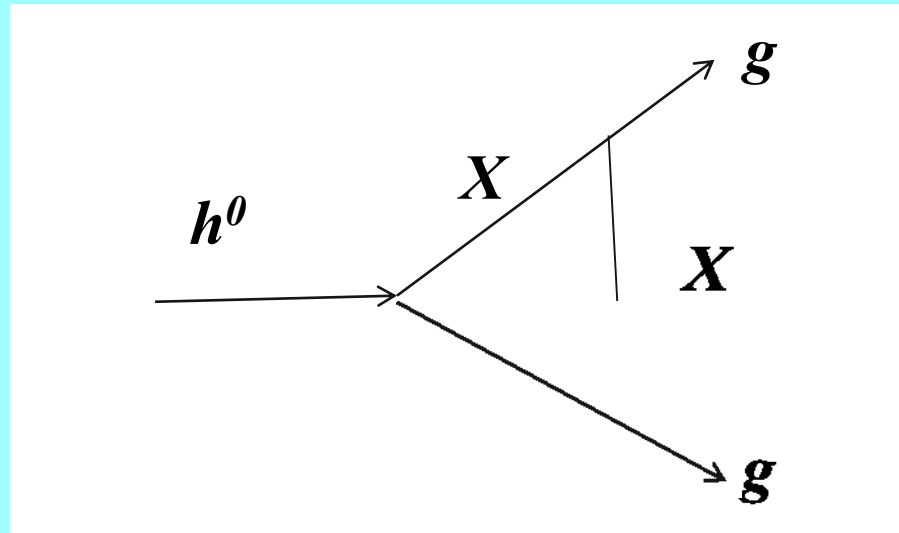
[top-quark/su] - loops [su = (\tilde{t} - \tilde{c} mixture)]

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!

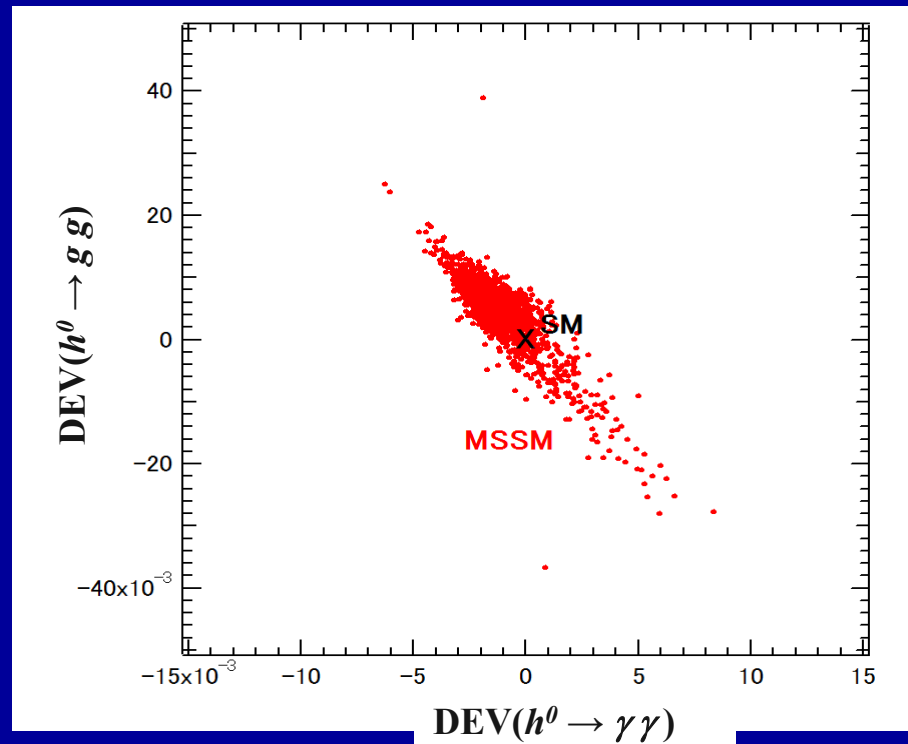
$$X = W^+ / t / \tilde{u}_{1,2}$$



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



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



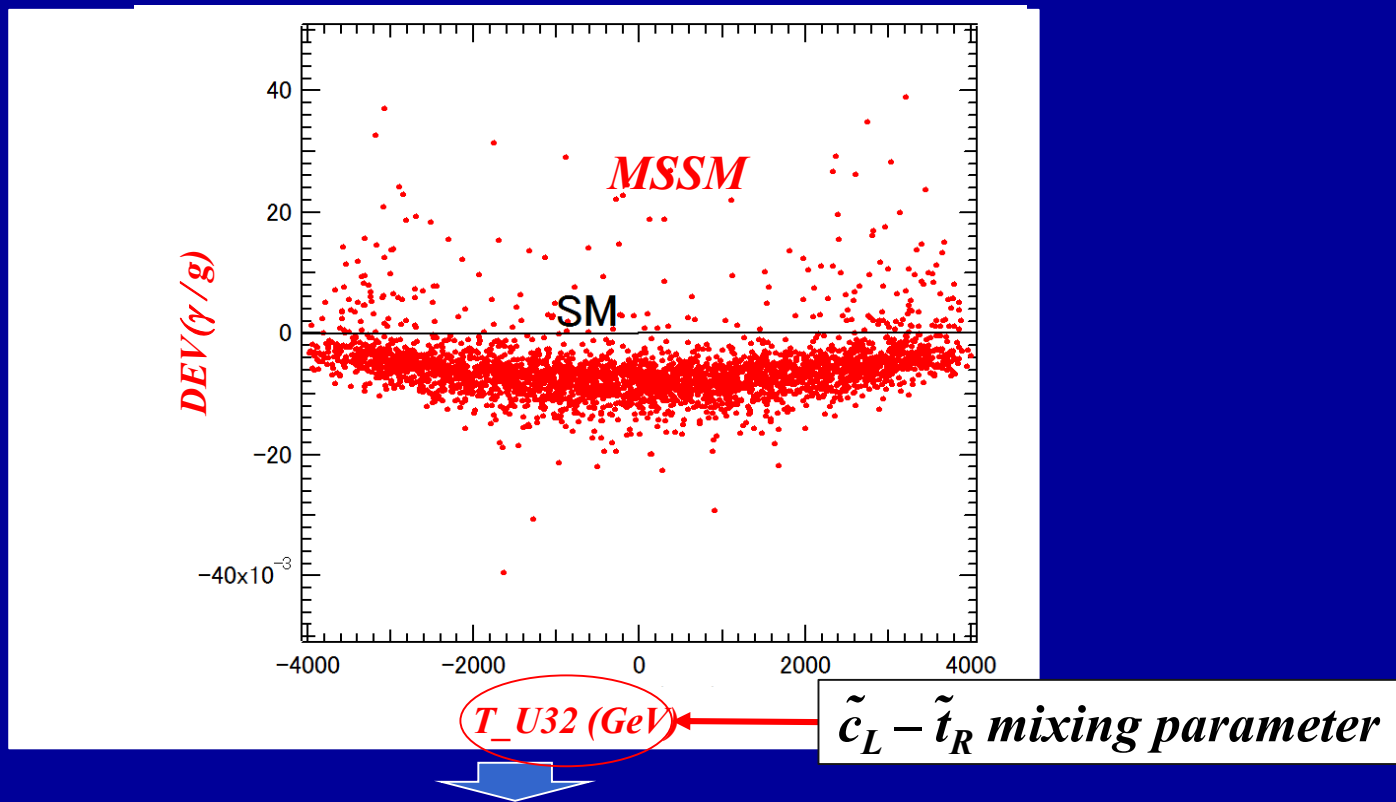
- There is a strong correlation between $\text{DEV}(h^0 \rightarrow \gamma\gamma)$ and $\text{DEV}(h^0 \rightarrow g g)$!
 - $\text{DEV}(h^0 \rightarrow \gamma\gamma)$ and $\text{DEV}(h^0 \rightarrow g g)$ can be sizable simultaneously!:
 - $\text{DEV}(h^0 \rightarrow \gamma\gamma)$ can be as large as $\sim \pm 1\%$
 - $\text{DEV}(h^0 \rightarrow g g)$ can be as large as $\sim \pm 4\%$.
 - Expected absolute 1σ errors at (ILC250, ILC250+500, ILC250+500+1000):
 - $\Delta \text{DEV}(h^0 \rightarrow \gamma\gamma) = (2.4\%, 2.2\%, 2.0\%)$
 - $\Delta \text{DEV}(h^0 \rightarrow g g) = (1.8\%, 1.4\%, 1.1\%)$
- [Jorge de Blas et al., Snowmass2021 Report: arXiv:2206.08326;
Private communication with Jorge de Blas.] (See Backup slides)
- ILC can observe such sizable deviation $\text{DEV}(h^0 \rightarrow g g)$ at high significance!

