Imprint of quark flavor violating SUSY in h(125) decay width ratios at future lepton colliders

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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]]
ILC White Paper for Snowmass 2021 [arXiv:2203.07622]
PoS(ICHEP2022) 536, 2022 [arXiv:2211.07243 [hep-ph]]

EPS-HEP2023, 21-25 Aug. 2023, Hamburg, Germany

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

1. Introduction

- *What is the SM-like Higgs boson discovered at LHC?*

- *It can be the SM Higgs boson.*

- *It can be a Higgs boson of New Physics.*

- *This is one of the most important issues in the present particle physics field!*

- *Here we study a possibility that it is the lightest Higgs boson h^0 of the Minimal Supersymmetric Standard Model (MSSM), focusing on the widths & width ratios of the decays $h^0(125) \to c\,\bar{c}$, $b\,\bar{b}$, $\gamma\gamma$, $g\,g$*

  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 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.

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

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

121.6 GeV < m_h^0 < 128.6 GeV (allowing for theoretical uncertainty) ,

$0.71 < \kappa_b < 1.43$ (ATLAS), $0.56 < \kappa_b < 1.70$ (CMS)

(5) The experimental limit on SUSY contributions to the electroweak ρ parameter

$\Delta\rho$ (SUSY) < 0.0012.

(6) Theoretical constraints from the vacuum stability conditions for the trilinear couplings $T_{U\alpha\beta}$ and $T_{D\alpha\beta}$.

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

** 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 accont this m_W constraint on the MSSM parameters in our analysis.

** Constraint from muon g-2:*

- Tension btw the new Fermilab/BNL muon g-2 data [1] and the SM prediction is ~ 4.2 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 CDM-3 data [3] supports the SM prediction with lattice QCD!

[1] Muon g-2 Collaboration, Phys. Rev. Lett. 126 (2021) 141801 [arXiv:2104.03281[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 - > b s):*

The current best experimental upper limit on B(Z - > b s) can not give any significant constraint on the sstrange-sbottom and scharm -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 -> b s) is listed in PDG2022 .

4. Parameter scan

- *We compute the $h^0(125)$ decay widths in the MSSM with QFV.*

- *We take parameter scan ranges as follows:*

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

$10 < \tan\beta < 80$

$2500 < M_3 < 5000\ GeV$

$100 < M_2 < 2500\ GeV$

$100 < M_1 < 2500\ GeV$

$100 < \mu < 2500\ GeV$

$1350 < m_A(pole) < 6000\ GeV$

etc. etc.

- *In the parameter scan, all of the relevant experimental and theoretical constraints are imposed.*

- *377180 parameter points are generated and 3208 points survive the constraints.*

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

- *We compute the decay widths $\Gamma(h^0 \rightarrow c\,\bar{c})$, $\Gamma(h^0 \rightarrow b\,\bar{b})$, 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 $h^0 \rightarrow b\,\bar{b}$:*

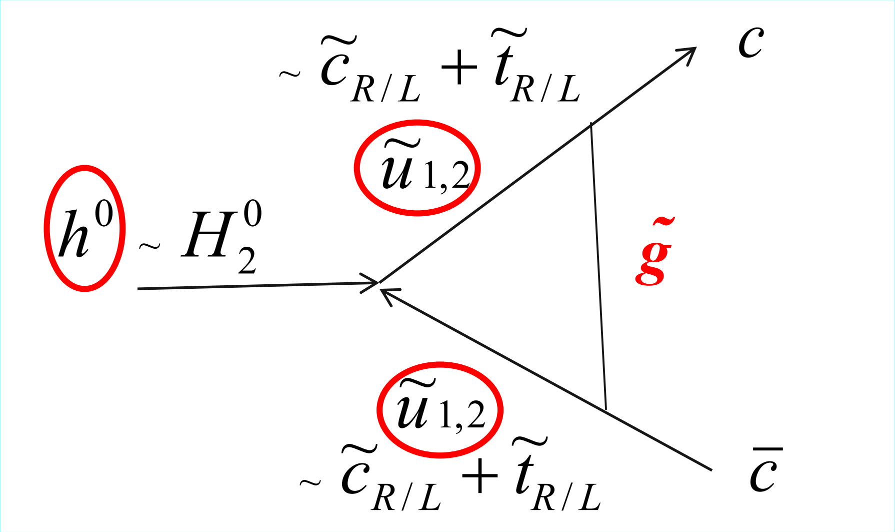
  gluino – sd loops [sd = ($\tilde{b}$ - $\tilde{s}$ mixture)]
  can be enhanced by large trilinear couplings T_{D23} , T_{D32} , T_{D33}

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

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

$h^0 \sim H_2^0$

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



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

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

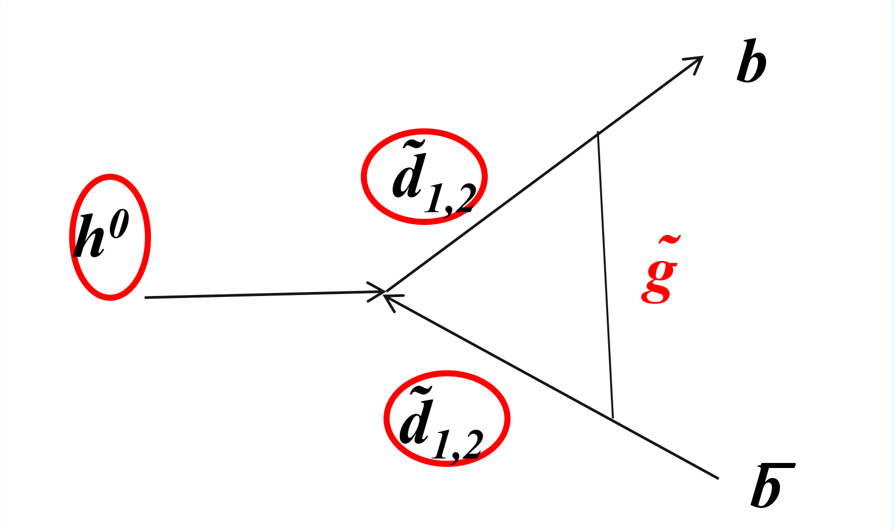
Gluino loop contributions can be large!

Deviation of $\Gamma(h^0 \to c\,\bar{c})$ 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!*

Gluino loop contributions can be sizable!

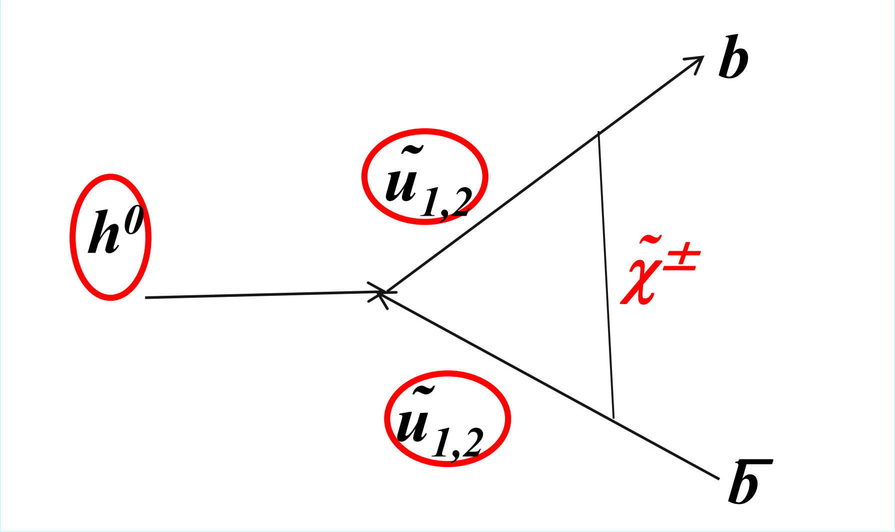
Deviation of $\Gamma(h^0 \to b\,\bar{b}/\bar{s})$ *from SM width can be sizable!*

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 $\Gamma(h^0 \to b\,\overline{b/s})$ from SM width can be large!

