

Imprint of quark flavor violating SUSY in $h(125)$ decays at future lepton colliders

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Collaboration with

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References:

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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]]

ILC White Paper for Snowmass 2021 [arXiv:2203.07622]

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

*2nd General Meeting of ILC-Japan Physics Working Group,
22 Feb. 2023, KEK, Tsukuba, 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 $h^0(125) \rightarrow c \bar{c}, b \bar{b}, b \bar{s}, \gamma \gamma, g g$ with special emphasis on Supersymmetric Quark Flavor Violation.*

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 LHC limits on the masses of squarks, sleptons, gluino, charginos and neutralinos.

(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.

$$121.6 \text{ GeV} < m_{h^0} < 128.6 \text{ GeV} \text{ (allowing for theoretical uncertainty) ,} \\ 0.71 < \kappa_b < 1.43 \text{ (ATLAS), } 0.56 < \kappa_b < 1.70 \text{ (CMS)}$$

(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 $T_{D\alpha\beta}$.

** Constraints on the MSSM parameters from W boson mass data:*

The recent m_W data from CDF II [1] is quite inconsistent with the other experimental data. (-> 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.

4. Parameter scan

- We compute the $h^0(125)$ decay widths in the *MSSM with QFV*.
- We take parameter scan ranges as follows:

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

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

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

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

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

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

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

etc. etc.

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

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

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

- Main 1-loop correction to $h^0 \rightarrow c \bar{c}$:

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

can be enhanced by large trilinear couplings $T_{U23}, T_{U32}, T_{U33}$

- Main 1-loop corrections to $h^0 \rightarrow b \bar{b}$ & $b \bar{s}$:

gluino - sd loops [sd = (\tilde{b} - \tilde{s} mixture)]

can be enhanced by large trilinear couplings $T_{D23}, T_{D32}, T_{D33}$

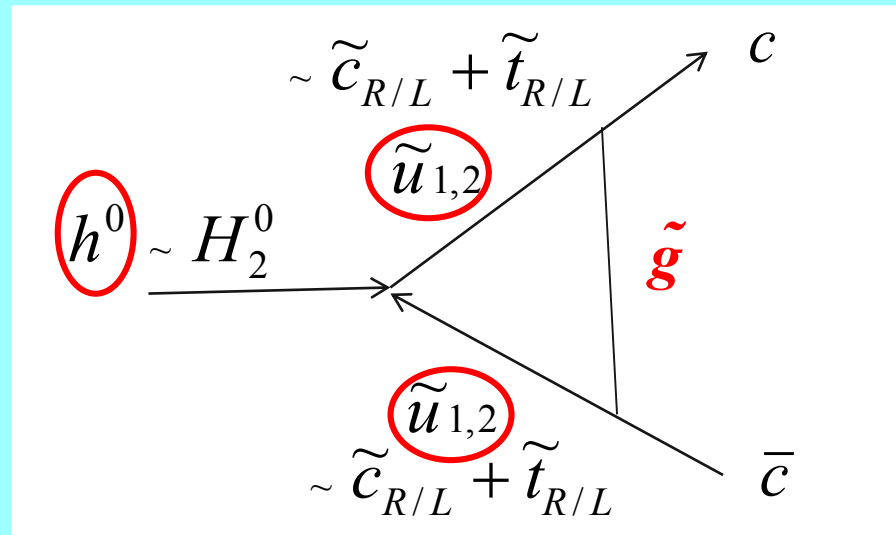
chargino - su loops [su = (\tilde{t} - \tilde{c} mixture)]

can be enhanced by large trilinear couplings $T_{U23}, T_{U32}, T_{U33}$

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

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

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



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

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

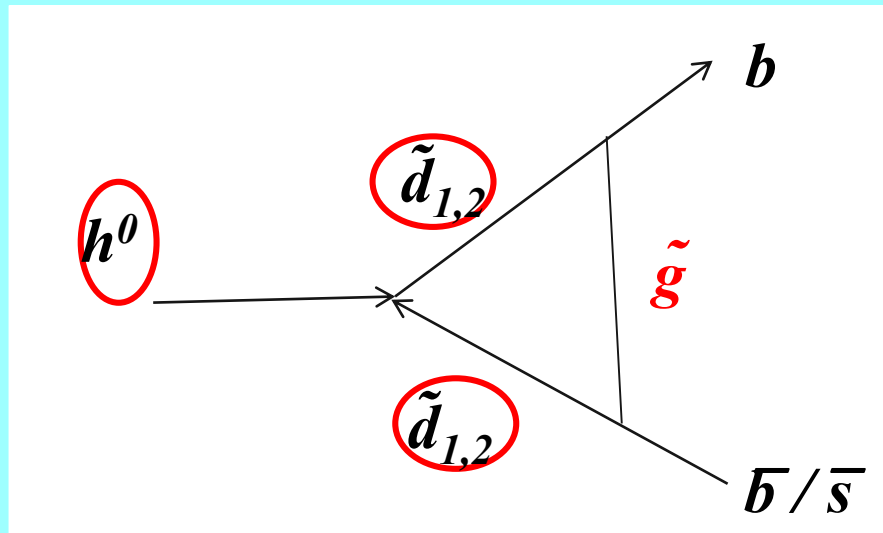
Gluino loop contributions can be large!

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

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

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

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



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

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

Glino loop contributions can be sizable!

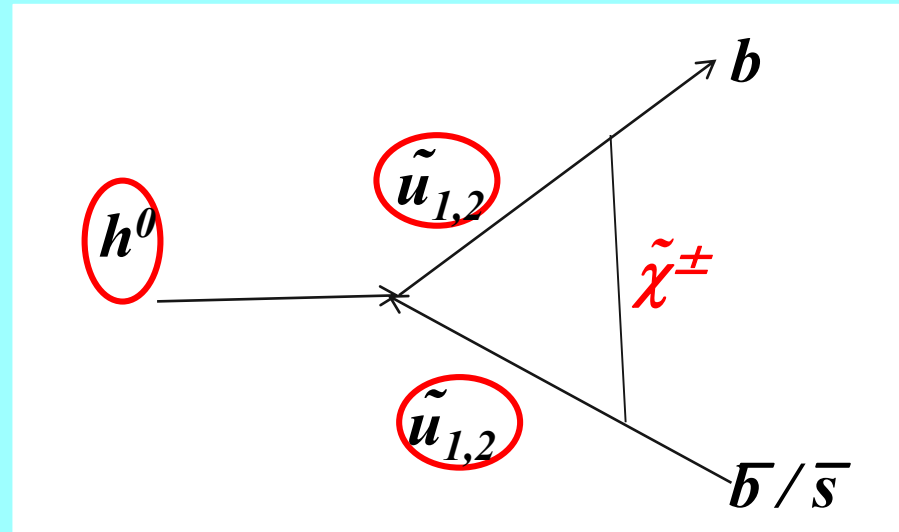
Deviation of $\Gamma(h^0 \rightarrow b \bar{b}/\bar{s})$ from SM width can be sizable!

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:*

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

$$X = c, b$$

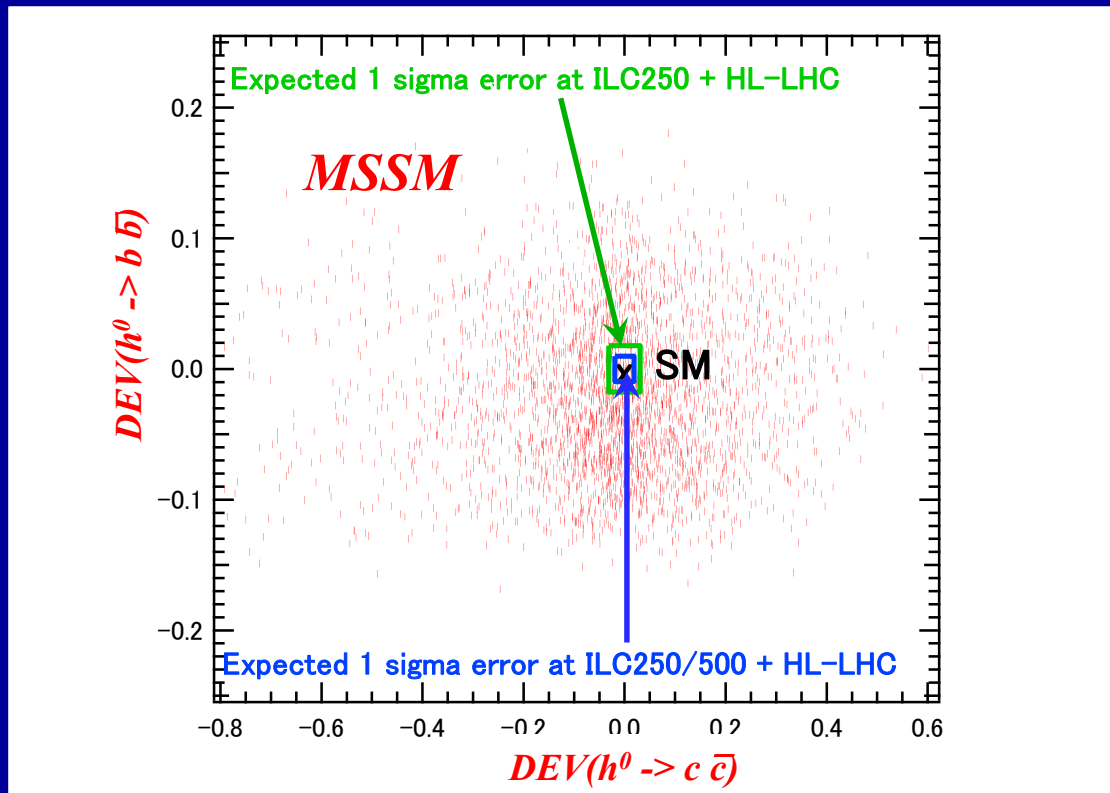
- *Coupling modifier:*

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

- *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 $\sim \pm 60\%$.