Expected absolute 1 sigma errors of the deviations DEVs at future lepton colliders

	ILC-I	ILC-II	ILC-III	CLIC-I	CLIC-II	CLIC-III
$\Delta DEV(b)$	1.7%	1.1%	0.9%	2.2%	1.2%	1.1%
$\Delta DEV(c)$	3.6%	2.4%	1.8%	8.6%	3.8%	3.0%
$\Delta DEV(\gamma)$	2.4%	2.2%	2.0%	2.6%	2.4%	2.2%
$\Delta DEV(g)$	1.8%	1.4%	1.1%	2.2%	1.6%	1.4%
$\Delta DEV(b/c)$	3.12%	2.07%	1.3%	8.16%	3.5%	2.54%
$\Delta DEV(\gamma/g)$	3.29%	2.82%	2.3%	3.41%	3.05%	2.61%
$\Delta DEV(g/b)$	1.51%	1.14%	0.85%	1.62%	1.3%	1.1%
$\Delta DEV(g/c)$	3.4%	2.34%	1.52%	8.3%	3.72%	2.75%

	FCC-ee I	FCC-ee II	CEPC-I	CEPC-II	MuC-I	MuC-II	MuC-III
$\Delta DEV(b)$	1.3%	1.2%	0.86%	0.84%	1.8%	0.92%	1.1%
$\Delta DEV(c)$	2.8%	2.6%	2.4%	2.2%	12.4%	3.8%	3.6%
$\Delta DEV(\gamma)$	2.4%	2.2%	1.8%	1.8%	2.4%	1.4%	1.5%
$\Delta DEV(g)$	1.5%	1.4%	0.9%	0.88%	1.7%	0.92%	1.0%
$\Delta DEV(b/c)$	2.22%	2.06%	2.0%	1.94%	11.92%	3.53%	3.37%
$\Delta DEV(\gamma/g)$	3.03%	2.86%	2.07%	2.03%	3.18%	1.55%	1.55%
$\Delta DEV(g/b)$	1.29%	1.16%	0.73%	0.7%	1.69%	0.73%	0.72%
$\Delta DEV(g/c)$	2.54%	2.33%	2.13%	2.06%	12.0%	3.59%	3.43%

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



- There is a strong correlation between $T_{U32} - DEV(\gamma/g)$!
- $DEV(\gamma/g)$ can be as large as $\sim +4\%$ for large T_{U32} ! (from scatter plot analysis)
 $\sim +8\%$ for large T_{U32} ! (from contour plot analysis)
- Expected absolute 1 sigma error of $DEV(\gamma/g)$ at ILC:
 $\Delta DEV(\gamma/g) = (3.3\%, 2.8\%, 2.3\%)$ at (ILC250, ILC250+500, ILC250+500+1000).

[Jorge de Blas et al., Snowmass2021 Report: arXiv:2206.08326;
 Private communication with Jorge de Blas.] (See Backup slides)

- ILC can observe such sizable deviation from SM at high significance.

Expected absolute 1 sigma errors of the deviations DEVs at future lepton colliders

	ILC-I	ILC-II	ILC-III	CLIC-I	CLIC-II	CLIC-III
$\Delta DEV(b)$	1.7%	1.1%	0.9%	2.2%	1.2%	1.1%
$\Delta DEV(c)$	3.6%	2.4%	1.8%	8.6%	3.8%	3.0%
$\Delta DEV(\gamma)$	2.4%	2.2%	2.0%	2.6%	2.4%	2.2%
$\Delta DEV(g)$	1.8%	1.4%	1.1%	2.2%	1.6%	1.4%
$\Delta DEV(b/c)$	3.12%	2.07%	1.3%	8.16%	3.5%	2.54%
$\Delta DEV(\gamma/g)$	3.29%	2.82%	2.3%	3.41%	3.05%	2.61%
$\Delta DEV(g/b)$	1.51%	1.14%	0.85%	1.62%	1.3%	1.1%
$\Delta DEV(g/c)$	3.4%	2.34%	1.52%	8.3%	3.72%	2.75%

	FCC-ee I	FCC-ee II	CEPC-I	CEPC-II	MuC-I	MuC-II	MuC-III
$\Delta DEV(b)$	1.3%	1.2%	0.86%	0.84%	1.8%	0.92%	1.1%
$\Delta DEV(c)$	2.8%	2.6%	2.4%	2.2%	12.4%	3.8%	3.6%
$\Delta DEV(\gamma)$	2.4%	2.2%	1.8%	1.8%	2.4%	1.4%	1.5%
$\Delta DEV(g)$	1.5%	1.4%	0.9%	0.88%	1.7%	0.92%	1.0%
$\Delta DEV(b/c)$	2.22%	2.06%	2.0%	1.94%	11.92%	3.53%	3.37%
$\Delta DEV(\gamma/g)$	3.03%	2.86%	2.07%	2.03%	3.18%	1.55%	1.55%
$\Delta DEV(g/b)$	1.29%	1.16%	0.73%	0.7%	1.69%	0.73%	0.72%
$\Delta DEV(g/c)$	2.54%	2.33%	2.13%	2.06%	12.0%	3.59%	3.43%

7. Benchmark scenario

- *In our analysis we also take into account the expected sparticle mass limits from the future HL-LHC experiment .*
- *From the allowed MSSM parameter points in the scan, we have selected a benchmark point P1 shown in Table 2 .*
- *This benchmark scenario P1 satisfies also all the expected sparticle mass limits [including $(m_{A/H^+}, \tan\beta)$ limits] from future HL-LHC experiment .*
[see CERN Yellow Rep., arXiv:1812.07831;
Snowmass Rep. of EF, arXiv:2209.13128; ...]
- *The resulting physical masses of the particles are shown in Table 3.*

Physical masses for Benchmark scenario P1

Table 3: Physical masses in GeV of the particles for the scenario of Table 2.