5.1 Deviation of the width from the SM prediction

- Deviation of the width from the SM prediction:

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

$X = c, b$

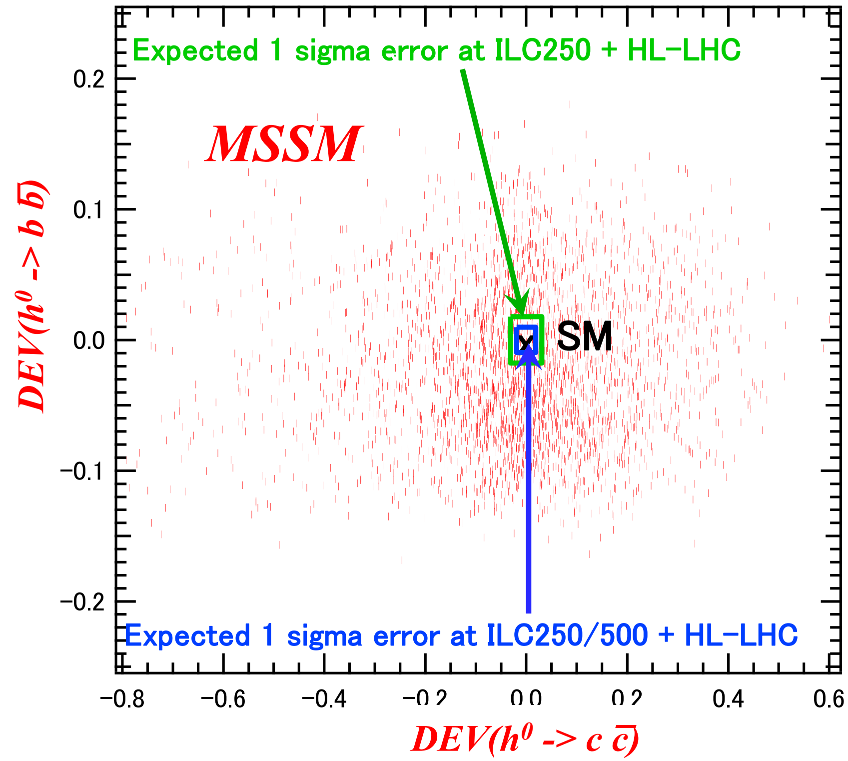
- Coupling modifier:

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

- DEV - κ_X relation:

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

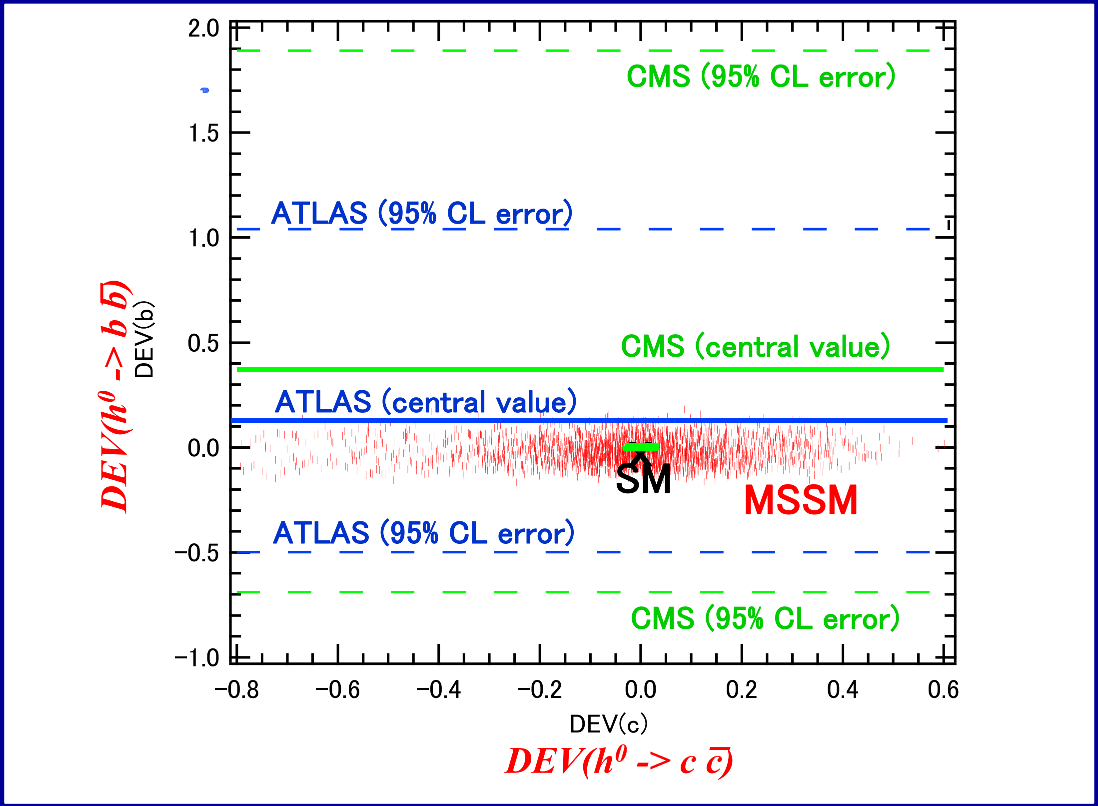
Scatter plot in $DEV(h^0 \to c\,\bar{c})$ - $DEV(h^0 \to b\,\bar{b})$ plane



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

- *ILC can observe such large deviations from SM at high significance (arXiv:2206.08326)!:*
  $\Delta\, DEV(h^0 \to c\,\bar{c})$ = (3.6%, 2.4%, 1.8%) at (ILC250, ILC250/500, ILC250/500/1000)
  $\Delta\, DEV(h^0 \to b\,\bar{b})$ = (1.7%, 1.1%, 0.9%) at (ILC250, ILC250/500, ILC250/500/1000)

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



$$DEV(h^0 \to X\,X) = \kappa_X^{\,2} - 1$$

- *Recent LHC data*:

  $DEV(h^0 \to b\,\bar{b}) = 0.12 + 0.92/-0.62 = [-0.50, 1.04]$ *(ATLA S) (arXiv:1909.02845)*

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

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

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

5.2 Deviation of width ratio from the SM prediction

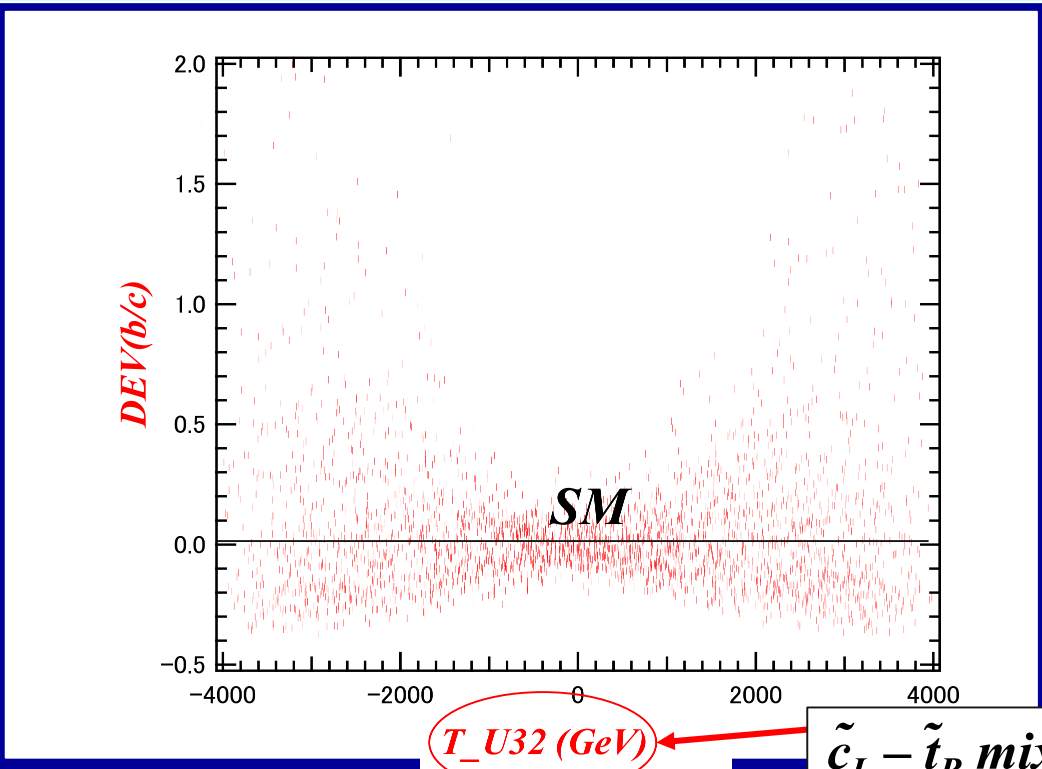
- The deviation of the width ratio from the SM prediction:

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

$$\Gamma(X) = \Gamma(h^0 \text{->} X \bar{X})$$

- 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



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

- *There is a strong correlation between $T_{U32} - DEV(b/c)$!*
- *DEV(b/c) can exceed ~ +100% for large T_{U32} !*
- *Expected absolute 1 σ error of DEV(b/c) at ILC:*

  ΔDEV(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!**

6. $h^0 \to \gamma\gamma$, $g\,g$ 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 $\Gamma(h^0 \to \gamma\gamma)$ and $\Gamma(h^0 \to g\,g)$ at NLO QCD level in the MSSM with QFV.*

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

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

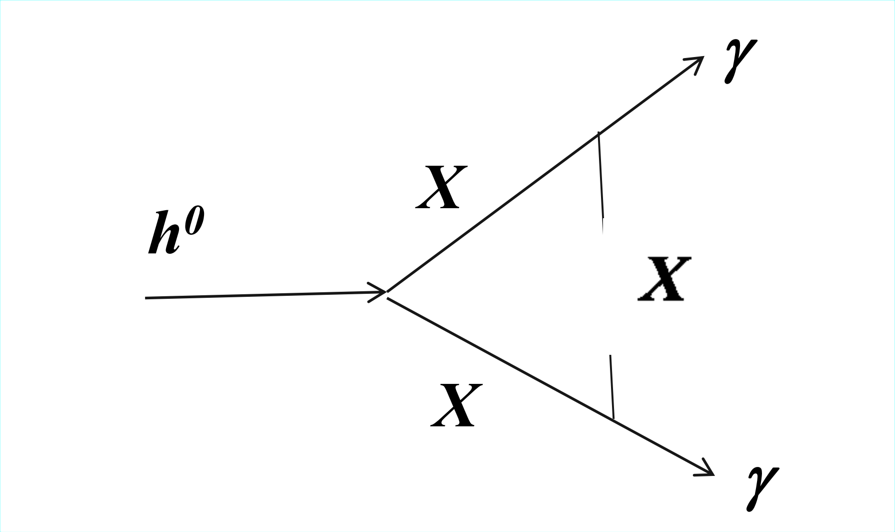
  The su-loops can be enhanced by large trilinear couplings T_{U23}, T_{U32}, T_{U33}, resulting in sizable deviation of $\Gamma(h^0 \to \gamma\gamma)$ from the SM width!

- *Main 1-loop contributions to $h^0 \to g\,g$:*

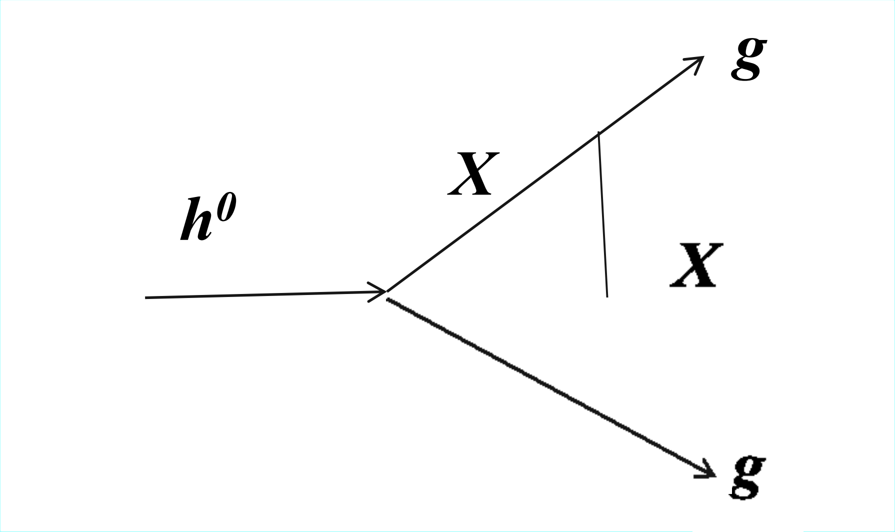
  [*top-quark / su*] *- loops* [*su = ($\tilde{t}$ - $\tilde{c}$ mixture)*]