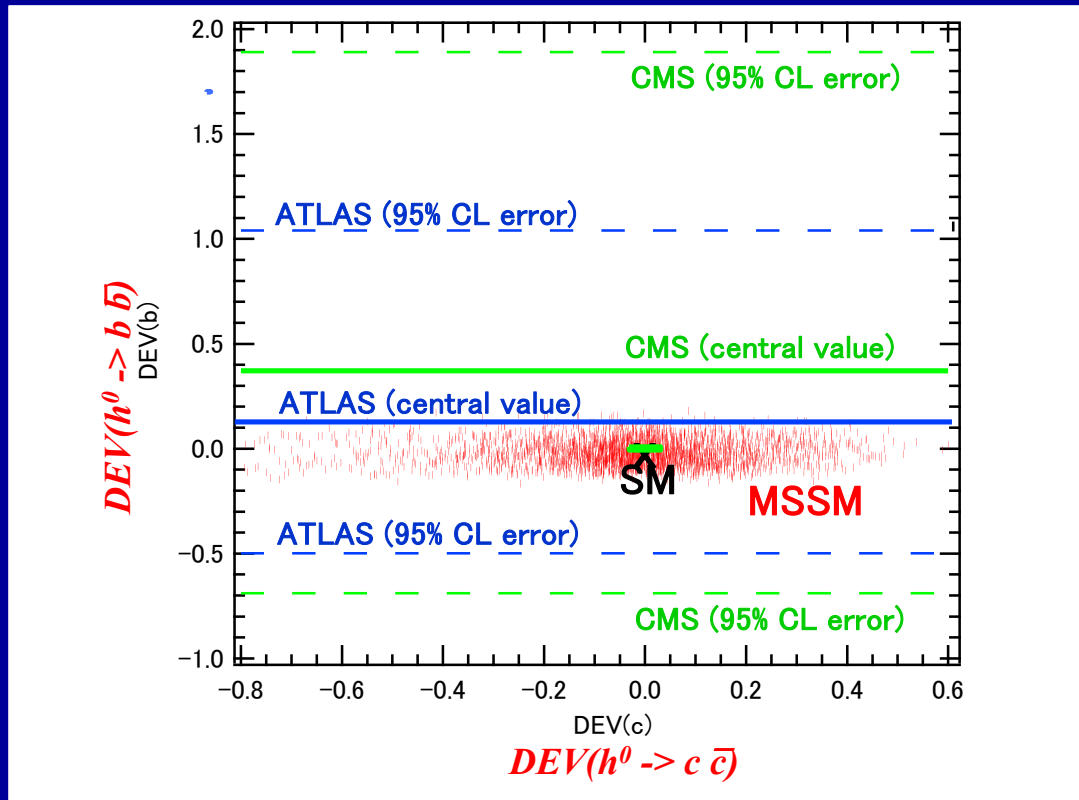
$DEV(h^0 \rightarrow b \bar{b})$ can be as large as $\sim \pm 20\%$.

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

$\Delta DEV(h^0 \rightarrow c \bar{c}) = (3.60\%, 2.40\%, 1.58\%)$ at (ILC250, ILC500, ILC1000)

$\Delta DEV(h^0 \rightarrow b \bar{b}) = (1.98\%, 1.16\%, 0.94\%)$ at (ILC250, ILC500, ILC1000)

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:*

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

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

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

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

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

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

$BR(h^0 \rightarrow b \bar{s} / s \bar{b})$ can be as large as $\sim 0.2\%$ (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].

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 QFV*.

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

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

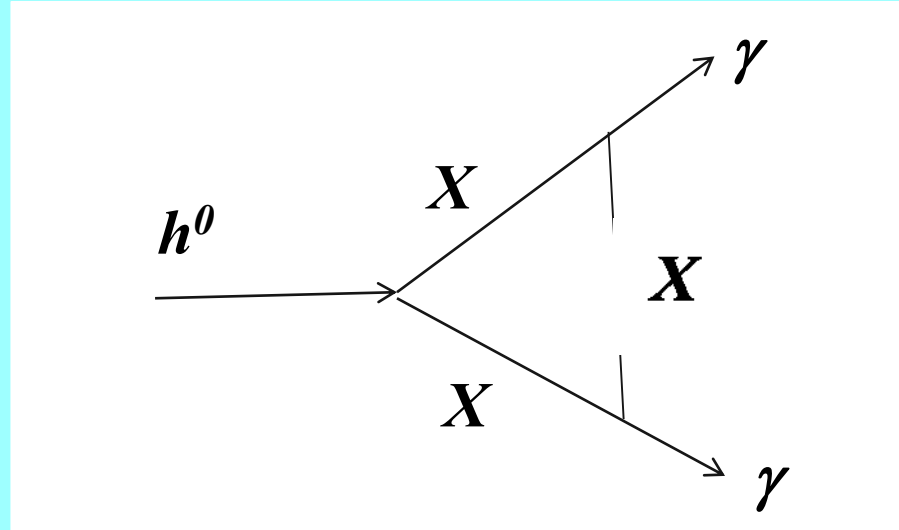
The su -loops can be enhanced by large trilinear couplings $T_{U23}, T_{U32}, T_{U33}$, resulting in sizable deviation of $\Gamma(h^0 \rightarrow \gamma\gamma)$ from the SM width!

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

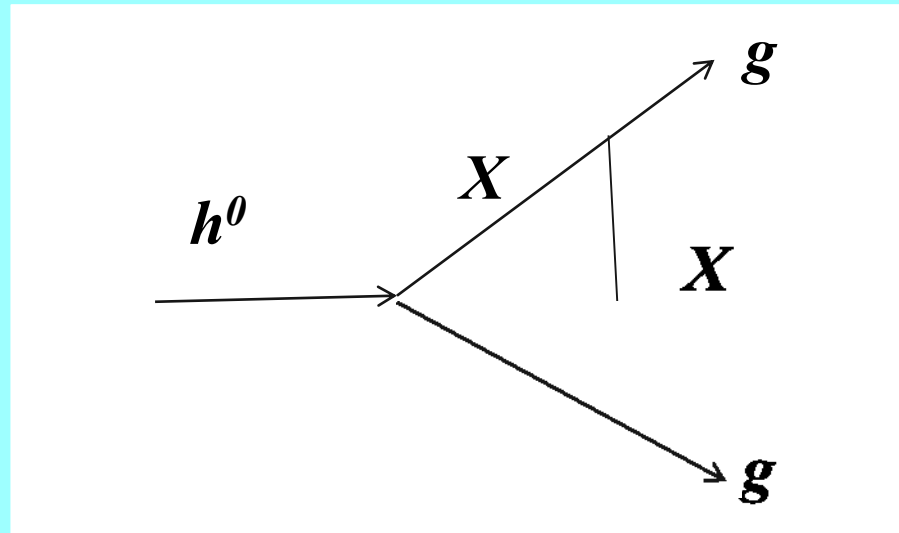
[top-quark / su] - loops [$su = (\tilde{t} - \tilde{c}$ mixture)]

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!

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



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



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

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

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

$\text{DEV}(h^0 \rightarrow \gamma\gamma)$ can be as large as $\sim \pm 1\%$,

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

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

(3) The deviation of the width ratio $\Gamma(h^0 \rightarrow \gamma\gamma) / \Gamma(h^0 \rightarrow gg)$ in the MSSM from the SM value can be as large as $\sim \pm 5\%$.

(4) Future lepton colliders such as ILC together with HL-LHC can observe such sizable deviations from SM at fairly high significance! (See arXiv:1908.11299 and Backup slides)

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

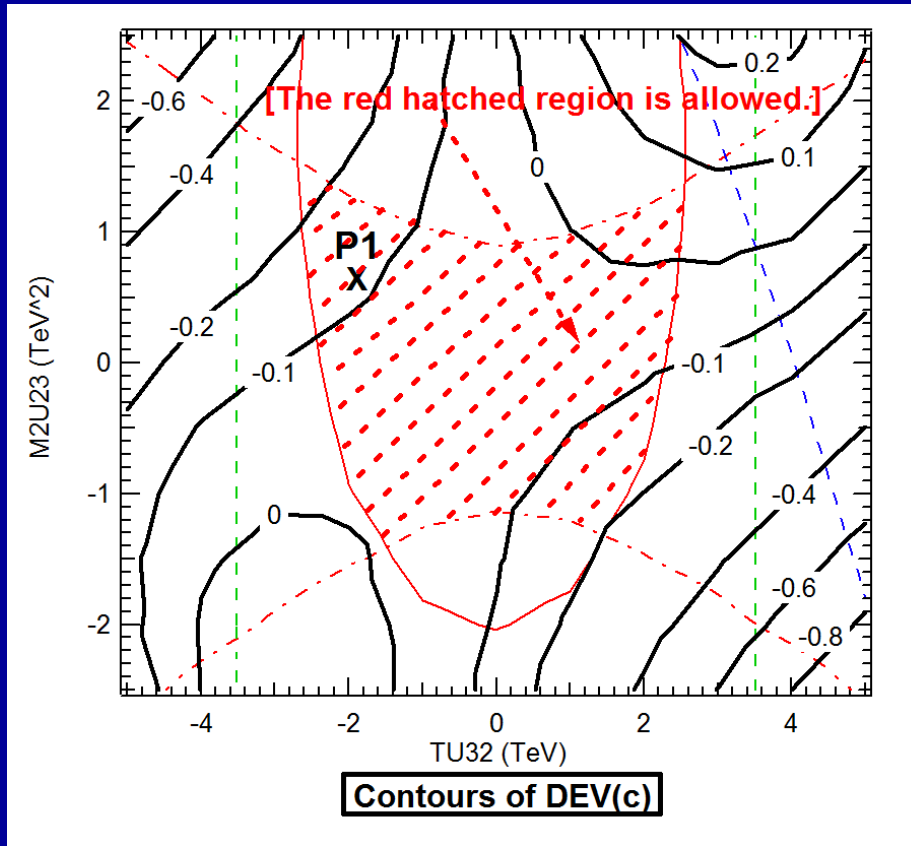
m_{h^0}	m_{H^0}	m_{A^0}	m_{H^+}
124	5325	5325	5359

$m_{\tilde{g}}$	$m_{\tilde{u}_1}$	$m_{\tilde{u}_2}$	$m_{\tilde{u}_3}$	$m_{\tilde{u}_4}$	$m_{\tilde{u}_5}$	$m_{\tilde{u}_6}$
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