$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{\chi}_3^0}$	$m_{\tilde{\chi}_4^0}$	$m_{\tilde{\chi}_1^+}$	$m_{\tilde{\chi}_2^+}$
781	882	911	1669	782	914

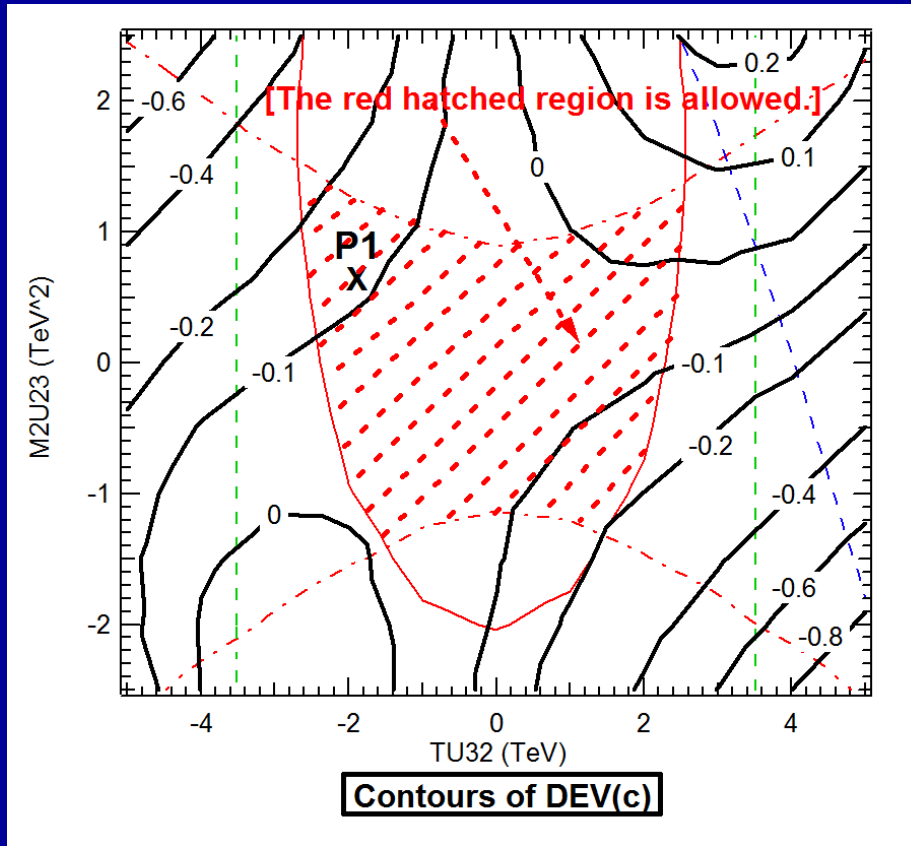
m_{h^0}	m_{H^0}	m_{A^0}	m_{H^\pm}
124	5325	5325	5359

$m_{\tilde{g}}$	$m_{\tilde{u}_1}$	$m_{\tilde{u}_2}$	$m_{\tilde{u}_3}$	$m_{\tilde{u}_4}$	$m_{\tilde{u}_5}$	$m_{\tilde{u}_6}$
4424	868	3011	3331	3877	4402	4402

$m_{\tilde{d}_1}$	$m_{\tilde{d}_2}$	$m_{\tilde{d}_3}$	$m_{\tilde{d}_4}$	$m_{\tilde{d}_5}$	$m_{\tilde{d}_6}$
1705	2833	3010	3877	4397	4403

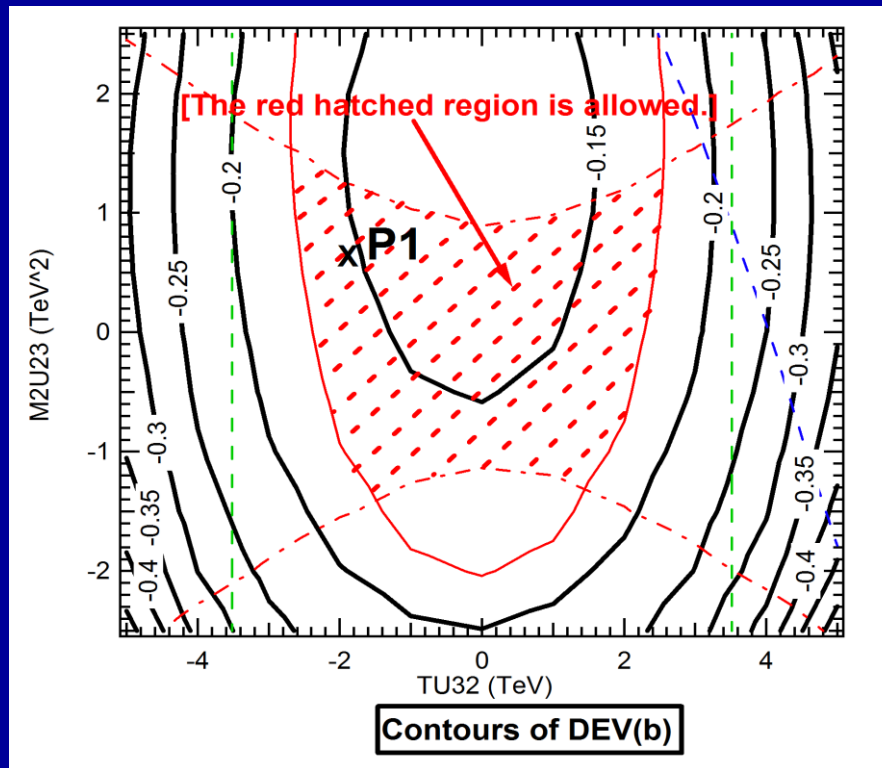
$m_{\tilde{\nu}_1}$	$m_{\tilde{\nu}_2}$	$m_{\tilde{\nu}_3}$	$m_{\tilde{l}_1}$	$m_{\tilde{l}_2}$	$m_{\tilde{l}_3}$	$m_{\tilde{l}_4}$	$m_{\tilde{l}_5}$	$m_{\tilde{l}_6}$
1509	1509	1528	1489	1489	1509	1512	1512	1545

Contours of $DEV(h^0 \rightarrow c \bar{c})$ in $T_{U32} - M_{U23}^2$ plane around P1



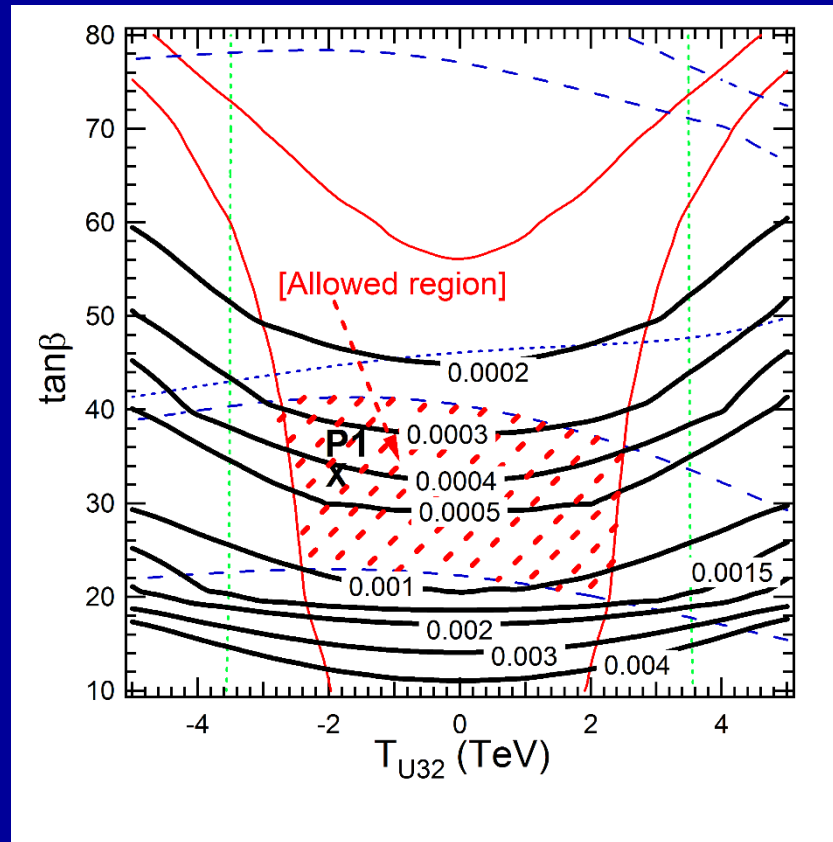
We find that $DEV(c)$ can be very large (about -30% to 10%) in a sizable region allowed by all the constraints including the expected sparticle mass limits from the future HL-LHC experiment!

Contours of $DEV(h^0 \rightarrow b \bar{b})$ in $T_{U32} - M^2_{U23}$ plane around P1



- We find that $DEV(b)$ can be very large (about -10% to -18%) in a sizable region allowed by all the constraints including the expected sparticle mass limits from the future HL-LHC experiment!
- For $DEV(g)$, $DEV(\gamma)$, $DEV(\gamma/g)$ and $DEV(b/c)$ we have obtained similar results to those for $DEV(c)$ and $DEV(b)$.