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

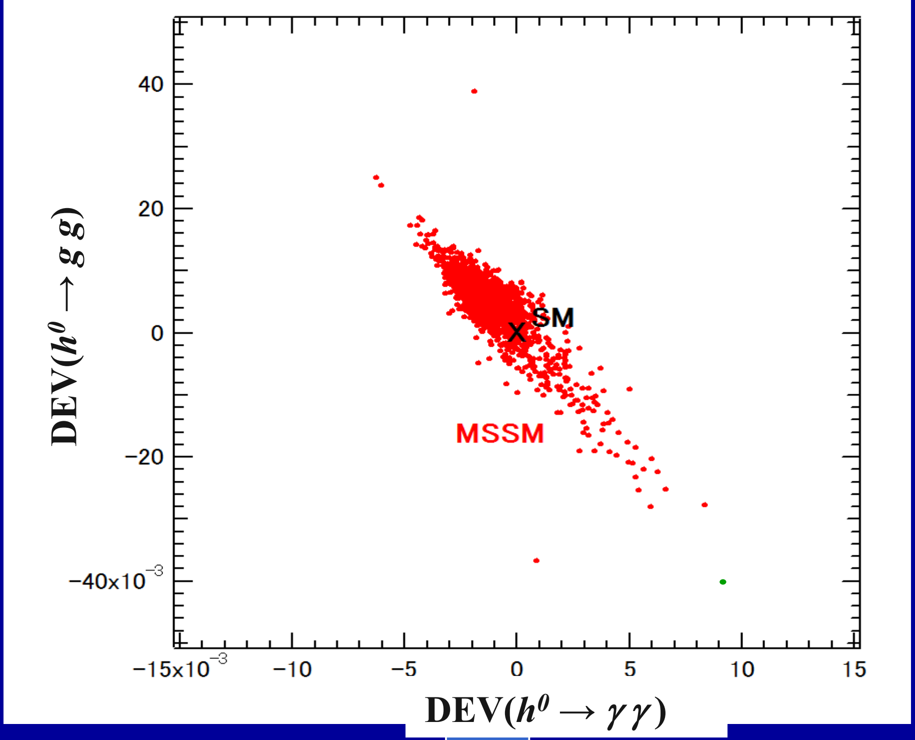
$$X = W^{+} / t / \tilde{u}_{1,2}$$



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



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



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

  DEV($h^0 \to \gamma\gamma$) *can be as large as* ~ *±1%*

  DEV($h^0 \to g\,g$) *can be as large as* ~ *±4%.*

-*Expected absolute 1 σ errors at (ILC250, ILC250+500, ILC250+500+1000):*

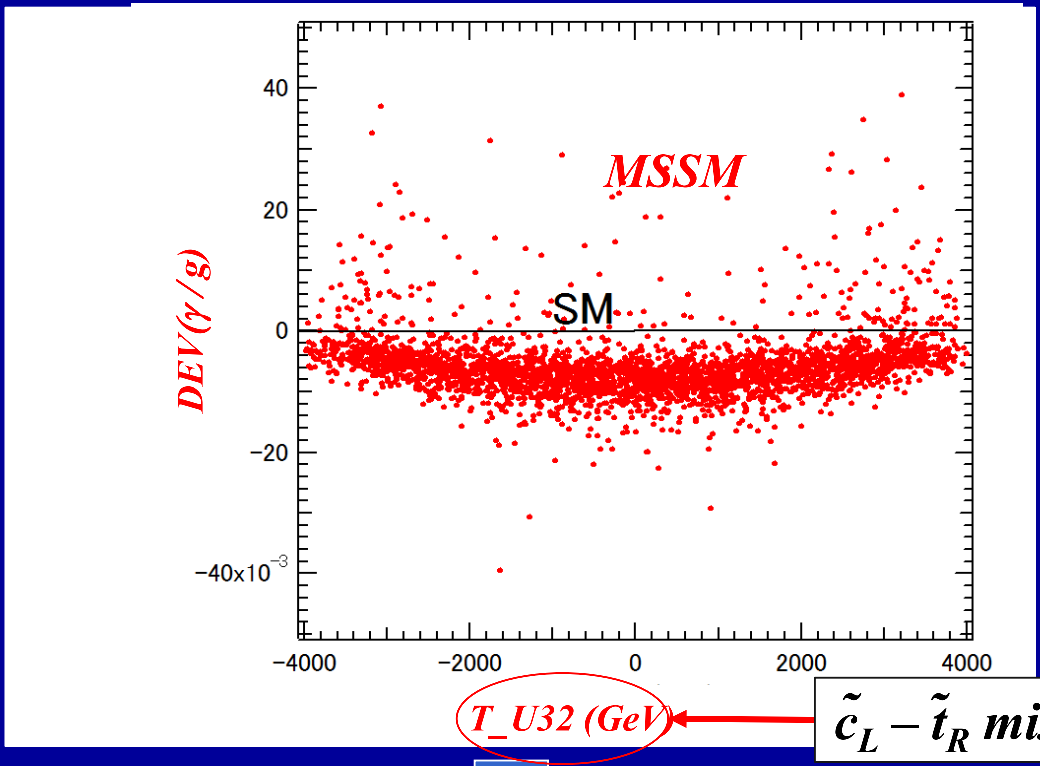
  Δ DEV($h^0 \to \gamma\gamma$) = (2.4%, 2.2%, 2.0%)

  Δ DEV($h^0 \to g\,g$) = (1.8%, 1.4%, 1.1%)

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

- **ILC can observe such sizable deviation DEV($h^0 \to g\,g$) at high significance!**

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



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

- ***There is a strong correlation between $T_{U32} - DEV(\gamma/g)$!***
- ***$DEV(\gamma/g)$ can be as large as $\sim +4\%$ 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.]

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

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^+} , tanβ) 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.*

Benchmark scenario P1

Table 2: The MSSM parameters for the reference point P1 (in units of GeV or GeV^2 expect for $\tan\beta$). All parameters are defined at scale Q = 1 TeV, except $m_A(pole)$. The parameters that are not shown here are taken to be zero.

$\tan\beta$	M_1	M_2	M_3	mu	$m_A(pole)$
33	1660	765	4615	870	5325

$M^2_{\tilde{Q}22}$	$M^2_{\tilde{Q}33}$	$M^2_{\tilde{Q}23}$	$M^2_{\tilde{U}22}$	$M^2_{\tilde{U}33}$	$M^2_{\tilde{U}23}$
3975^2	3160^2	920^2	3465^2	1300^2	795^2

$M^2_{\tilde{D}22}$	$M^2_{\tilde{D}33}$	$M^2_{\tilde{D}23}$	T_{U23}	T_{U32}	T_{U33}
2620^2	2425^2	-1625^2	-2040	-1880	-4945

T_{D23}	T_{D32}	T_{D33}	T_{E33}
-2360	1670	-2395	-300

$M^2_{\tilde{Q}11}$	$M^2_{\tilde{U}11}$	$M^2_{\tilde{D}11}$	$M^2_{\tilde{L}11}$	$M^2_{\tilde{L}22}$	$M^2_{\tilde{L}33}$	$M^2_{\tilde{E}11}$	$M^2_{\tilde{E}22}$	$M^2_{\tilde{E}33}$
4500^2	4500^2	4500^2	1500^2	1500^2	1500^2	1500^2	1500^2	1500^2

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

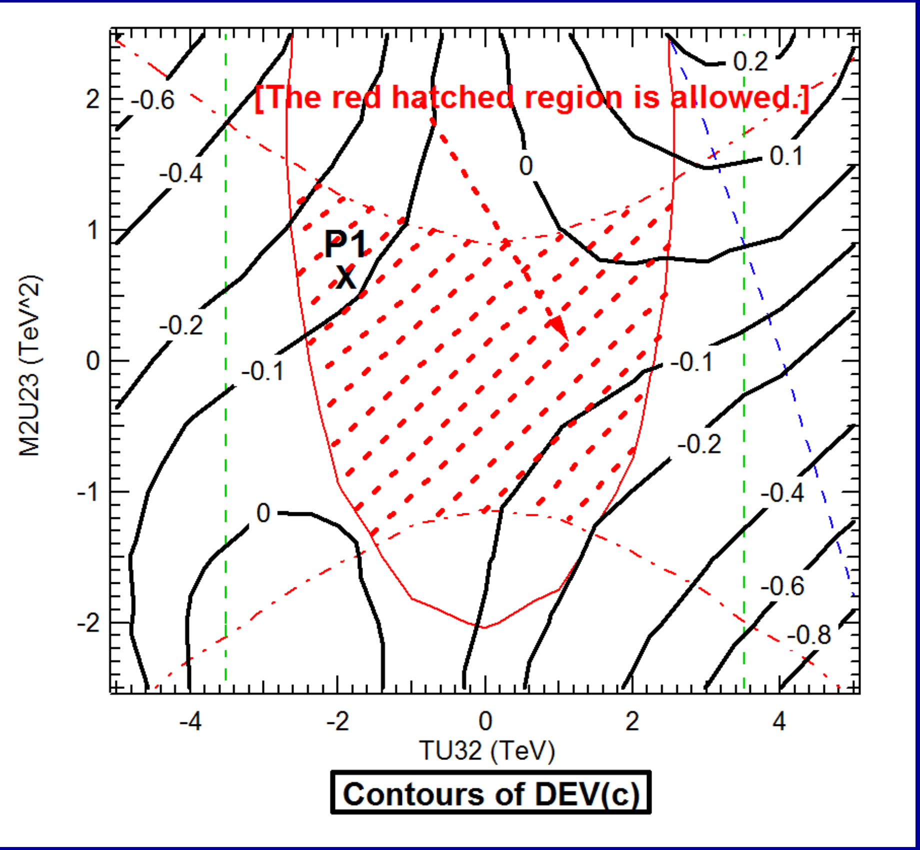
m_{h^0}	m_{H^0}	m_{A^0}	m_{H^+}
124	5325	5325	5359