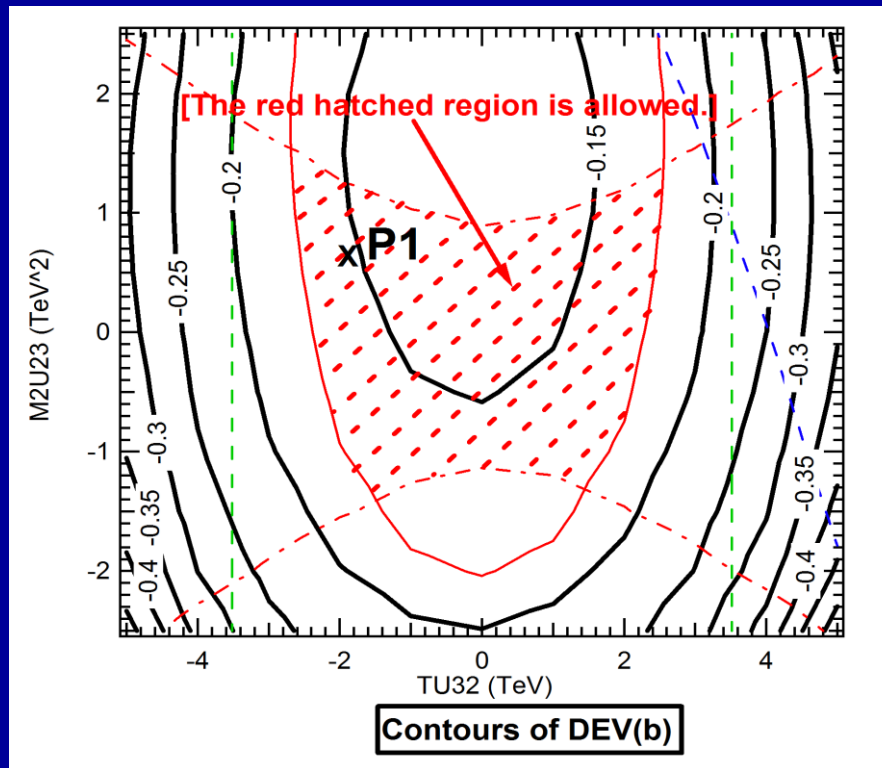
$m_{\tilde{\nu}_1}$	$m_{\tilde{\nu}_2}$	$m_{\tilde{\nu}_3}$	$m_{\tilde{l}_1}$	$m_{\tilde{l}_2}$	$m_{\tilde{l}_3}$	$m_{\tilde{l}_4}$	$m_{\tilde{l}_5}$	$m_{\tilde{l}_6}$
1509	1509	1528	1489	1489	1509	1512	1512	1545

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 the 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 the sizable region allowed by all the constraints **including the expected sparticle mass limits from the future HL-LHC experiment!**
- For $DEV(g)$ and $DEV(\gamma)$ we have obtained similar results to those for $DEV(c)$ and $DEV(b)$.
- We have also found that $BR(h^0 \rightarrow b s)$ is sizable ($\sim 0.1\%$) in the allowed region of this plane.

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 the systematic MSSM parameter scan respecting all of the relevant theoretical and experimental constraints.*

- *In strong contrast to the usual studies in the MSSM with quark flavor conservation, we have found that the deviations of these MSSM decay widths from the SM values can be quite sizable in the MSSM with general QFV.*

- *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

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

2. Key parameters of MSSM

Key parameters in this study are:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Constraints on the MSSM parameters from W boson mass data:

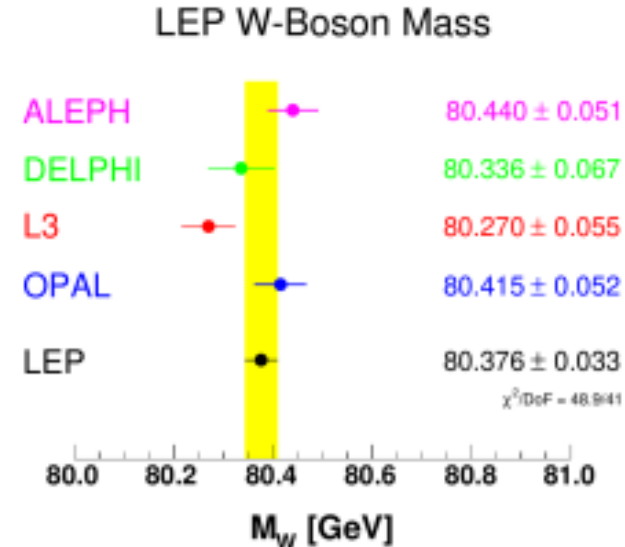
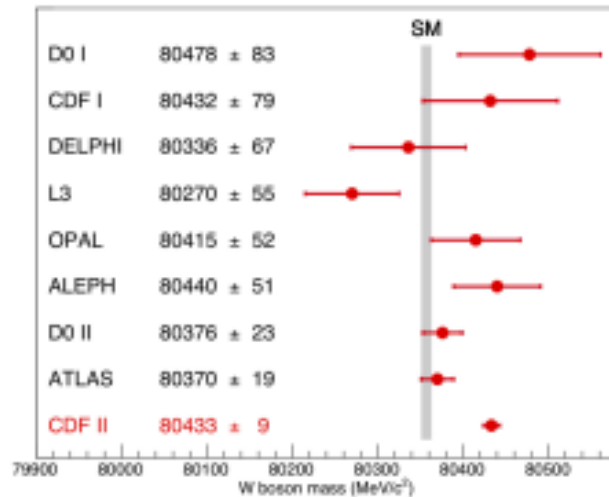
The recent m_W data from CDF II [1] is quite inconsistent with the other experimental data. (-> See next slides.)

[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?

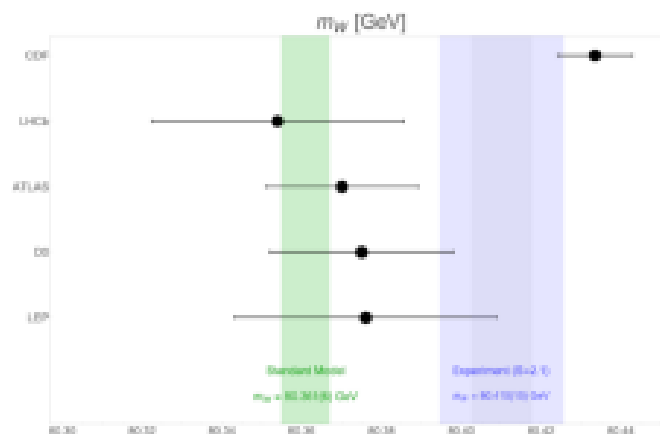
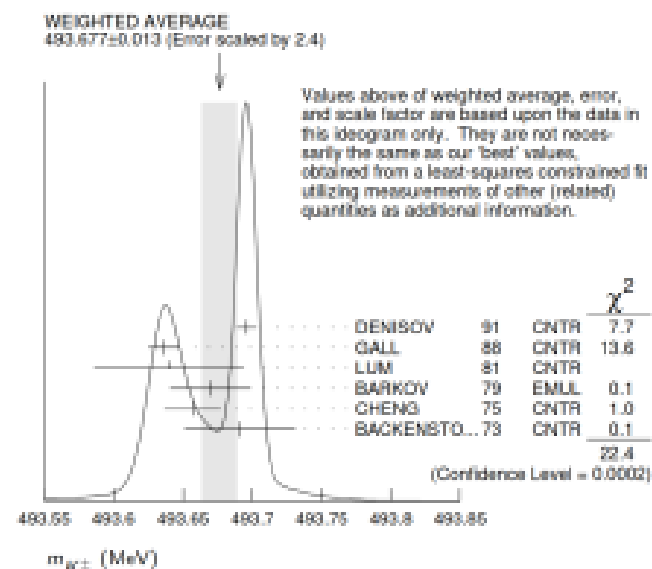


- The LEP results are based on 42 separate measurements with a **healthy** χ^2 .
- The LEP-combined (33 MeV), LHCb (32 MeV), D0 Run II (23 MeV), ATLAS (19 MeV) and CDF Run II (9.4 MeV) measurements have a $\chi^2/\text{DoF} = 17.1/4$, with p-value of **0.2%** for compatibility (neglecting correlations).
- 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

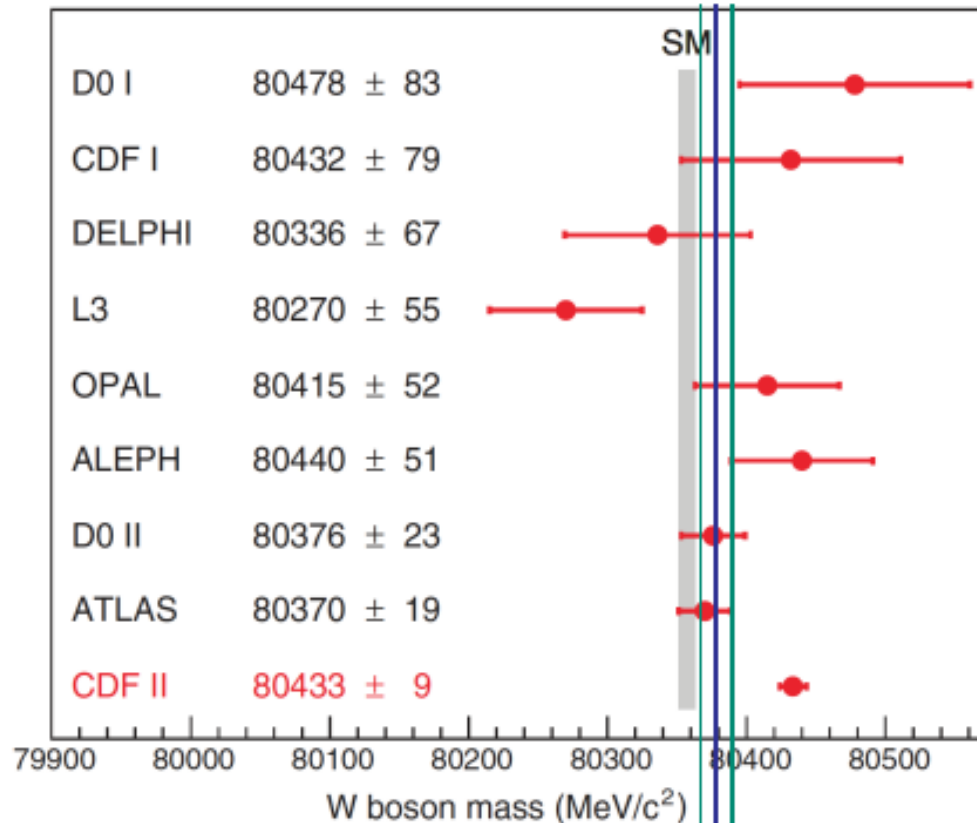
The charged kaon mass has been in this scale-factored state for 30 years!

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!