Contours of $B(h^0 \rightarrow b \bar{s} / s \bar{b})$ in $T_{U32} - \tan\beta$ plane around P1



- $B(h^0 \rightarrow b \bar{s} / s \bar{b})$ can be as large as $\sim 0.15\%$ in a sizable region allowed by all the constraints including the expected sparticle mass limits from the future HL-LHC!
- 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].

8. 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 general QFV.

- *For the first time, we have performed a systematic MSSM parameter scan respecting all of the relevant theoretical and experimental constraints.*

- *In strong contrast to the usual studies in the MSSM with minimal flavor violation (MFV), we have found that the deviations of these MSSM decay widths and width ratios from the SM values can be quite sizable in the MSSM with general QFV.*

- *All of these large deviations in the $h (125)$ 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 $T_{D23}, T_{D32}, T_{D33}$.

- *Future lepton colliders such as ILC, CLIC, CEPC, FCC-ee and MuC can observe such sizable deviations from the SM at high signal significance even after the failure of SUSY particle discovery at the HL-LHC.*

- *In case the deviation pattern shown here is really observed at the lepton colliders, then it would strongly suggest the discovery of QFV SUSY (the MSSM with general QFV).*

- *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, lepton colliders, such as 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

Expected absolute 1 sigma errors of the deviations DEVs at future lepton colliders

Table 6: The expected *absolute* 1σ error of the deviations $DEV(X)$ and $DEV(X/Y)$ (denoted by $\Delta DEV(X)$ and $\Delta DEV(X/Y)$) at future lepton colliders: ILC-I = ILC250 + Giga-Z, ILC-II = ILC250+500 + Giga-Z, ILC-III = ILC250+500+1000 + Giga-Z; CLIC-I = CLIC380, CLIC-II = CLIC380+1500, CLIC-III = CLIC380+1500+3000; FCC-ee I = FCC-ee240 + Z/WW, FCC-ee II = FCC-ee240+365 + Z/WW; CEPC-I = CEPC240 + Z/WW, CEPC-II = CEPC240+360 + Z/WW; MuC-I = MuC3TeV, MuC-II = MuC10TeV, MuC-III = MuC10TeV+125GeV. As for ILC the results without Giga-Z run are almost identical to those with Giga-Z one. The Z/WW denote Z-pole and WW threshold runs. All results except for MuC-I and MuC-II are those from the free- Γ_H fit and the results for MuC-I and MuC-II are those from the constrained- Γ_H fit, where Γ_H is the total width of the Higgs boson h^0 . The details of run scenarios of the lepton colliders are explained in Ref. [14]. The HL-LHC and LEP/SLD measurements are combined with all lepton collider run scenarios.

*Jorge de Blas et al., Snowmass2021 Report: arXiv:2206.08326 [hep-ph];
Private communication with Jorge de Blas.*

Expected absolute 1 sigma errors of the deviations DEVs at future lepton colliders

	ILC-I	ILC-II	ILC-III	CLIC-I	CLIC-II	CLIC-III
$\Delta DEV(b)$	1.7%	1.1%	0.9%	2.2%	1.2%	1.1%
$\Delta DEV(c)$	3.6%	2.4%	1.8%	8.6%	3.8%	3.0%
$\Delta DEV(\gamma)$	2.4%	2.2%	2.0%	2.6%	2.4%	2.2%
$\Delta DEV(g)$	1.8%	1.4%	1.1%	2.2%	1.6%	1.4%
$\Delta DEV(b/c)$	3.12%	2.07%	1.3%	8.16%	3.5%	2.54%
$\Delta DEV(\gamma/g)$	3.29%	2.82%	2.3%	3.41%	3.05%	2.61%
$\Delta DEV(g/b)$	1.51%	1.14%	0.85%	1.62%	1.3%	1.1%
$\Delta DEV(g/c)$	3.4%	2.34%	1.52%	8.3%	3.72%	2.75%

	FCC-ee I	FCC-ee II	CEPC-I	CEPC-II	MuC-I	MuC-II	MuC-III
$\Delta DEV(b)$	1.3%	1.2%	0.86%	0.84%	1.8%	0.92%	1.1%
$\Delta DEV(c)$	2.8%	2.6%	2.4%	2.2%	12.4%	3.8%	3.6%
$\Delta DEV(\gamma)$	2.4%	2.2%	1.8%	1.8%	2.4%	1.4%	1.5%
$\Delta DEV(g)$	1.5%	1.4%	0.9%	0.88%	1.7%	0.92%	1.0%
$\Delta DEV(b/c)$	2.22%	2.06%	2.0%	1.94%	11.92%	3.53%	3.37%
$\Delta DEV(\gamma/g)$	3.03%	2.86%	2.07%	2.03%	3.18%	1.55%	1.55%
$\Delta DEV(g/b)$	1.29%	1.16%	0.73%	0.7%	1.69%	0.73%	0.72%
$\Delta DEV(g/c)$	2.54%	2.33%	2.13%	2.06%	12.0%	3.59%	3.43%

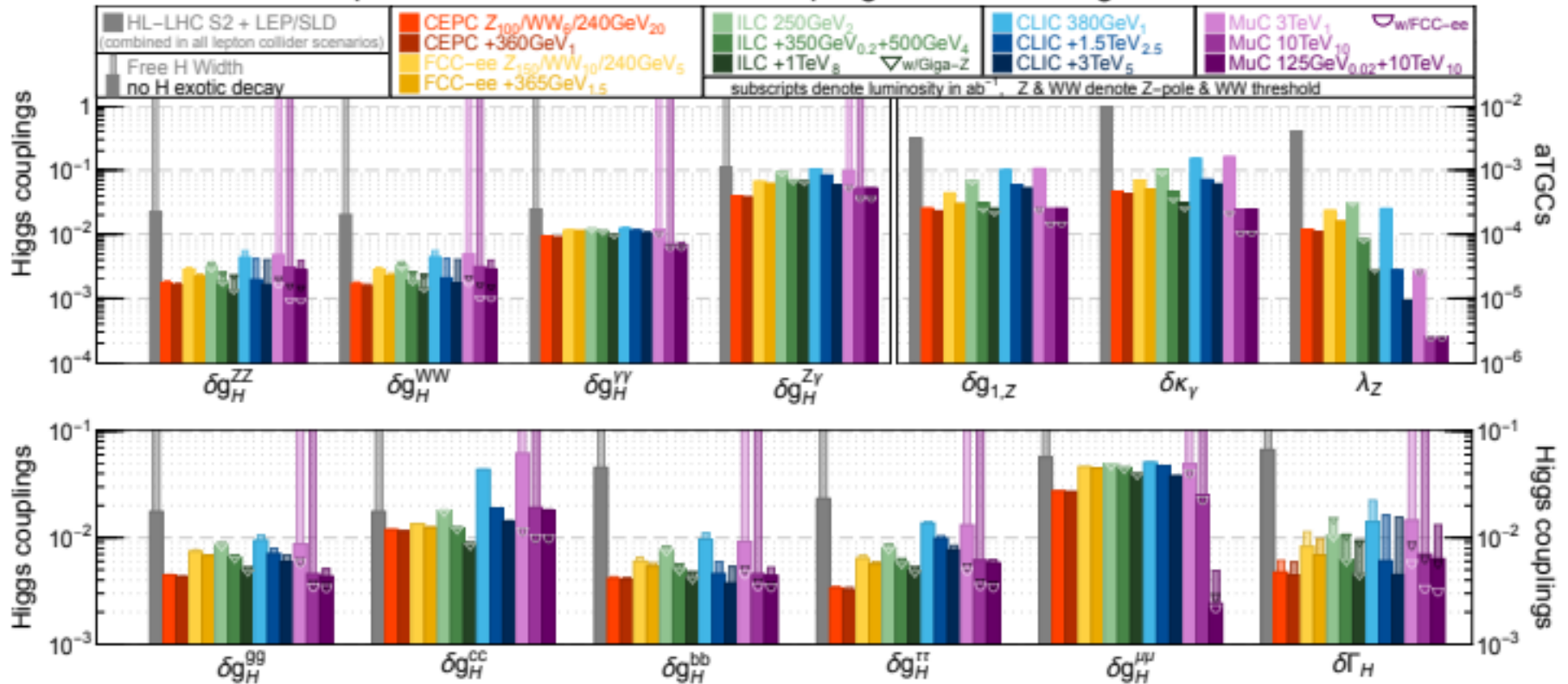
Higgs couplings at future colliders

Snowmass2021 Report: arXiv:2206.08326

(See Fig. 3 in page 37; Table 29 in page 40)