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

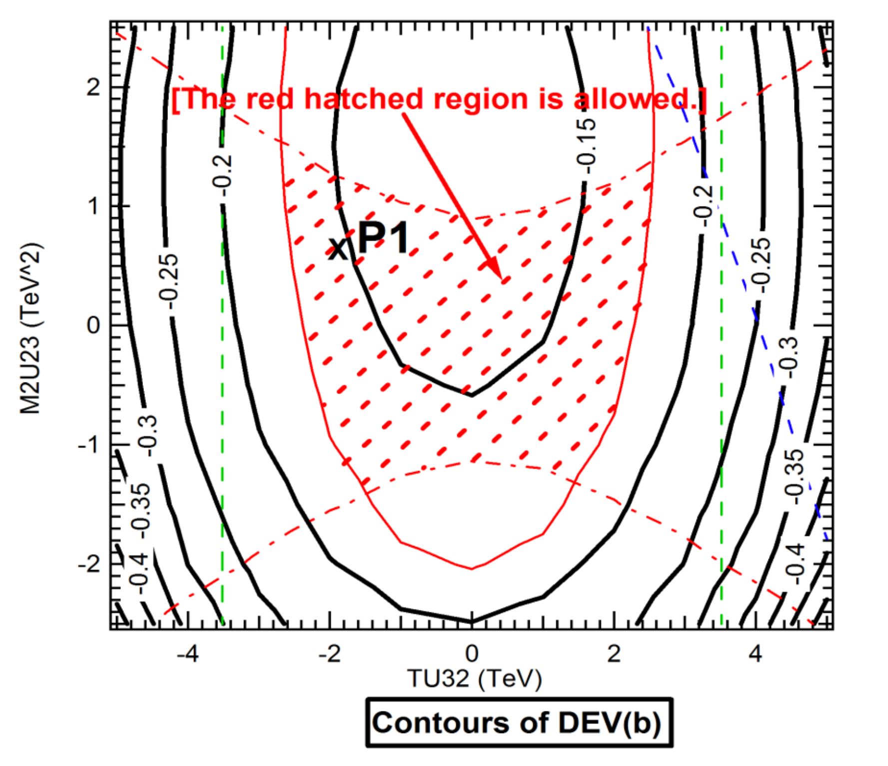
$m_{\tilde{\nu}_1}$	$m_{\tilde{\nu}_2}$	$m_{\tilde{\nu}_3}$	$m_{\tilde{l}_1}$	$m_{\tilde{l}_2}$	$m_{\tilde{l}_3}$	$m_{\tilde{l}_4}$	$m_{\tilde{l}_5}$	$m_{\tilde{l}_6}$
1509	1509	1528	1489	1489	1509	1512	1512	1545

Contours of DEV(h^0 -> c $\bar{c}$) in T_{U32} - M^2_{U23} 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 -> 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(γ) we have obtained similar results to those for DEV(c) and DEV(b).*

8. Conclusion

- *We have studied the decays*

  h^0 *(125GeV)* $\to c\bar{c}, b\bar{b}, \gamma\gamma, gg$ *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 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%

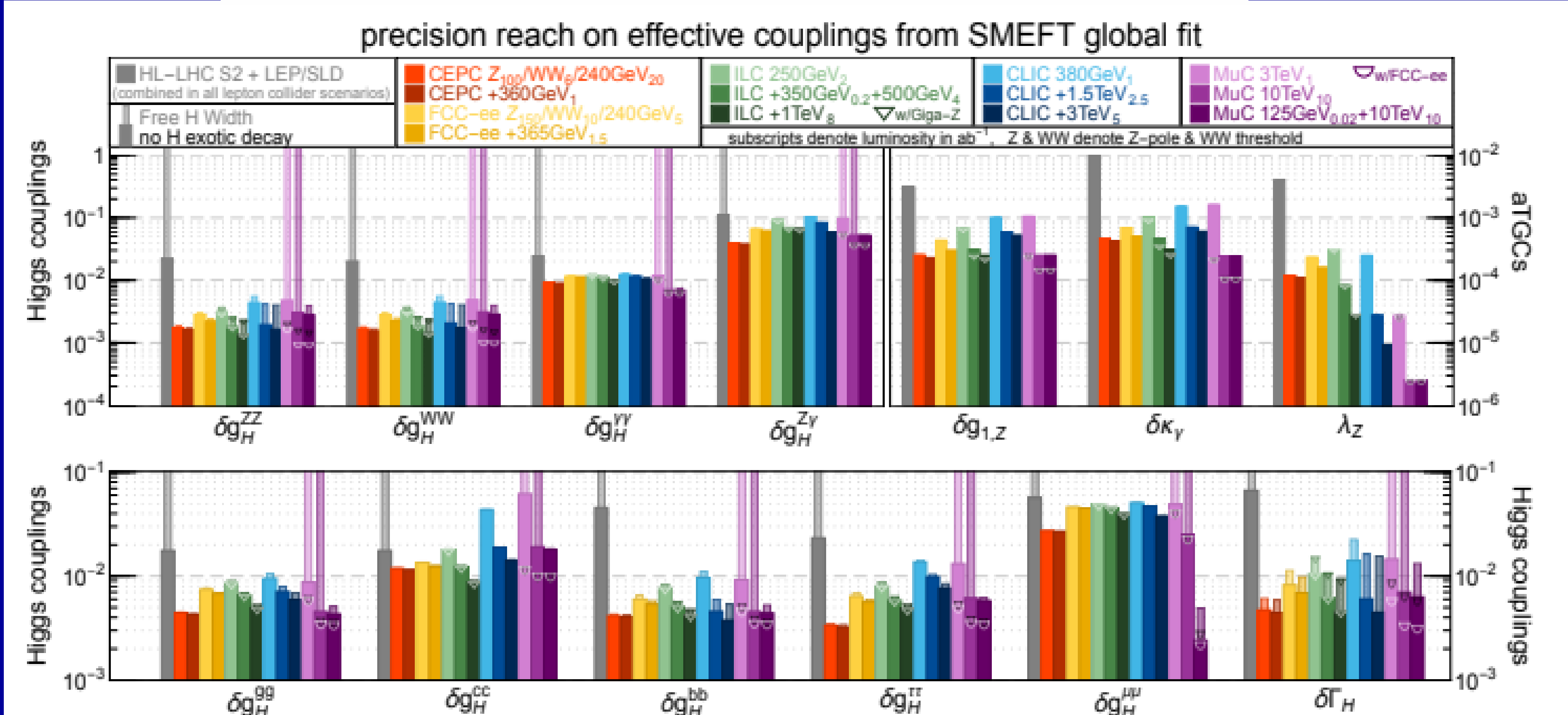
	FCC-ee I	FCC-ee II	CEPC-I	CEPC-II	MuC-I	MuC-II	MuC-III
$\Delta DEV(b)$	1.3%	1.2%	0.86%	0.84%	1.8%	0.92%	1.1%
$\Delta DEV(c)$	2.8%	2.6%	2.4%	2.2%	12.4%	3.8%	3.6%
$\Delta DEV(\gamma)$	2.4%	2.2%	1.8%	1.8%	2.4%	1.4%	1.5%
$\Delta DEV(g)$	1.5%	1.4%	0.9%	0.88%	1.7%	0.92%	1.0%
$\Delta DEV(b/c)$	2.22%	2.06%	2.0%	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



Higgs couplings at future colliders

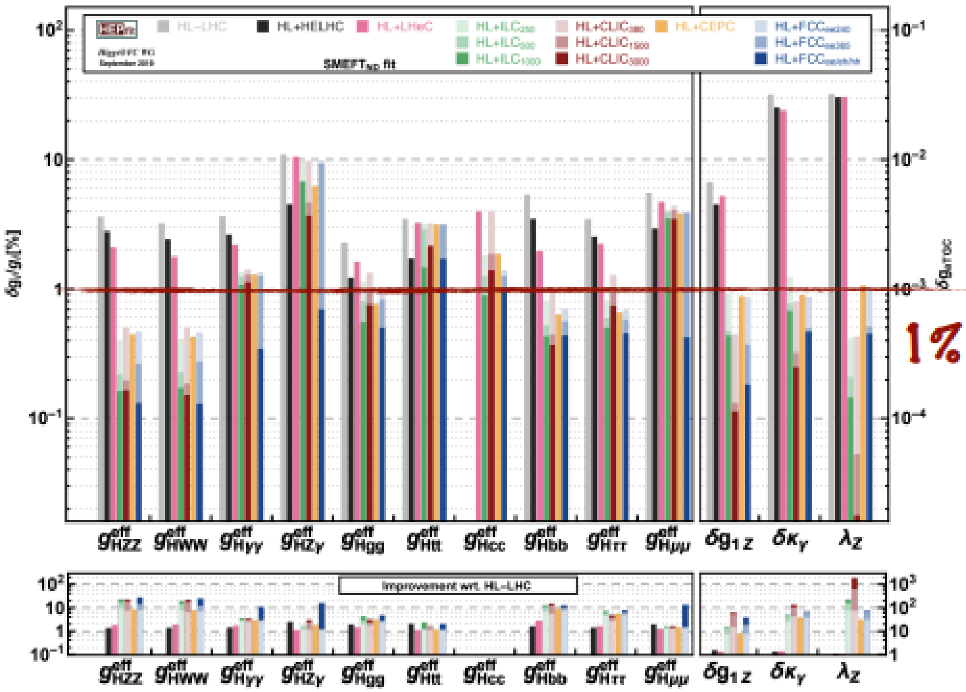
ESU2020 Report: arXiv:1905.03764

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 ~1% in future e+e- machines
  - **Couplings to μ/γ/Zγ** benefit the most from the large dataset available at HL-LHC
  - At low energy top-Higgs coupling is not accessible at future lepton colliders