1. Introduction: the mass of the W -boson

[CDF '22]

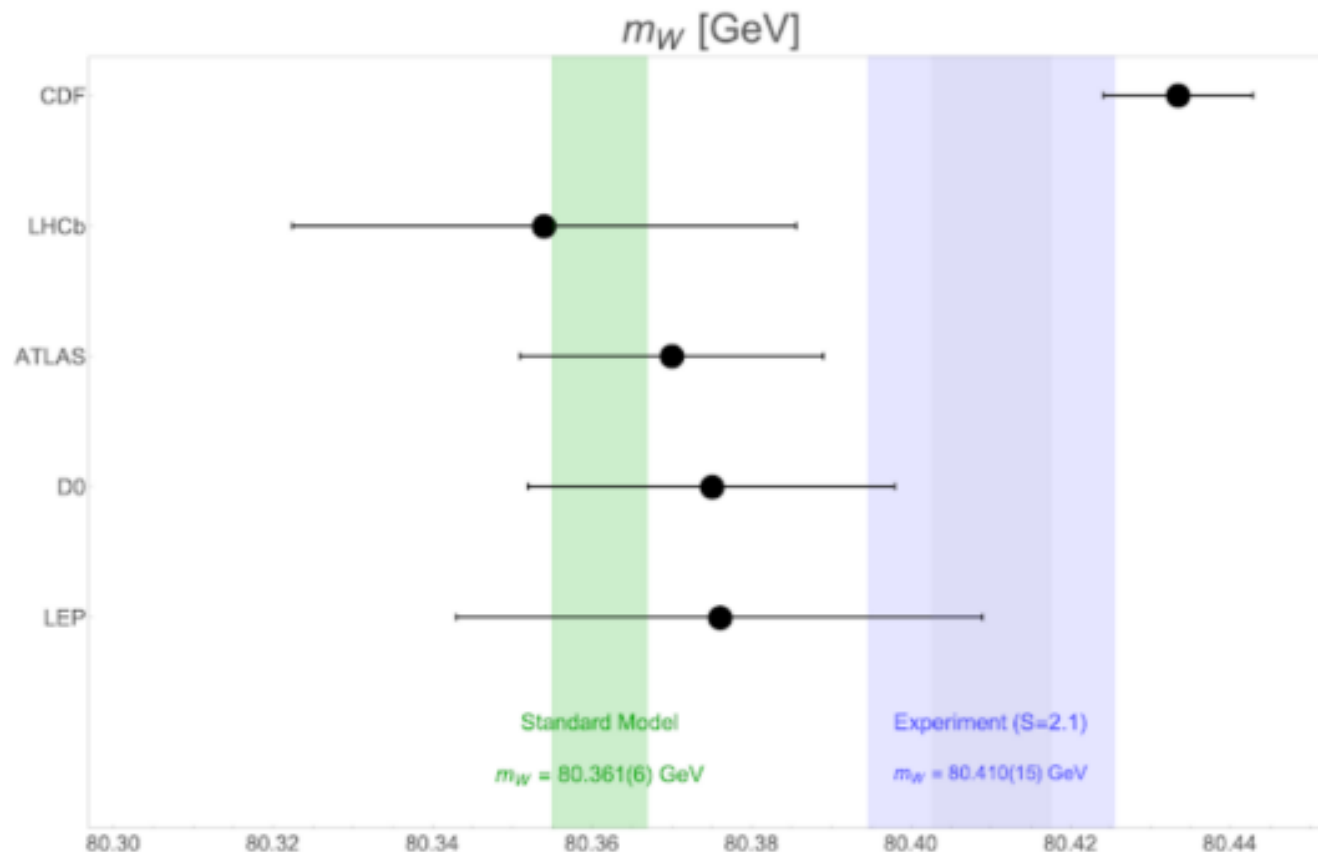


⇒ large discrepancy with the SM prediction

⇒ large discrepancy with other measurements: $M_W^{\text{PDG}} = 80379 \pm 12 \text{ MeV}$

Approximation for a new world average:

[A. Falkowski '22]



⇒ approximation yields $M_W^{\text{approx-av.}} = 80410 \pm 15 \text{ MeV} \sim 3\sigma$

⇒ enlarged uncertainty because of "bad agreement" between older and new measurements ⇒ PDG prescription

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

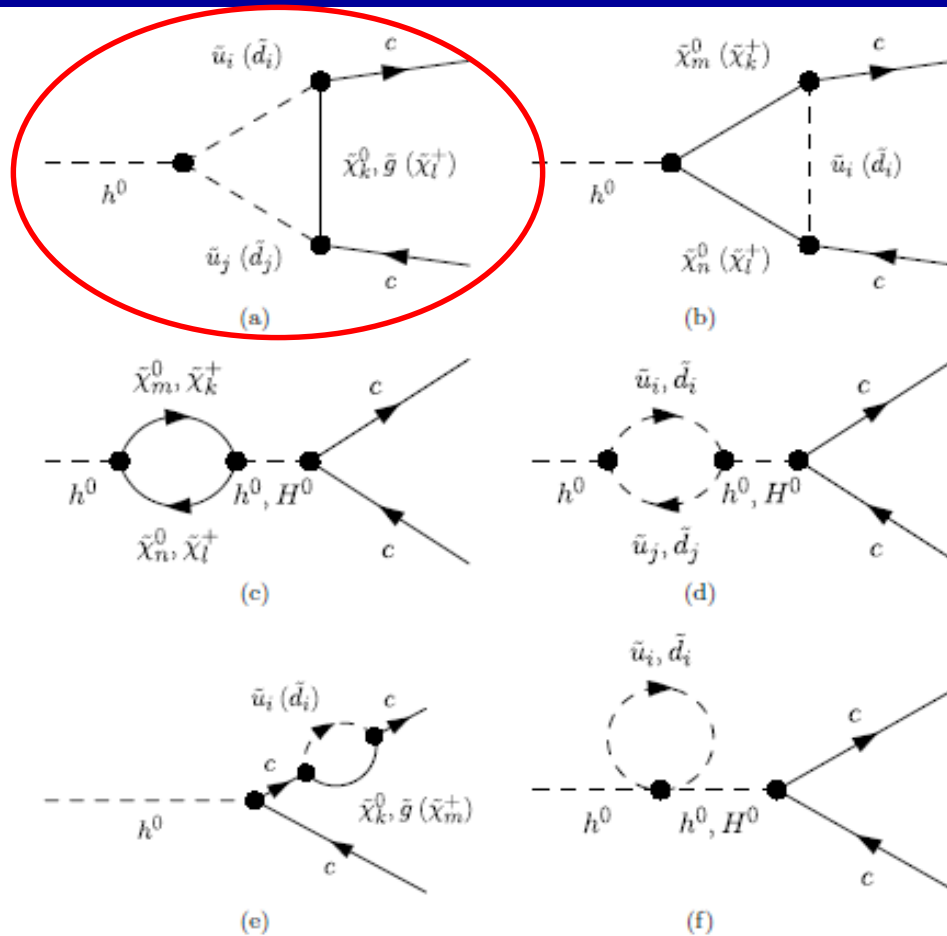


Figure 2: The main one-loop contributions with SUSY particles in $h^0 \rightarrow c \bar{c}$. The corresponding diagram to (e) with the self-energy contribution to the other charm quark is not shown explicitly.

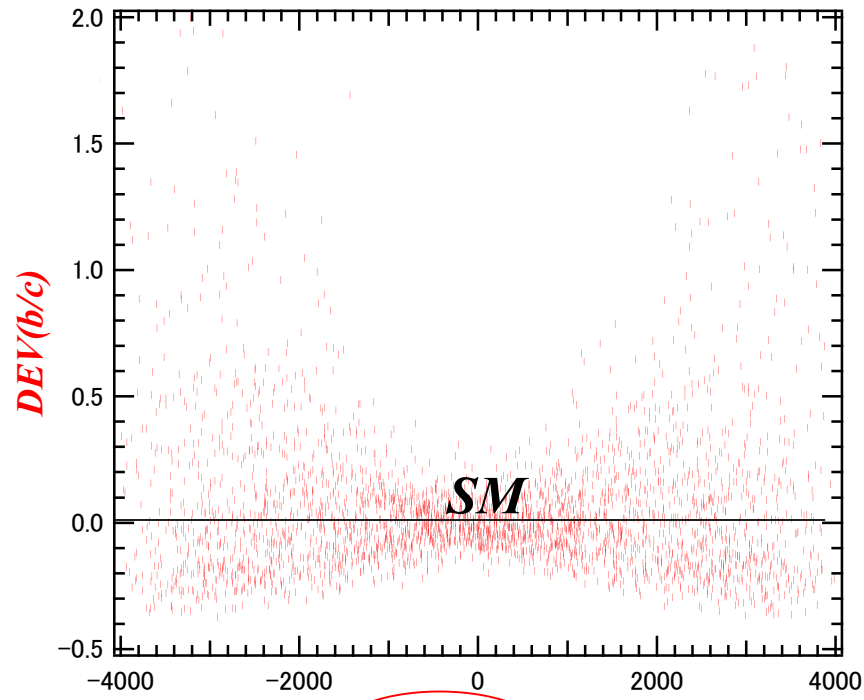
5.2 Deviation of width ratio from the SM prediction

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

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

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

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



T_{U32} (GeV)

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

- There is a strong correlation between $T_{U32} - DEV(b/c)$!
- $DEV(b/c)$ can exceed $\sim +100\%$ for large T_{U32} !

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

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

$BR(h^0 \rightarrow b \bar{s} / s \bar{b})$ can be as large as $\sim 0.2\%$ (MSSM with QFV)!

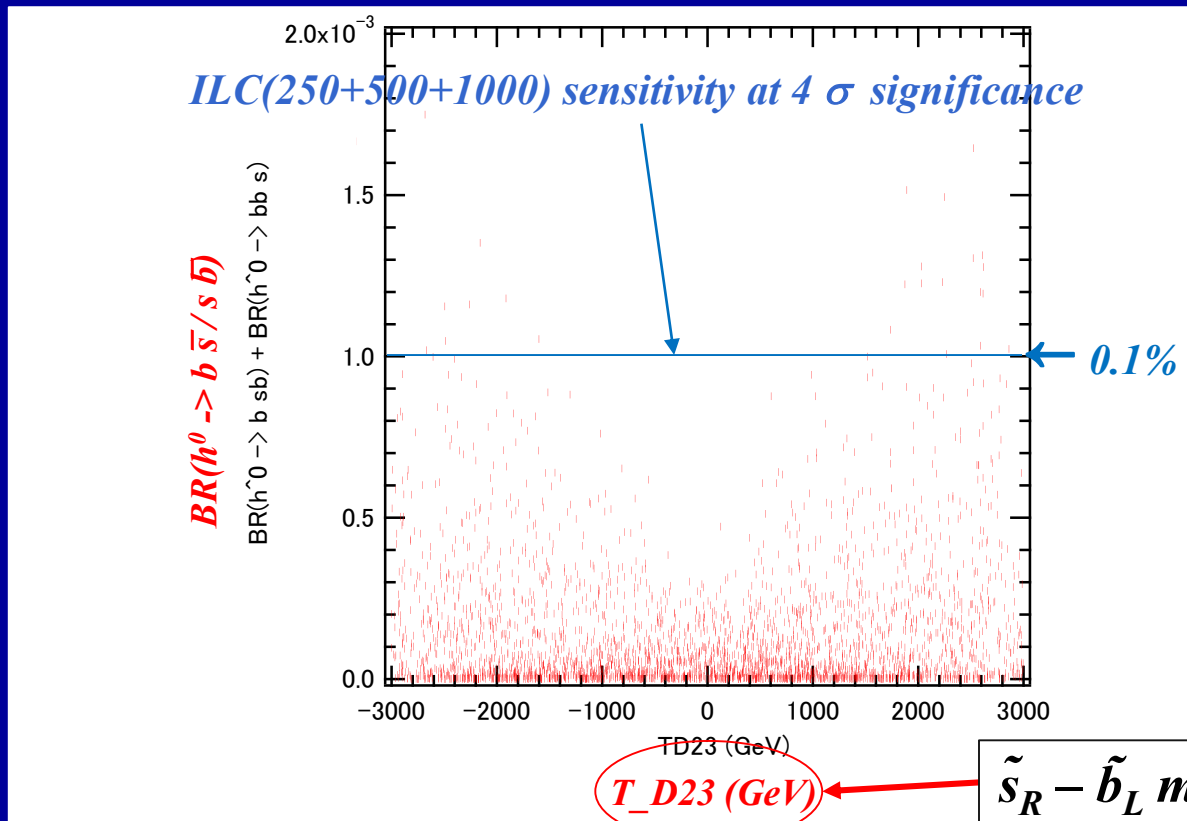
(See also Gomez-Heinemeyer-Rehman, PR D93 (2016) 095021 [arXiv:1511.04342].)