Higgs coupling precision at future colliders

precision reach on effective couplings from SMEFT global fit



Higgs couplings at future colliders

ESU2020 Report: arXiv:1905.03764

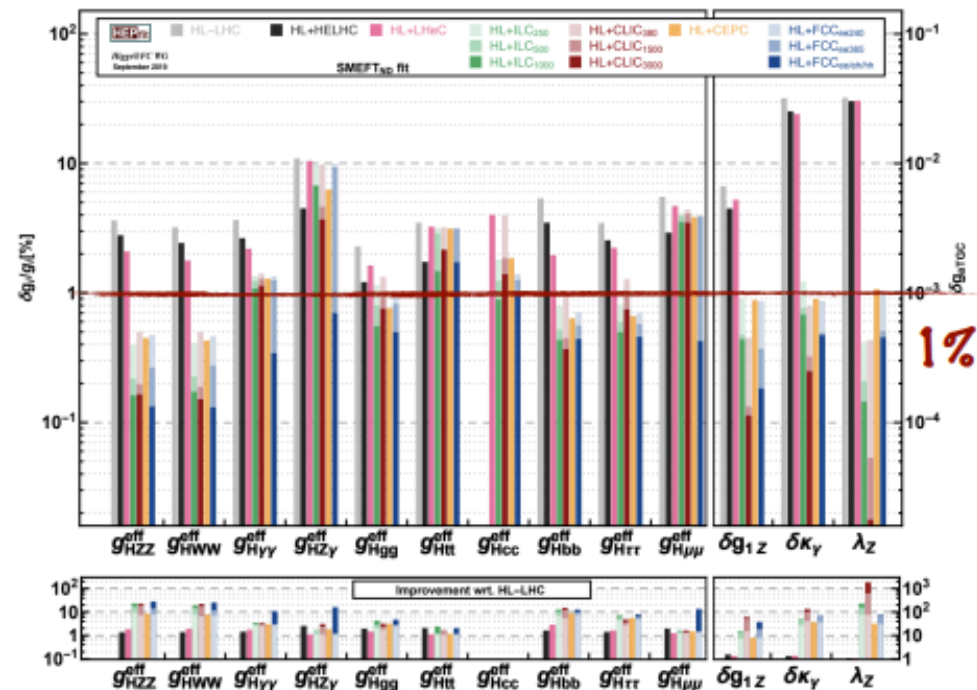
Higgs coupling precision in % at future colliders

arXiv:1910.11775, arXiv:1905.03764

CERN-LPCC-2018-04



- Future colliders under consideration will improve with respect to the HL-LHC the understanding of the Higgs boson couplings - 1-5%
- **Coupling to charm** quark could be measured with an accuracy of $\sim 1\%$ in future e+e- machines
- **Couplings to $\mu/\gamma/Z\gamma$** benefit the most from the large dataset available at HL-LHC
- At low energy top-Higgs coupling is not accessible at future lepton colliders



Higgs couplings at future colliders

ILC White Paper (Snowmass2021): arXiv:2203.07622

(See Fig. 12.1 in page 255; Table 12.2 in page 256)

Higgs coupling precision in % for ILC

arXiv:2203.07622

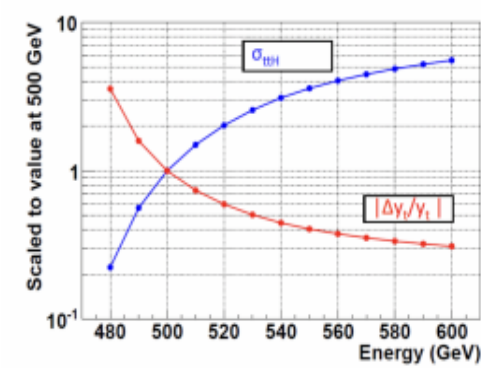
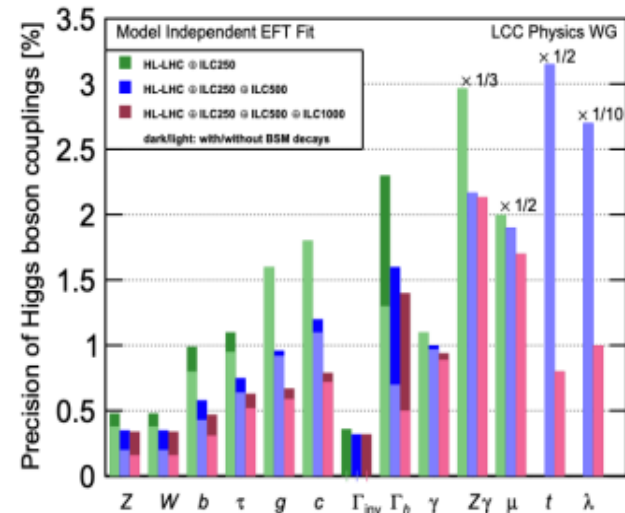
arXiv:1908.11299

arXiv:1506.07830



coupling	ILC250		ILC500		ILC1000	
	full	no BSM	full	no BSM	full	no BSM
hZZ	0.49	0.38	0.35	0.20	0.34	0.16
hWW	0.48	0.38	0.35	0.20	0.34	0.16
hbb	0.99	0.80	0.58	0.43	0.47	0.31
$h\tau\tau$	1.1	0.95	0.75	0.63	0.63	0.52
hgg	1.6	1.6	0.96	0.91	0.67	0.59
hcc	1.8	1.7	1.2	1.1	0.79	0.72
$h\gamma\gamma$	1.1	1.0	1.0	0.96	0.94	0.89
$h\gamma Z$	8.9	8.9	6.5	6.5	6.4	6.4
$h\mu\mu$	4.0	4.0	3.8	3.7	3.4	3.4
htt	—	—	6.3	6.3	1.0	1.0
hhh	—	—	20	20	10	10
Γ_{tot}	2.3	1.3	1.6	0.70	1.4	0.50
Γ_{inv}	0.36	—	0.32	—	0.32	—

Note C^3 would run at 550 GeV, a factor 2 improvement to the top-Yukawa coupling (*)



DEV error - coupling error relation

$$\Delta DEV(h \rightarrow X X) = 2 \delta g(hXX)$$

$$\delta g(hXX) = [\text{Expected } \textit{relative} \text{ error of coupling } g(hXX)]$$

$$\Delta DEV(h \rightarrow X X) = [\text{Expected } \textit{absolute} \text{ error of deviation } \\ DEV(h \rightarrow X X)]$$

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 $Q = 1 \text{ TeV}$ 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