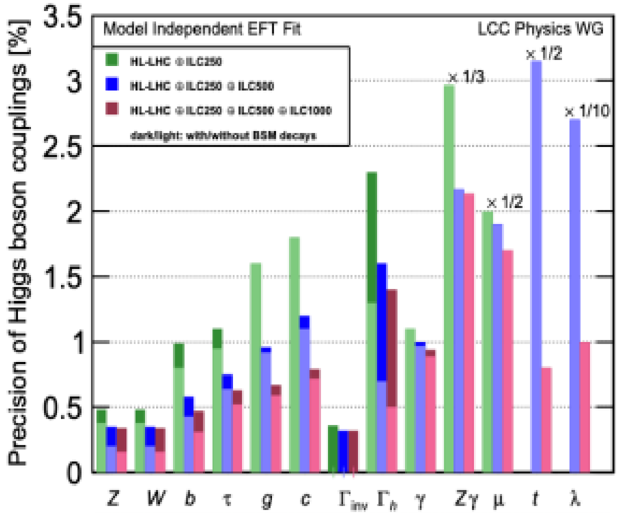
Higgs couplings at future colliders

ILC White Paper (Snowmass2021): arXiv:2203.07622
(See Fig. 12.1 in page 255; Table 12.2 in page 256)

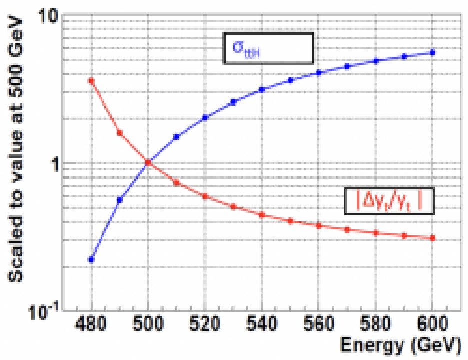
Higgs coupling precision in % for ILC

arXiv:2203.07622
arXiv:1908.11299
arXiv:1506.07830

	ILC250		ILC500		ILC1000	
coupling	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

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

$\delta\, g(hXX)$ = [Expected *relative* error of coupling $g(hXX)$]

$\Delta\, DEV(h \to X\,X)$ = [Expected *absolute* error of deviation $DEV(h \to X\,X)$]

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

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

m_A : *CP odd Higgs boson mass (pole mass)*

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

μ : *higgsino mass parameter*

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

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

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

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

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

2. Key parameters of MSSM

Key parameters in this study are:

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

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

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

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

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

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

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

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

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

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

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

4. Parameter scan for h^0 decay in the MSSM

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

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

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

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

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

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

* ***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.)*

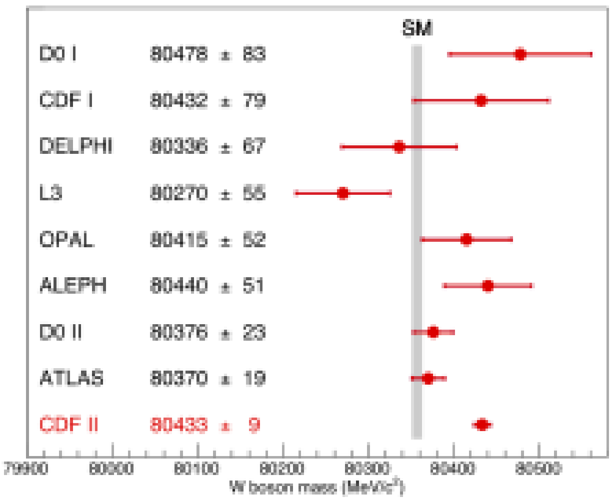
[1] *CDF Collaboration, Science 376, 170–176 (2022)*

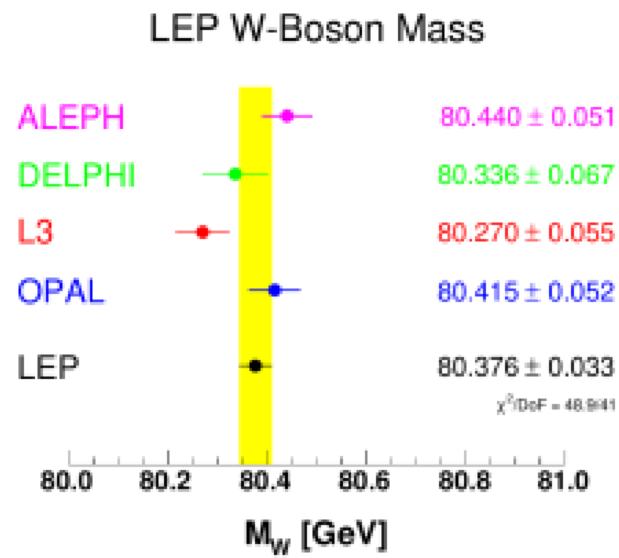
This issue of the m_W data is not yet settled.

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

From G. Wilson's talk at ECFA Higgs Factory seminars: Precision physics in the e+e- -> WW region, June 10 2022: https://indico.cern.ch/event/1163667/

What to think of m_W measurements?

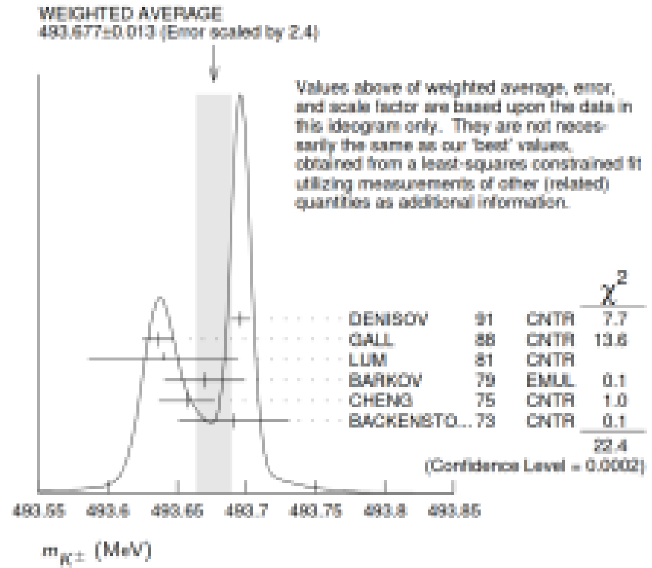




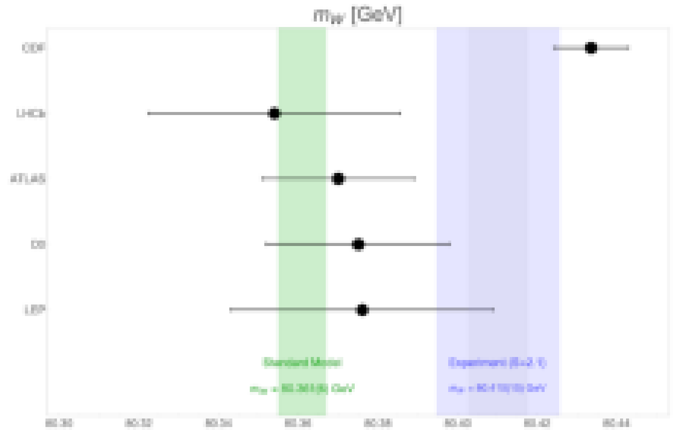
- The LEP results are based on 42 separate measurements with a **healthy** χ^2.
- The LEP-combined (33 MeV), LHCb (32 MeV), D0 Run II (23 MeV), ATLAS (19 MeV) and CDF Run II (9.4 MeV) measurements have a χ^2/DoF $= 17.1/4$, with p-value of **0.2%** for compatibility (neglecting correlations).
- So reasonably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