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

Private communication with Junping Tian;

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

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

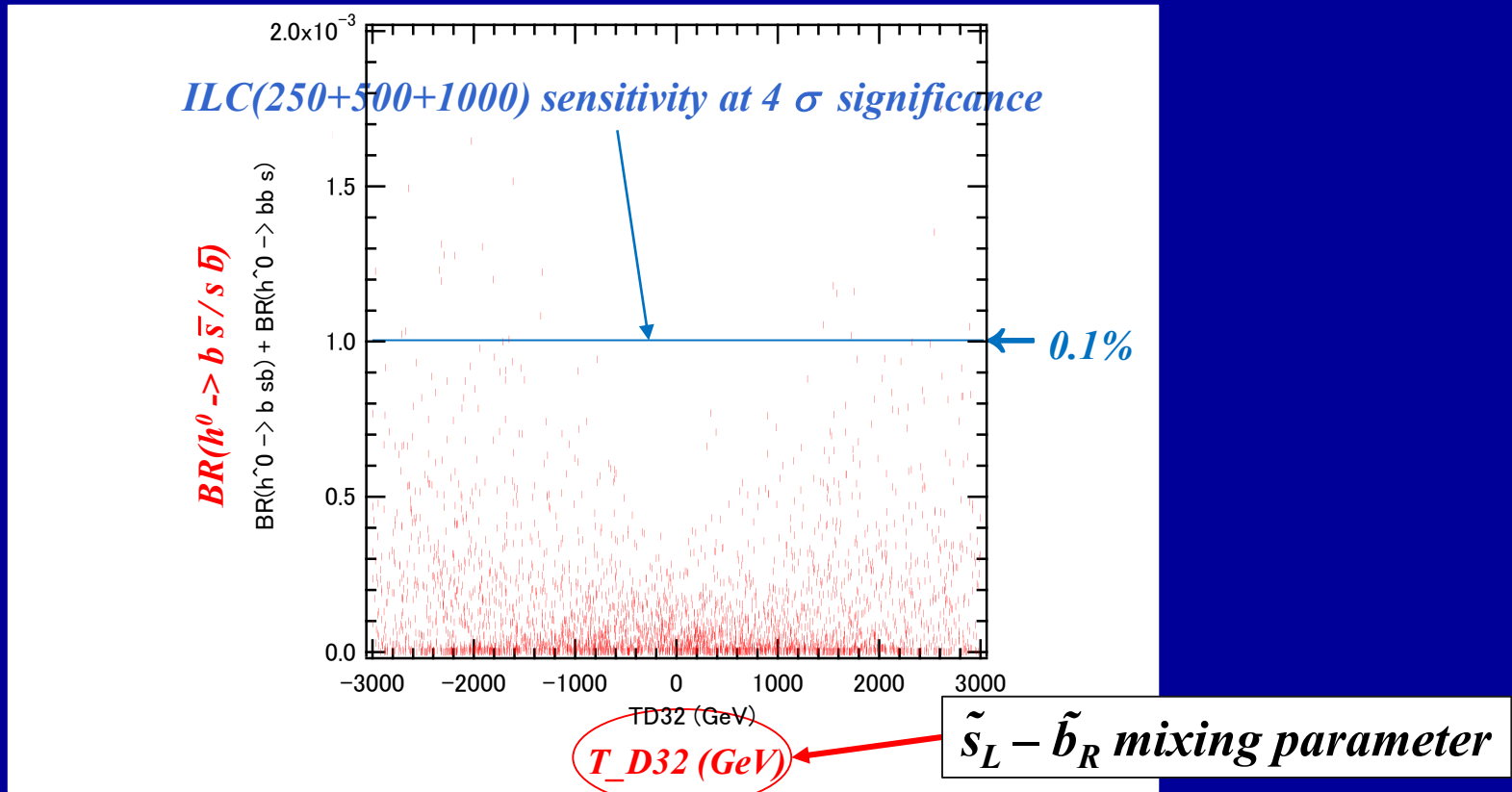


- There is a strong correlation between $T_{D23} - BR(h^0 \rightarrow b \bar{s} / s \bar{b})$!
- $BR(h^0 \rightarrow b \bar{s} / s \bar{b})$ can be as large as **0.2%** for large T_{D23} !
- **$ILC(250 + 500 + 1000)$ sensitivity could be $\sim 0.1\%$ at 4 sigma significance!**

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

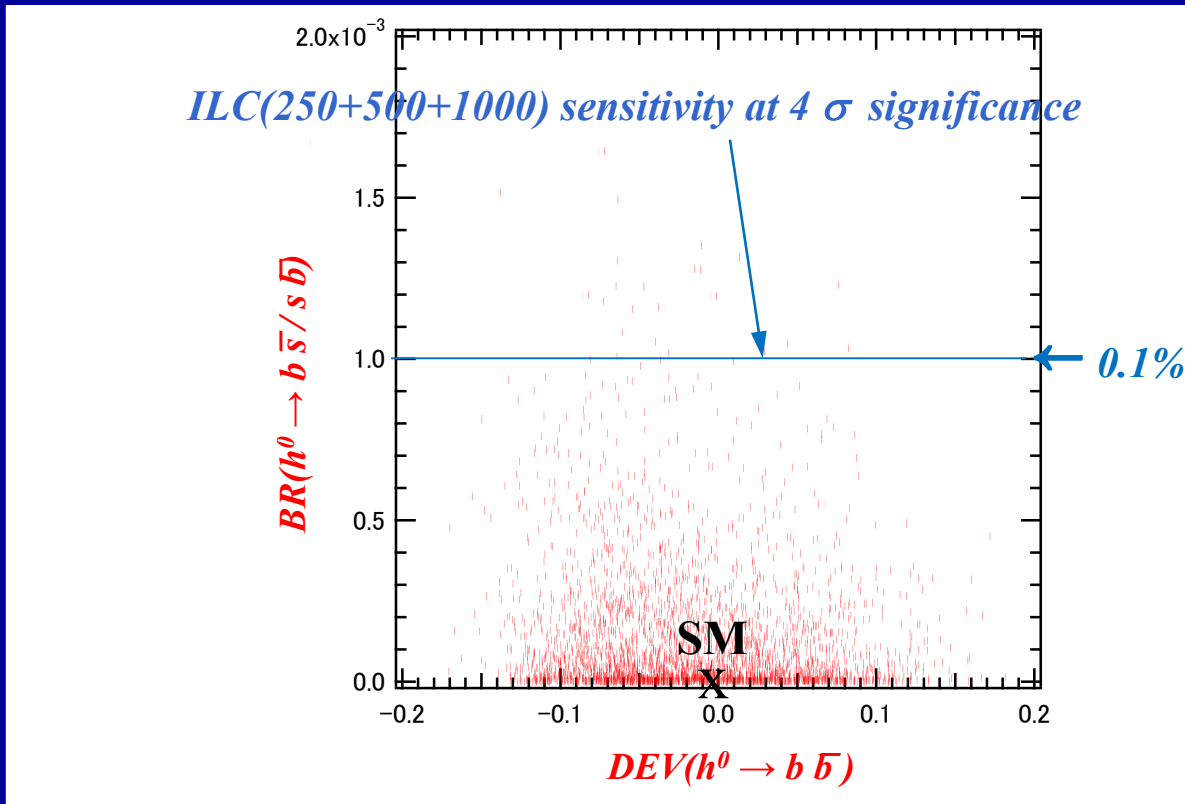
- LHC & HL-LHC sensitivity should not be so good due to huge QCD BG!

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



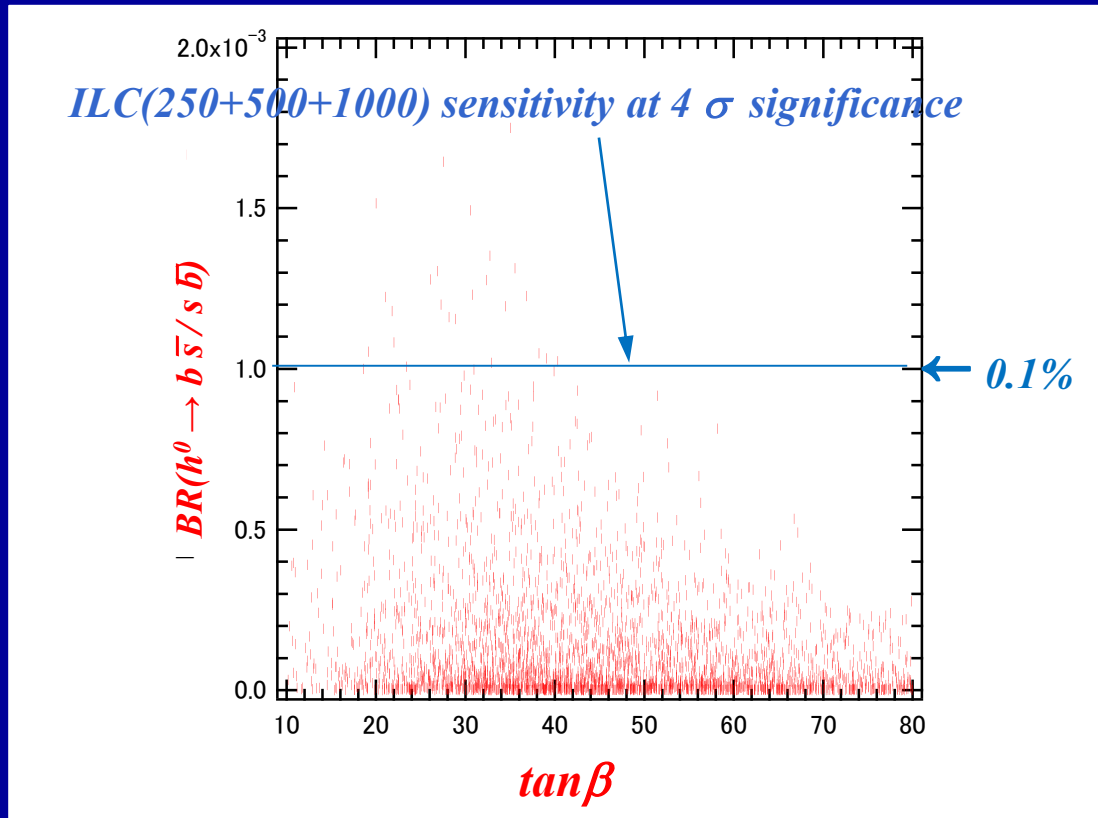
- There is also a strong correlation between $T_{D32} - BR(h^0 \rightarrow b \bar{s} / s \bar{b})$!
- $BR(h^0 \rightarrow b \bar{s} / s \bar{b})$ can be as large as 0.2% for large T_{D32} !