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) [20]	± 0.28 (68% CL) [28]	2.228 ± 0.549
$10^{15} \times \Delta M_K$ [GeV]	3.484 ± 0.006 (68% CL) [20]	± 1.2 (68% CL) [28]	3.484 ± 2.352
$10^9 \times B(K_L^0 \rightarrow \pi^0 \nu \bar{\nu})$	< 3.0 (90% CL) [20]	± 0.002 (68% CL) [20]	< 3.0 (90% CL)
$10^{10} \times B(K^+ \rightarrow \pi^+ \nu \bar{\nu})$	1.7 ± 1.1 (68% CL) [20]	± 0.04 (68% CL) [20]	$1.7_{-1.70}^{+2.16}$
ΔM_{B_s} [ps $^{-1}$]	17.757 ± 0.021 (68% CL) [20, 29]	± 2.7 (68% CL) [30]	17.757 ± 5.29
$10^4 \times B(b \rightarrow s \gamma)$	3.32 ± 0.15 (68% CL) [20, 29]	± 0.23 (68% CL) [17]	3.32 ± 0.54
$10^6 \times B(b \rightarrow s l^+ l^-)$ ($l = e$ or μ)	$1.60_{-0.45}^{+0.48}$ (68% CL) [31]	± 0.11 (68% CL) [32]	$1.60_{-0.91}^{+0.97}$
$10^9 \times B(B_s \rightarrow \mu^+ \mu^-)$	$2.69_{-0.35}^{+0.37}$ (68%CL) [33]	± 0.23 (68% CL) [34]	$2.69_{-0.82}^{+0.85}$
$10^4 \times B(B^+ \rightarrow \tau^+ \nu)$	1.06 ± 0.19 (68%CL) [29]	± 0.29 (68% CL) [35]	1.06 ± 0.69
m_{h^0} [GeV]	125.09 ± 0.24 (68% CL) [36]	± 3 [37]	125.09 ± 3.48
κ_b	$0.89_{-0.21}^{+0.22}$ (95% CL) [38]		$0.89_{-0.21}^{+0.22}$ (ATLAS)
	$0.99_{-0.31}^{+0.33}$ (95% CL) [39]		$0.99_{-0.31}^{+0.33}$ (CMS)
κ_g	$0.95_{-0.13}^{+0.14}$ (95% CL) [38]		$0.95_{-0.13}^{+0.14}$ (ATLAS)
	0.92 ± 0.16 (95% CL) [39]		0.92 ± 0.16 (CMS)
κ_γ	1.01 ± 0.12 (95% CL) [38]		1.01 ± 0.12 (ATLAS)
	1.10 ± 0.16 (95% CL) [39]		1.10 ± 0.16 (CMS)

* *Constraints from W boson mass data:*

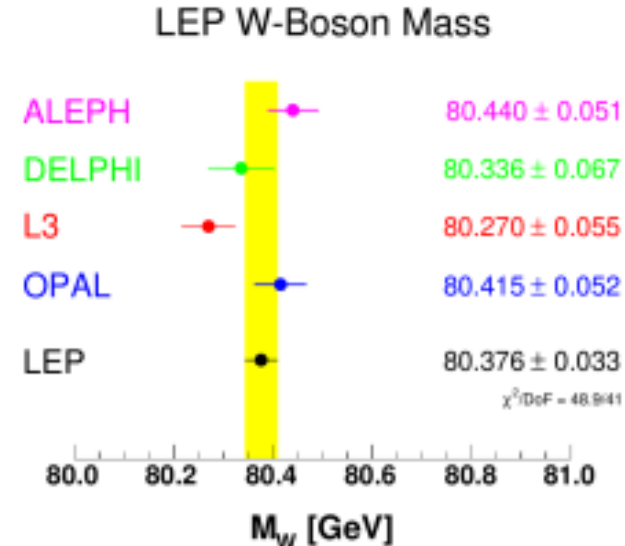
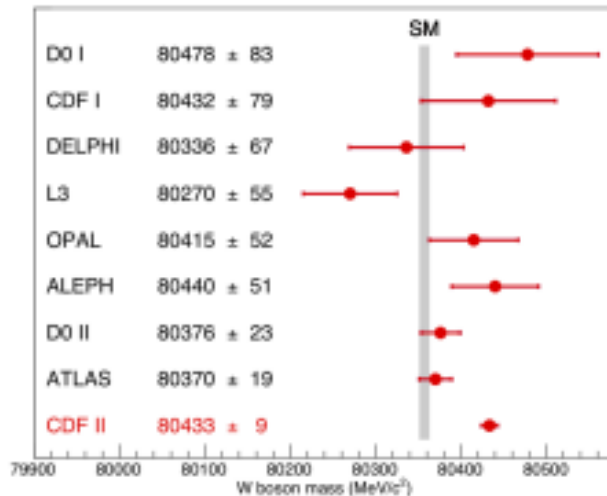
The recent m_W data from CDF II [1] disagrees significantly with the previous world average. (-> See backup slides.)

[1] CDF Collaboration, Science 376, 170–176 (2022)

This issue of the m_W data is not yet settled.

Hence, we do not take into account this m_W constraint on the MSSM parameters in our analysis.

What to think of m_W measurements?

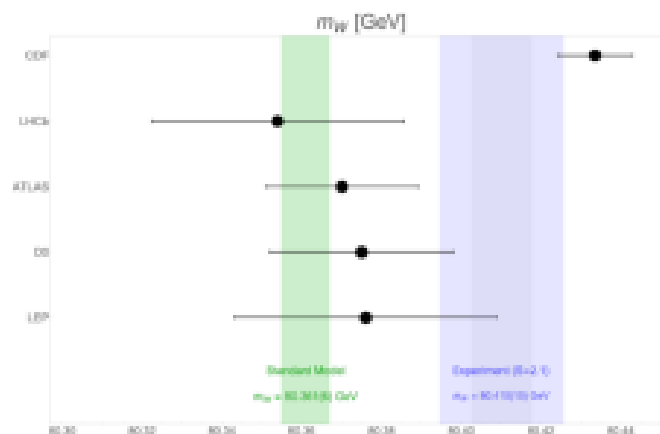
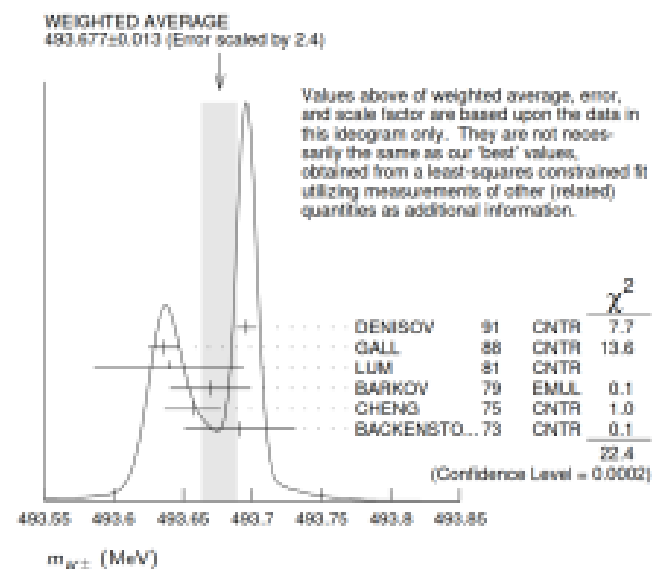


- The LEP results are based on 42 separate measurements with a **healthy** χ^2 .
- The LEP-combined (33 MeV), LHCb (32 MeV), D0 Run II (23 MeV), ATLAS (19 MeV) and CDF Run II (9.4 MeV) measurements have a $\chi^2/\text{DoF} = 17.1/4$, with p-value of **0.2%** for compatibility (neglecting correlations).
- So reasonably strong evidence that the ensemble of experimental results are **inconsistent with each other** independent of any SM prediction.
- The standard PDG procedure is to add a scale factor “democratically” to all measurements to parametrize our ignorance.

PDG scale factors

(What can happen with supposed high precision measurements)

The new world average m_W uncertainty should be scaled up by about 2.1 leading to an uncertainty of 15 MeV in PDG-2022 compared with 12 MeV in PDG-2020.



Plot from [Resonances blog](#) (Adam Falkowski). Independently I had also done this and concluded that the scale-factored world-average is $+3.2\sigma$ off the SM value used by CDF

The charged kaon mass has been in this scale-factored state for 30 years!