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



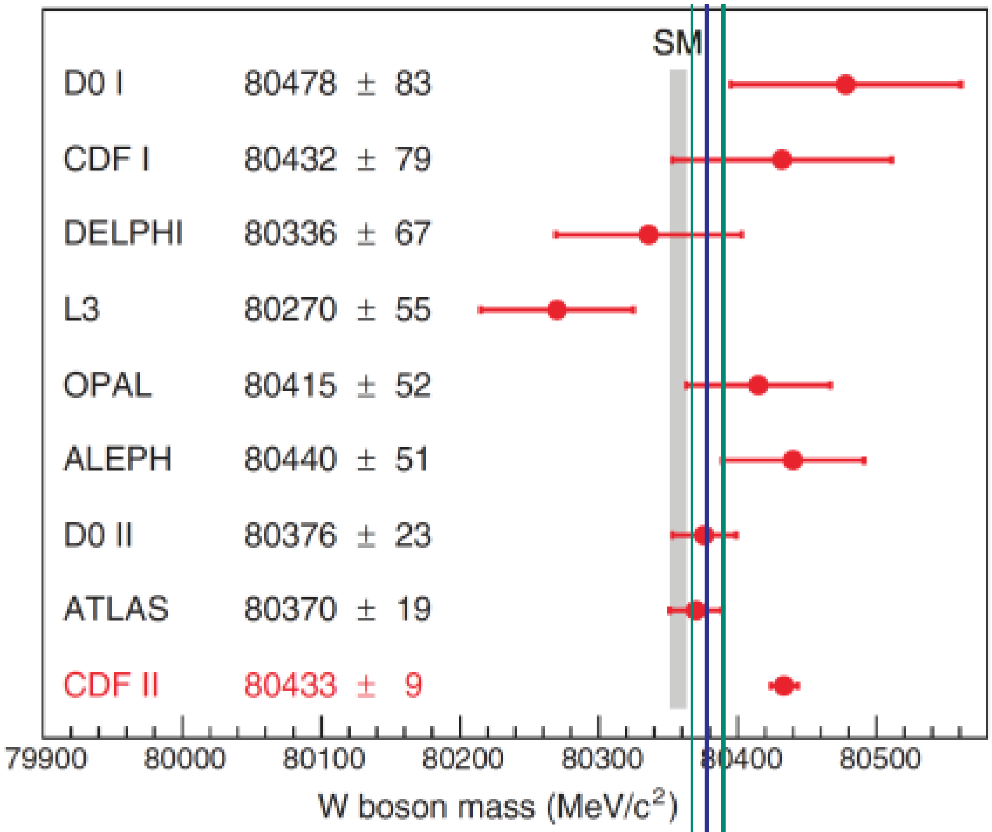
Plot from Resonaances blog (Adam Falkowski). Independently I had also done this and concluded that the scale-factored world-average is $+3.2\sigma$ off the SM value used by CDF

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!

From S. Heinemeyer's talk at IDT-WG3-Phys Open Meeting on mW, 12 May 2022: https://agenda.linearcollider.org/event/9357/

1. Introduction: the mass of the W-boson

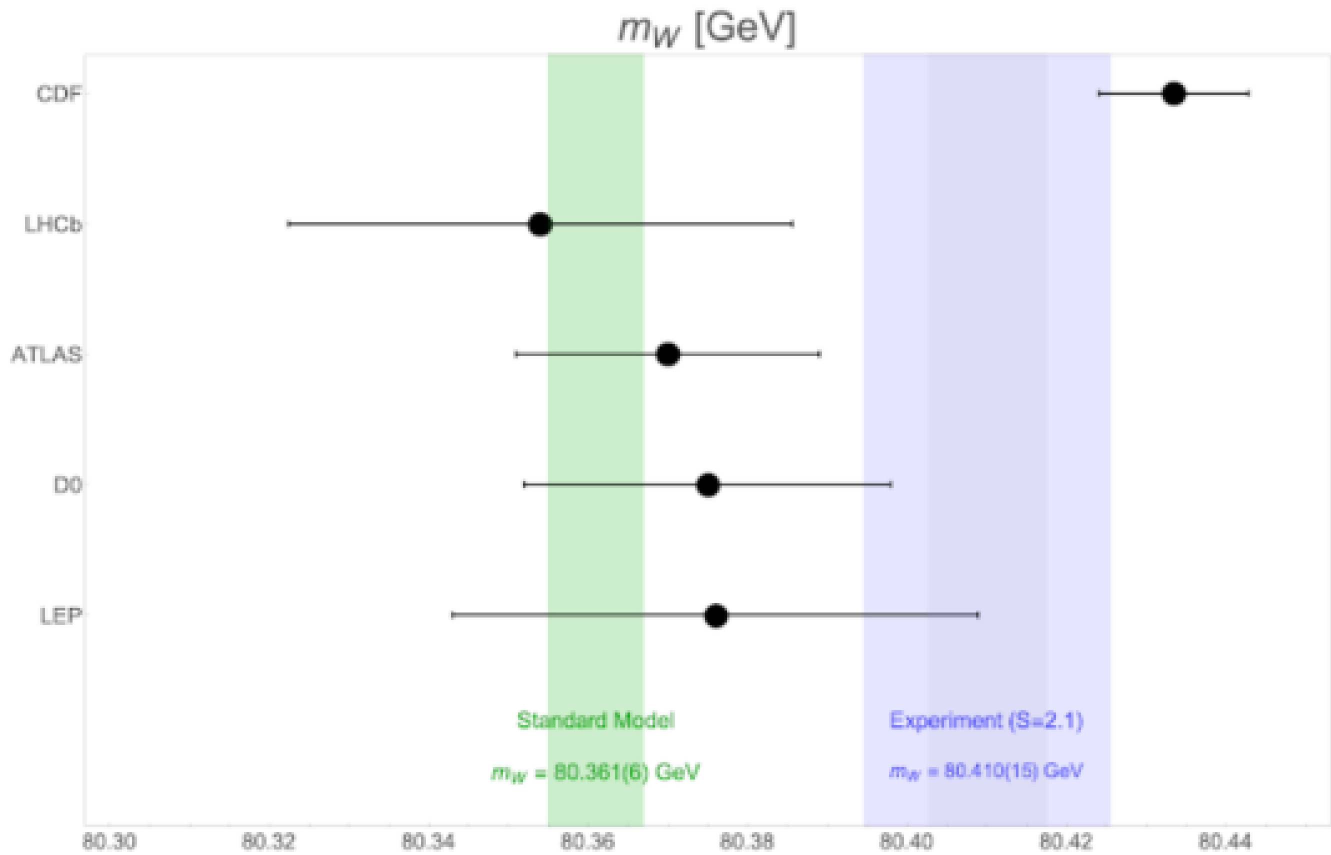
[CDF '22]



⇒ large discrepancy with the SM prediction

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

Approximation for a new world average: [A. Falkowski '22]



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

$\Rightarrow$ enlarged uncertainty because of "bad agreement" between older and new measurements $\Rightarrow$ PDG prescription