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



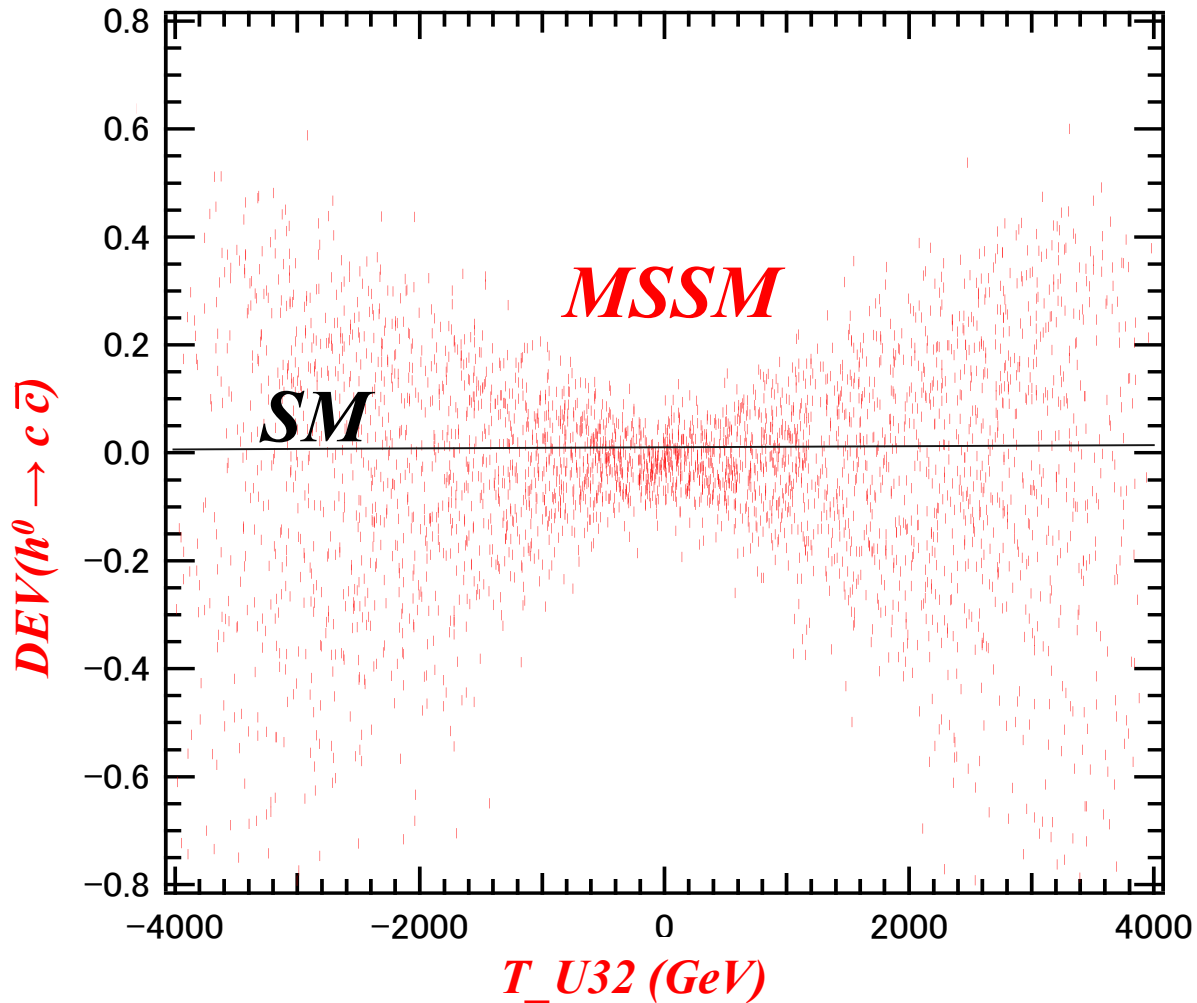
- *There is a strong correlation between $DEV(h^0 \rightarrow b \bar{b})$ & $BR(h^0 \rightarrow b \bar{s} / s \bar{b})$!*
- *This is due to the fact that $DEV(h^0 \rightarrow b \bar{b})$ & $BR(h^0 \rightarrow b \bar{s} / s \bar{b})$ have a common origin of enhancement effect, i.e. large trilinear couplings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

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



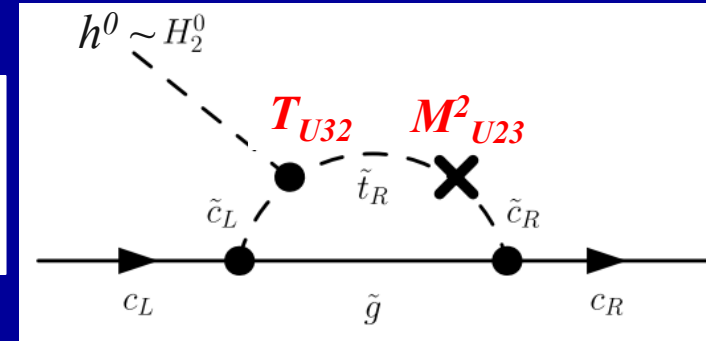
- There is a strong correlation between $BR(h^0 \rightarrow b \bar{s} / s \bar{b})$ & $\tan\beta$!
- $BR(h^0 \rightarrow b \bar{s} / s \bar{b})$ can be as large as 0.2% for $\tan\beta \sim 30$!

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 $T_{U32} * M^2_{U23}$!



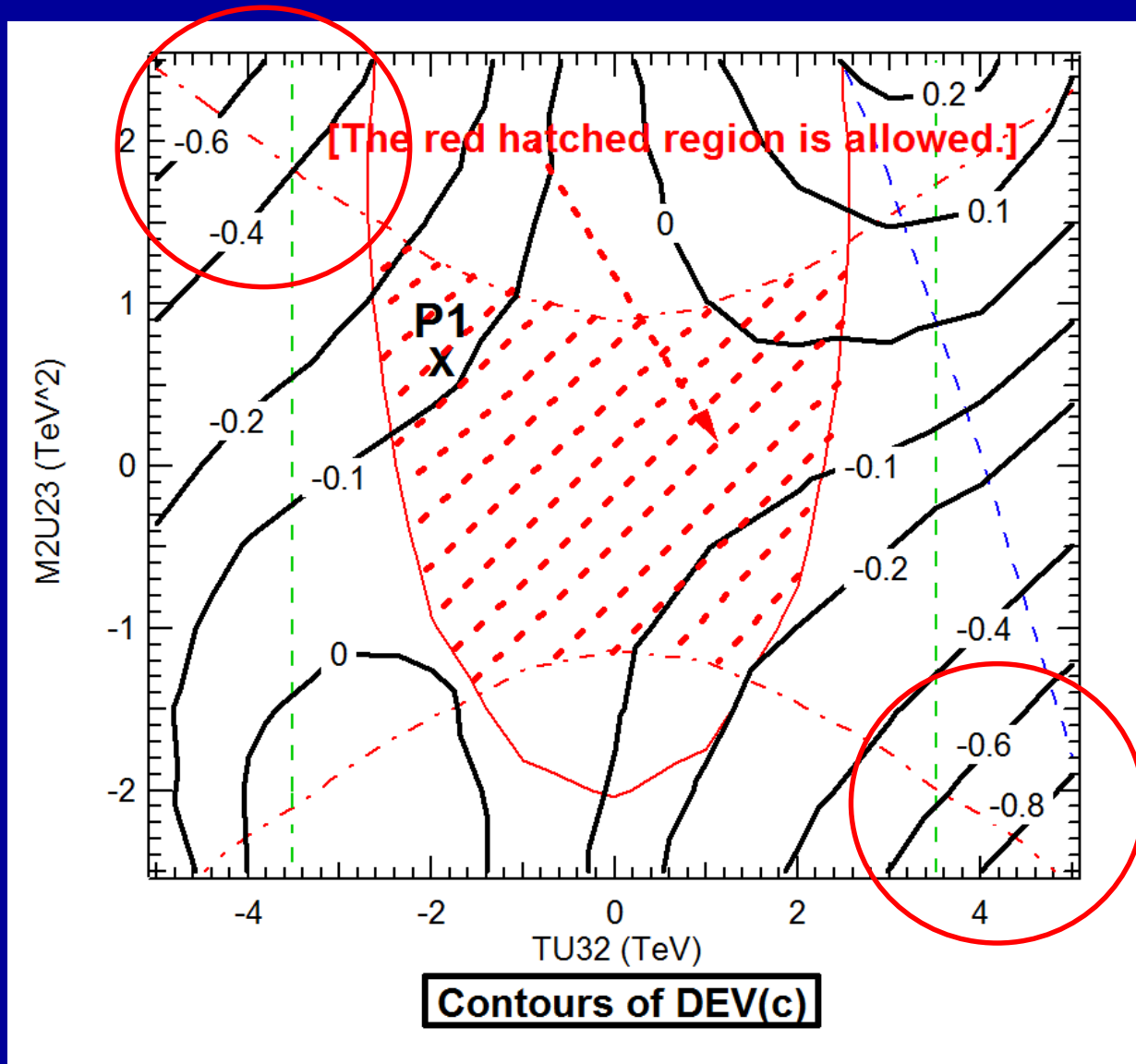
The interference term between the tree diagram and the gluino one-loop diagram can be very large (positive and negative) for large $T_{U32} * M^2_{U23}$, which can lead to even **NEGATIVE** width $\Gamma(h^0 \rightarrow c \bar{c})$ at one-loop level!