Perhaps one or more experiments has underestimated uncertainties. Also may be difficult to measure the same thing in $p\bar{p}$, pp , and e^+e^- collisions.

Strong motivation to measure m_W well in complementary ways in e^+e^- collisions!

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

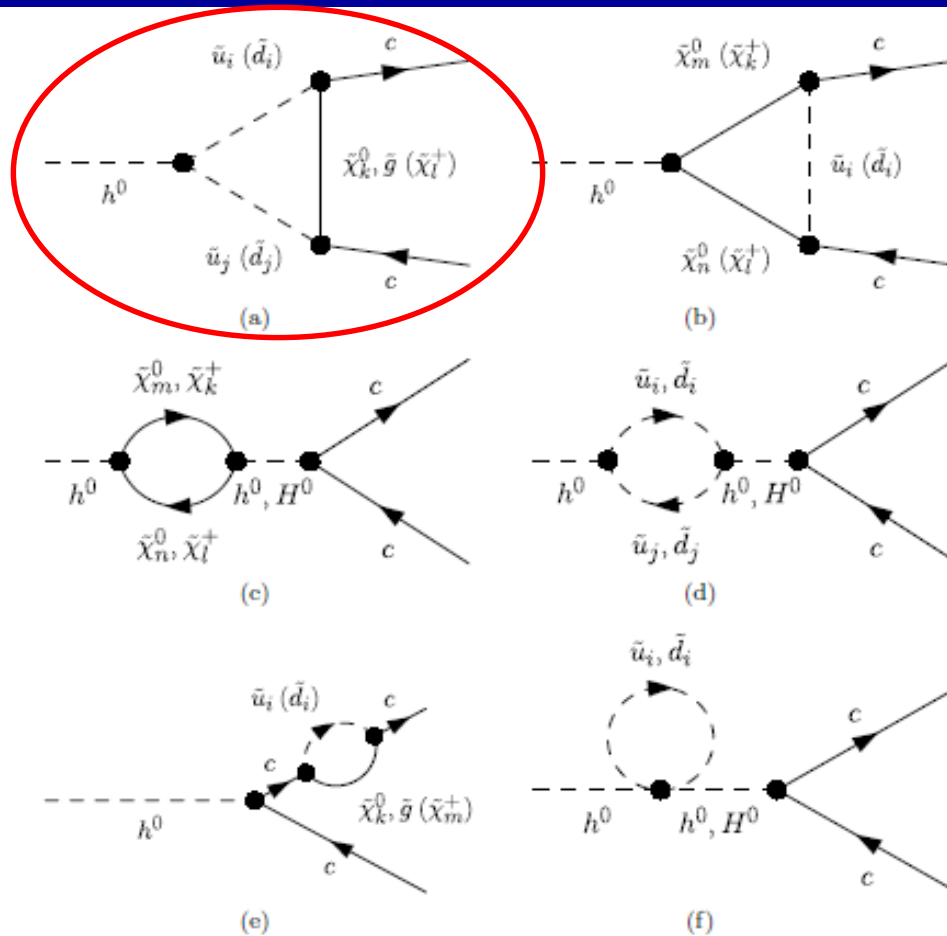
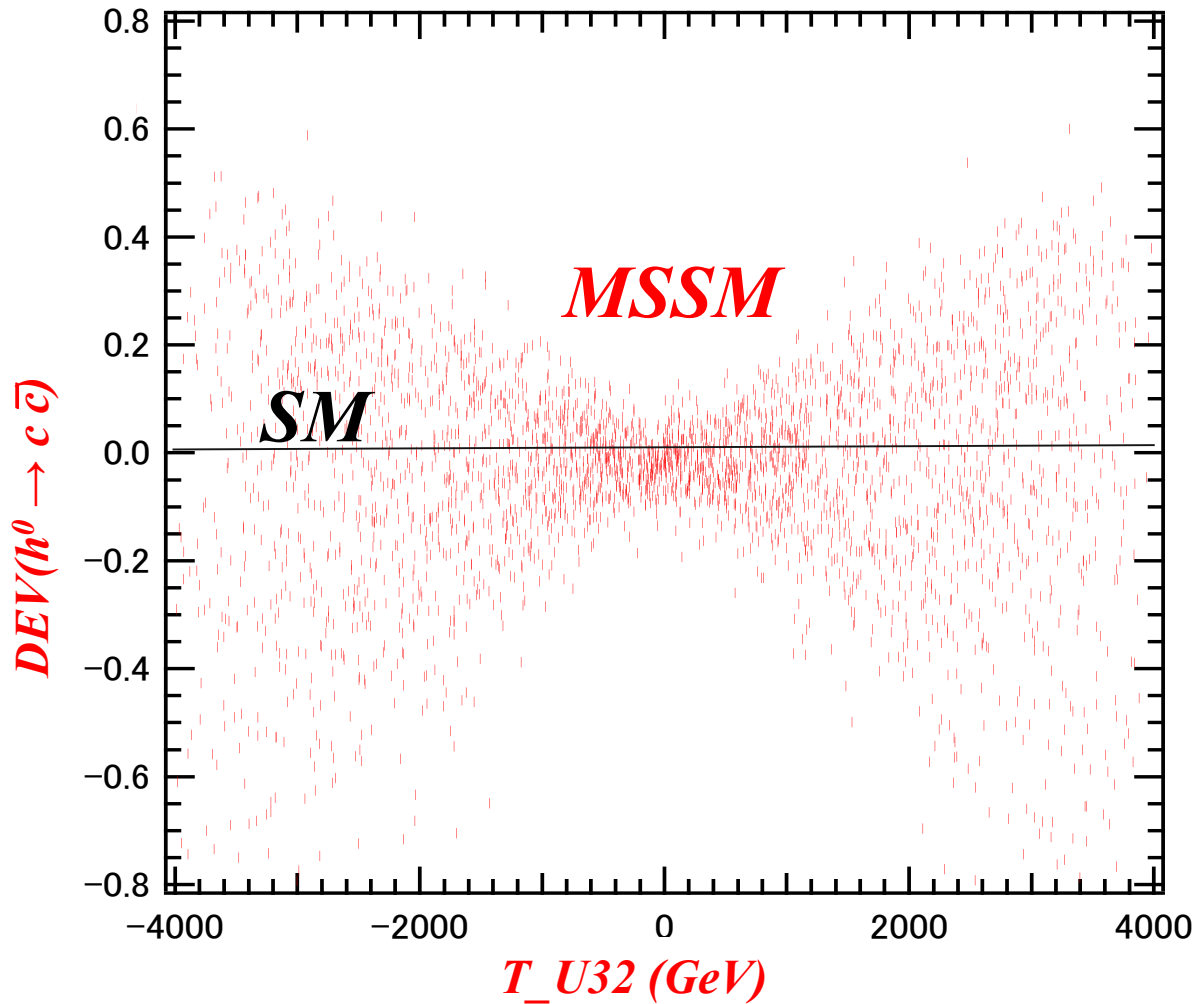


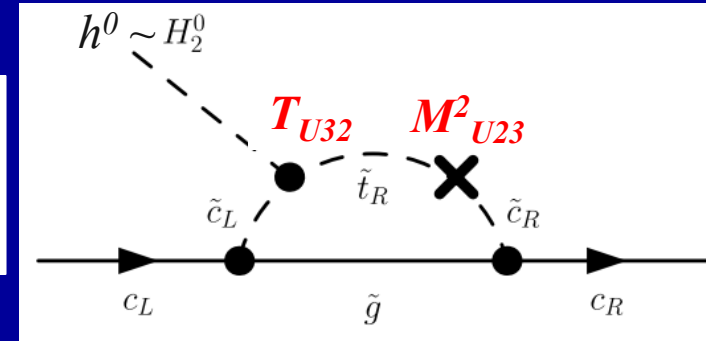
Figure 2: The main one-loop contributions with SUSY particles in $h^0 \rightarrow c \bar{c}$. The corresponding diagram to (e) with the self-energy contribution to the other charm quark is not shown explicitly.