In this case perturbation theory breaks down!

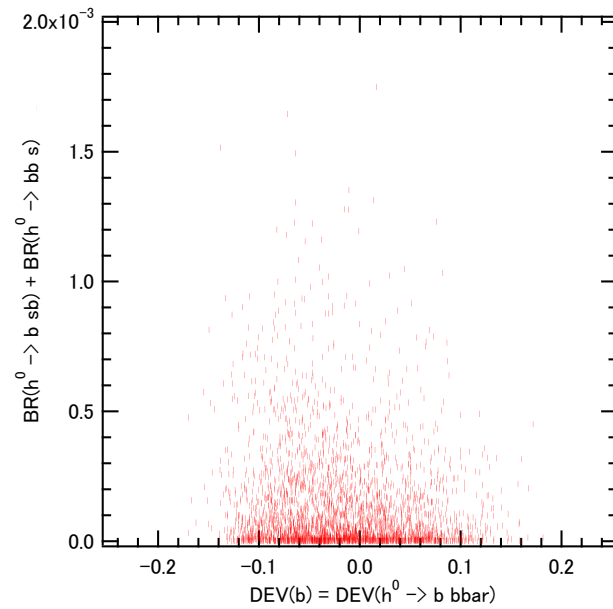
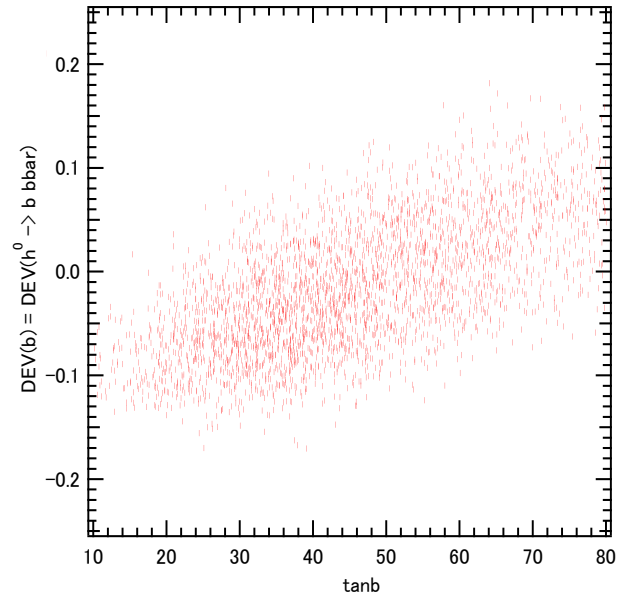
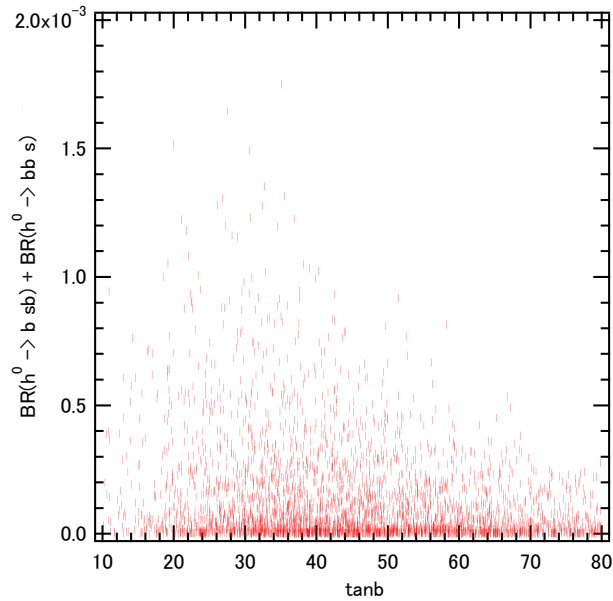
A large deviation of $\Gamma(h^0 \rightarrow c \bar{c})$ from the SM value is in principle possible due to large values of the product $T_{U32} * M^2_{U23}$.

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



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



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

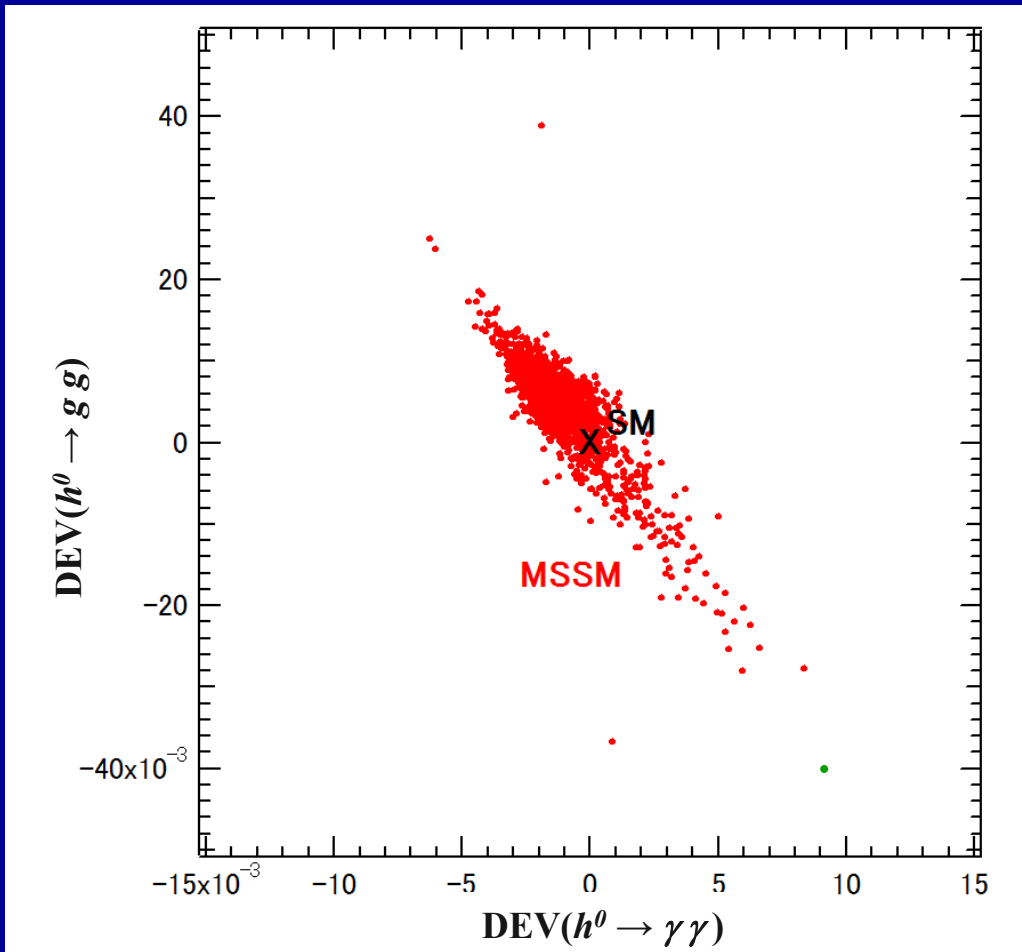
*As for $\Gamma(h^0 \rightarrow b \bar{b})$ & $\Gamma(h^0 \rightarrow b \bar{s} / s \bar{b})$, we have considered the large $\tan\beta$ enhancement and the resummation of the bottom Yukawa coupling [1]. It turns out, however, that in our case with large m_A close to the decoupling Higgs limit, the **resummation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

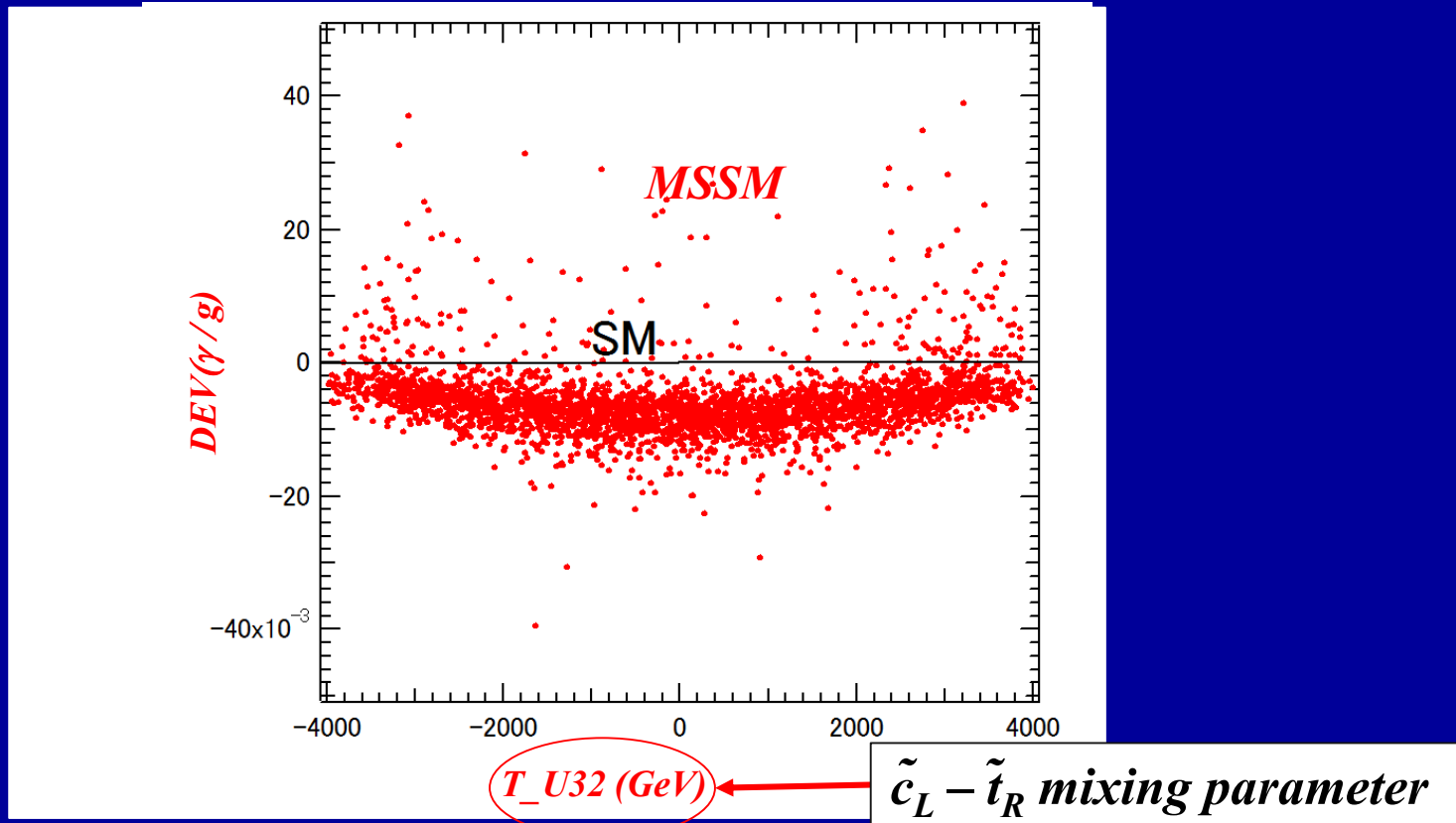
E. Ginina, A. Bartl, H. Eberl, K. Hidaka and W. Majerotto, PoS(EPS-HEP2015)146 [arXiv:1510.03714 [hep-ph]].

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



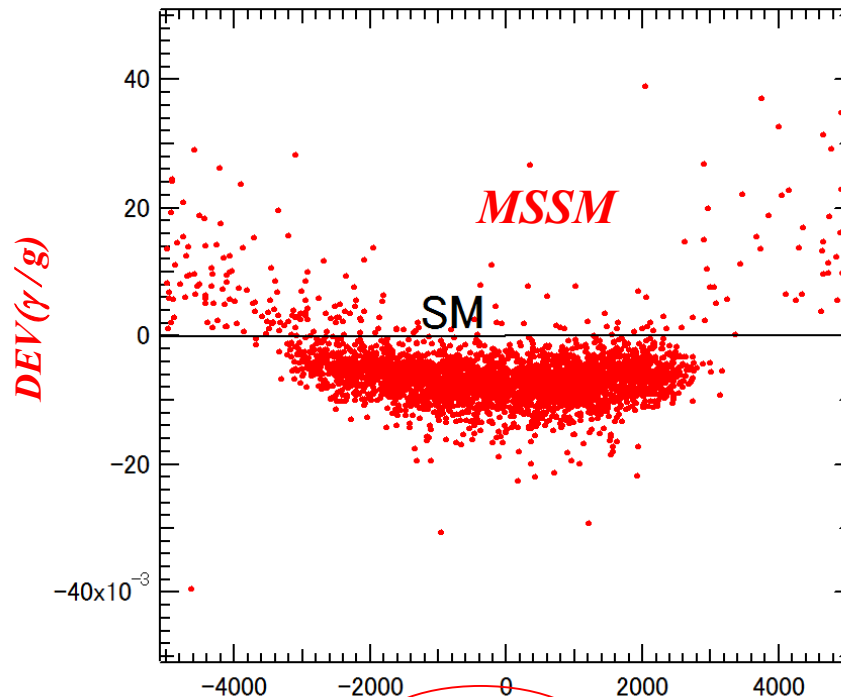
- $\text{DEV}(h^0 \rightarrow \gamma\gamma)$ and $\text{DEV}(h^0 \rightarrow gg)$ can be sizable simultaneously!
- There is a strong correlation between $\text{DEV}(h^0 \rightarrow \gamma\gamma)$ and $\text{DEV}(h^0 \rightarrow gg)$!
- Future lepton colliders such as ILC can observe such sizable deviations from SM!
(See arXiv:1908.11299 and Backup slides)

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} !

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 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 $\sim 0.2\%$!*

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 $\sim \pm 5\%$.

* 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 QFV)!

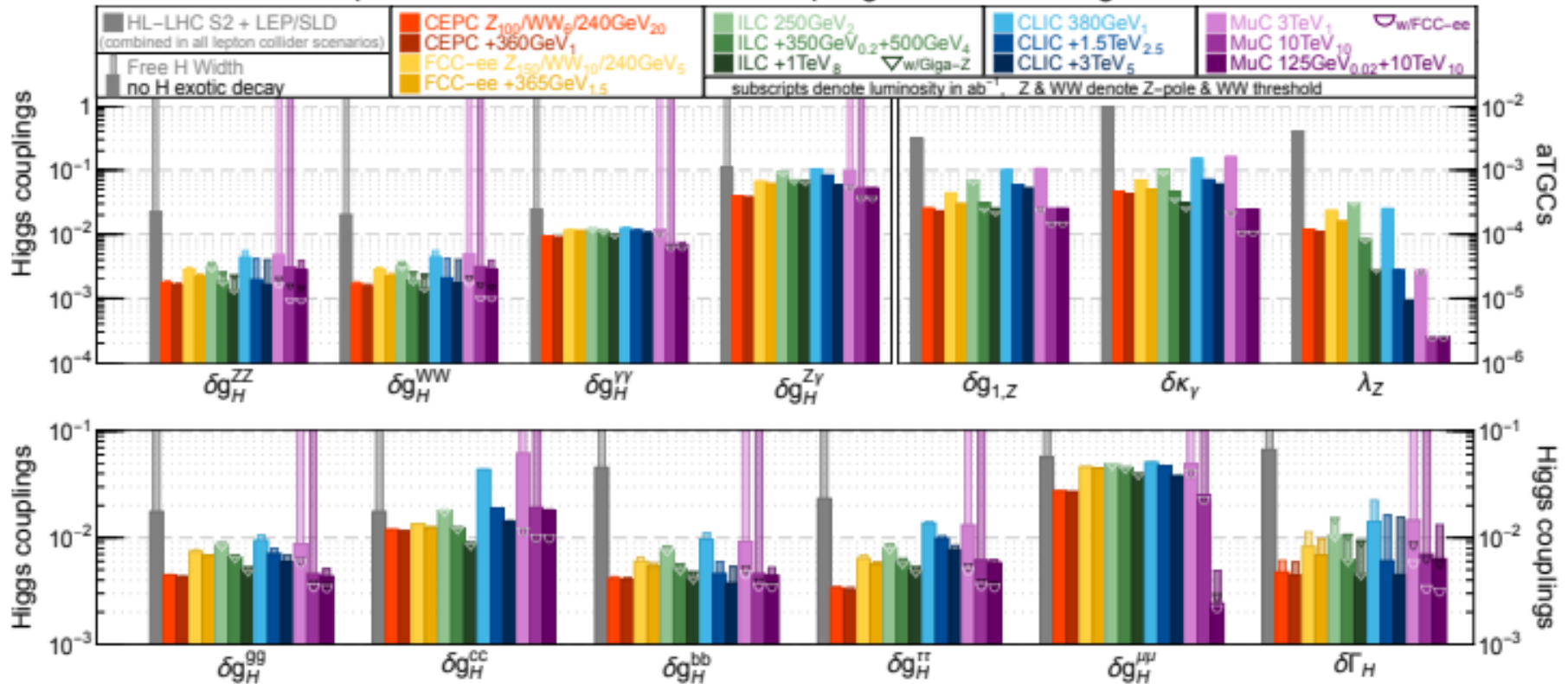
Higgs couplings at future colliders

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

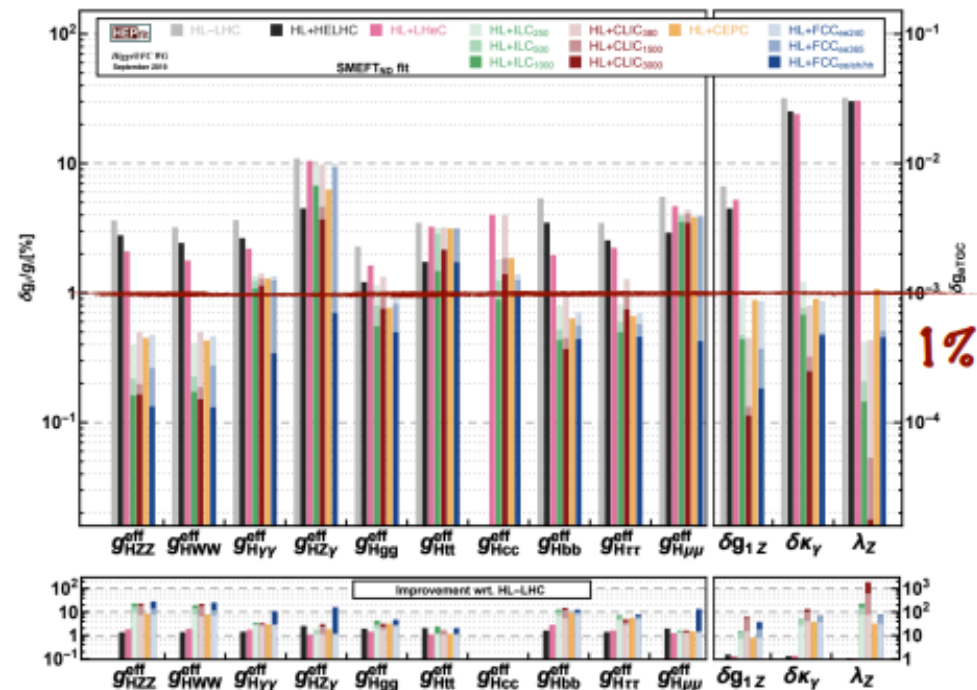
Higgs coupling precision in % at future colliders

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

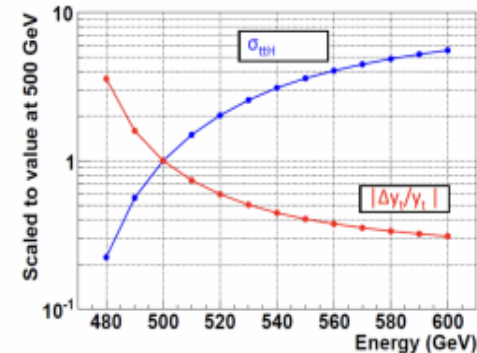
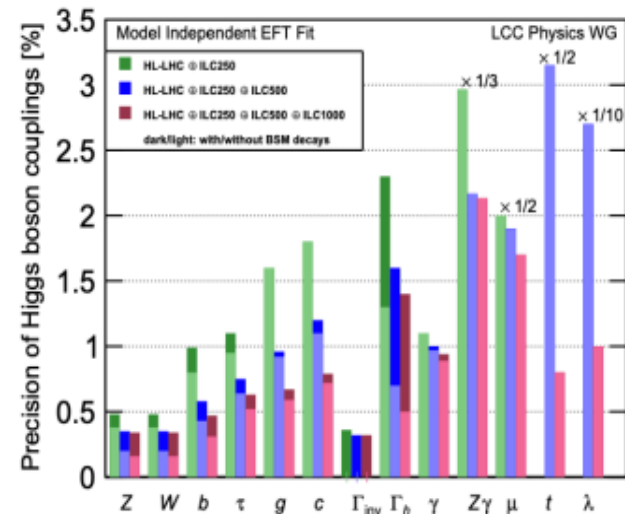
arXiv:1908.11299

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 C³ would run at 550 GeV, a factor 2 improvement to the top-Yukawa coupling (*)



DEV error - coupling error relation

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

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

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