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



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

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



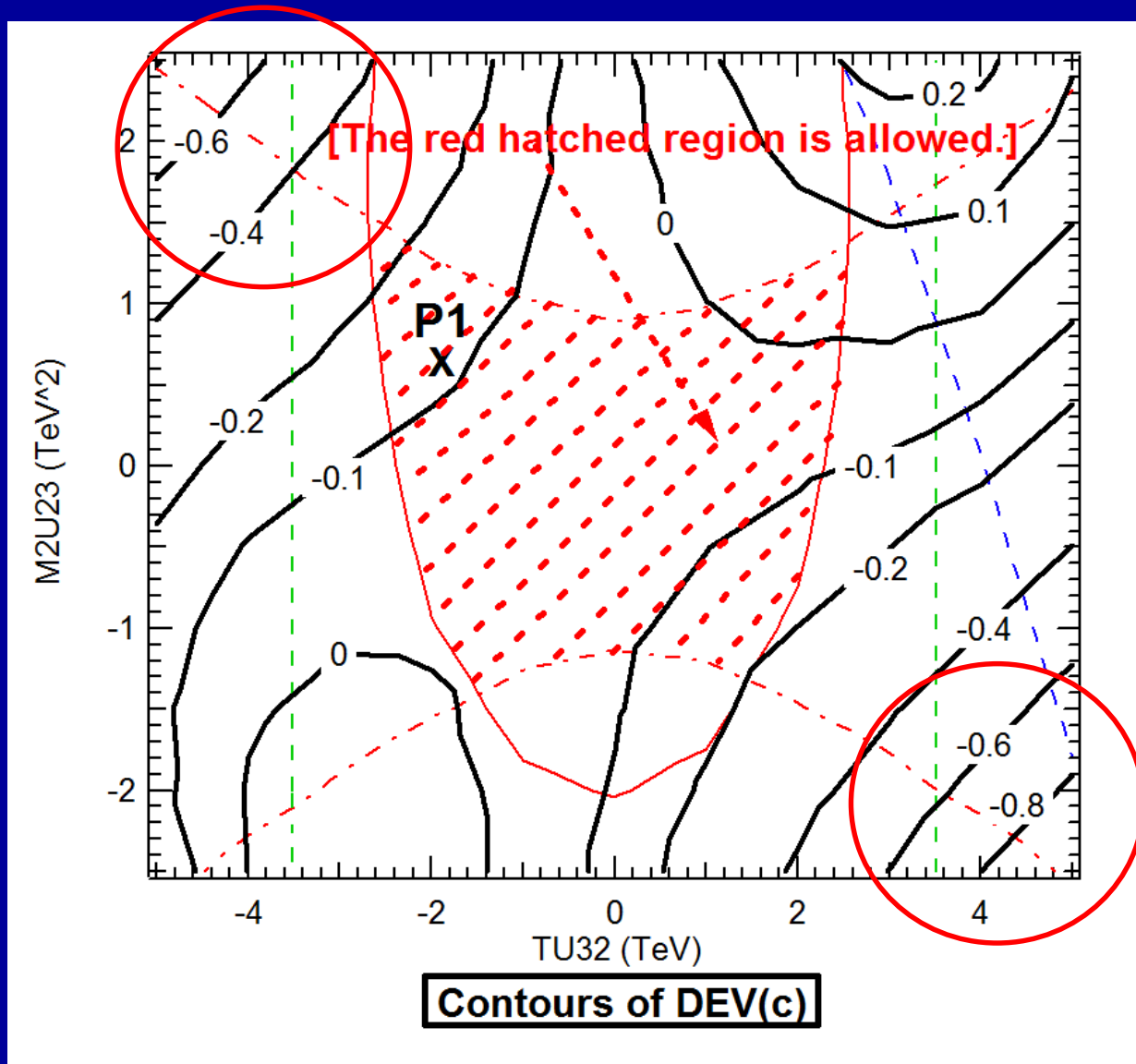
The interference term between the tree diagram and the gluino one-loop diagram can be very large (positive and negative) for large $T_{U32} * M^2_{U23}$, which can lead to even **NEGATIVE** width $\Gamma(h^0 \rightarrow c \bar{c})$ at one-loop level!

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 is no significant 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 $\sim \pm 60\%$.

Contours of $DEV(h^0 \rightarrow c \bar{c})$ in $T_{U32} - M^2_{U23}$ plane



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

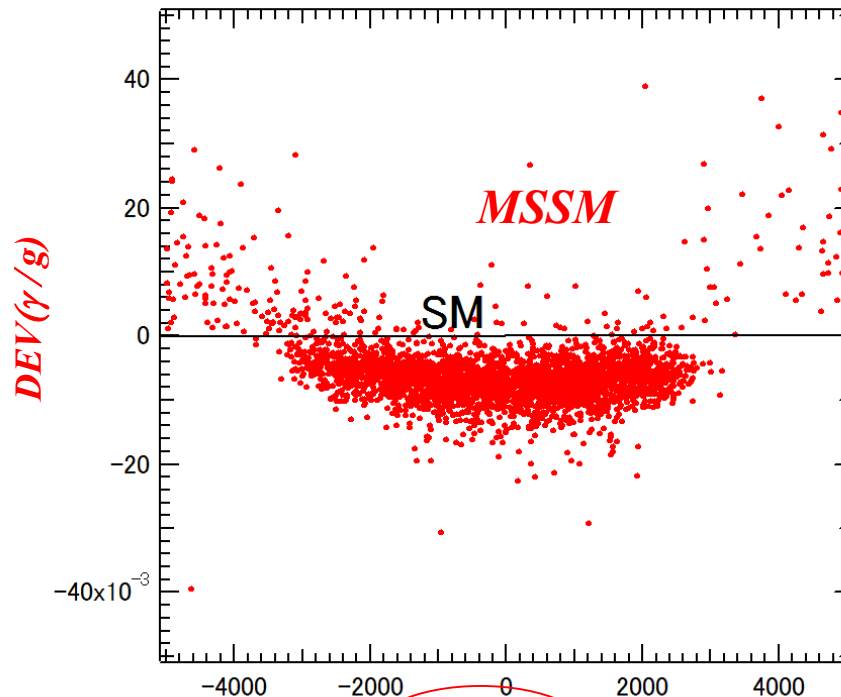
*As for $\Gamma(h^0 \rightarrow b \bar{b})$ & $\Gamma(h^0 \rightarrow b \bar{s} / s \bar{b})$, we have considered the large $\tan\beta$ enhancement and the resummation of the bottom Yukawa coupling [1]. It turns out, however, that in our case with large m_A close to the decoupling Higgs limit, the **resummation effect (Δ_b effect) is very small ($< 0.1\%$) [2].***

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

[2] *H. Eberl, E. Ginina, A. Bartl, K. Hidaka and W. Majerotto, JHEP 06 (2016) 143 [arXiv:1604.02366 [hep-ph]];*

E. Ginina, A. Bartl, H. Eberl, K. Hidaka and W. Majerotto, PoS(EPS-HEP2015)146 [arXiv:1510.03714 [hep-ph]].

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



T_{U33} (GeV)

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

- There is a strong correlation between $T_{U33} - DEV(\gamma/g)$!
- $DEV(\gamma/g)$ can be as large as $\sim +4\%$ for large T_{U33} !

8. 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 general 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 $\sim 0.15\%$!*

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 $\sim \pm 1\%$,

$DEV(h^0 \rightarrow gg)$ can be as large as $\sim \pm 4\%$.

* 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 $\sim -4\%$ to $+8\%$.

* 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} .

- Future lepton colliders such as ILC, CLIC, CEPC, FCC-ee can observe such large deviations from SM at high significance!

- In case the deviation pattern shown here is really observed at the future lepton colliders, then it would strongly suggest the discovery of QFV SUSY (MSSM with general QFV)!