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

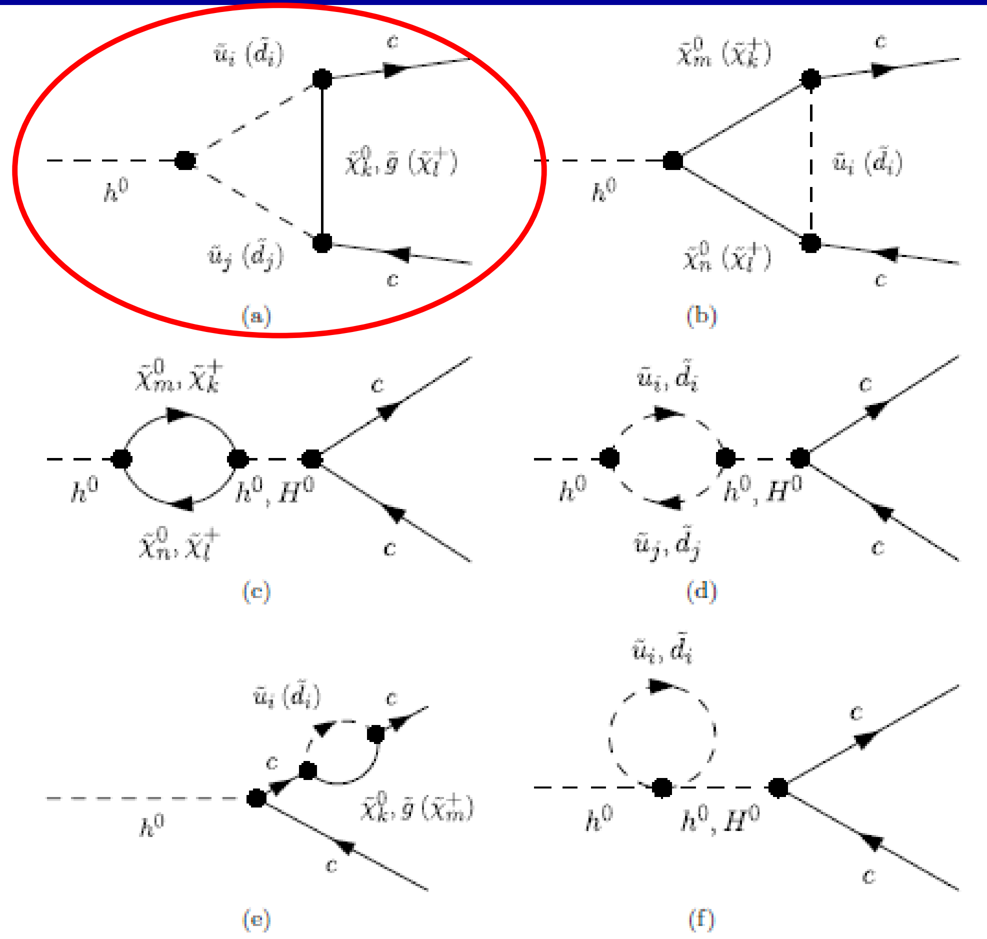
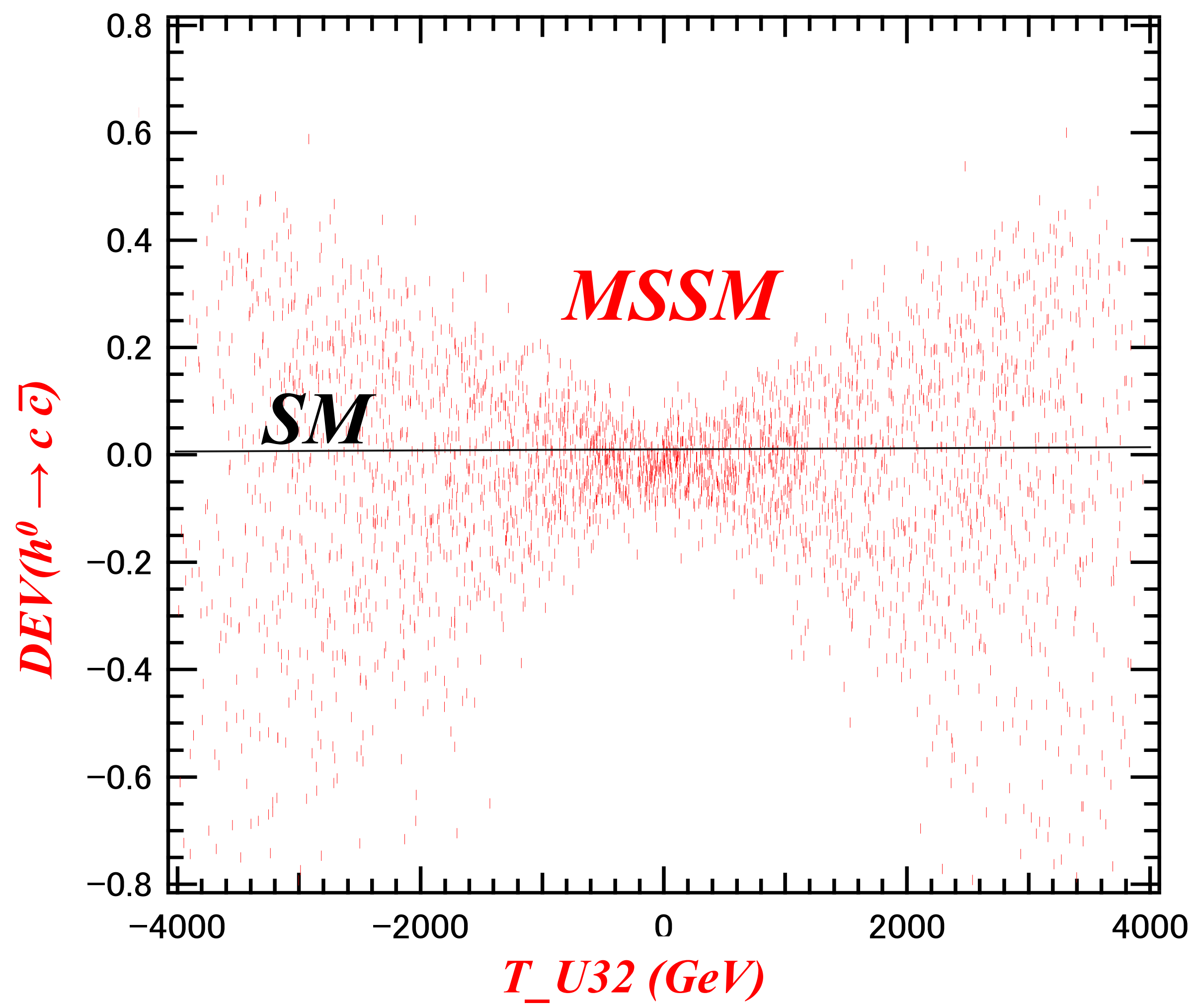


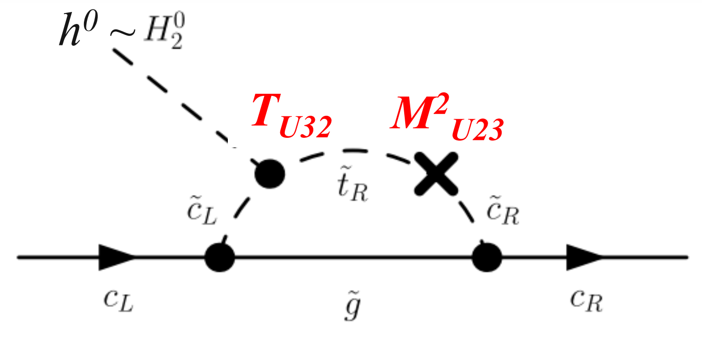
Figure 2: The main one-loop contributions with SUSY particles in $h^0 \to c\bar{c}$. The corresponding diagram to (e) with the self-energy contribution to the other charm quark is not shown explicitly.

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



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

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



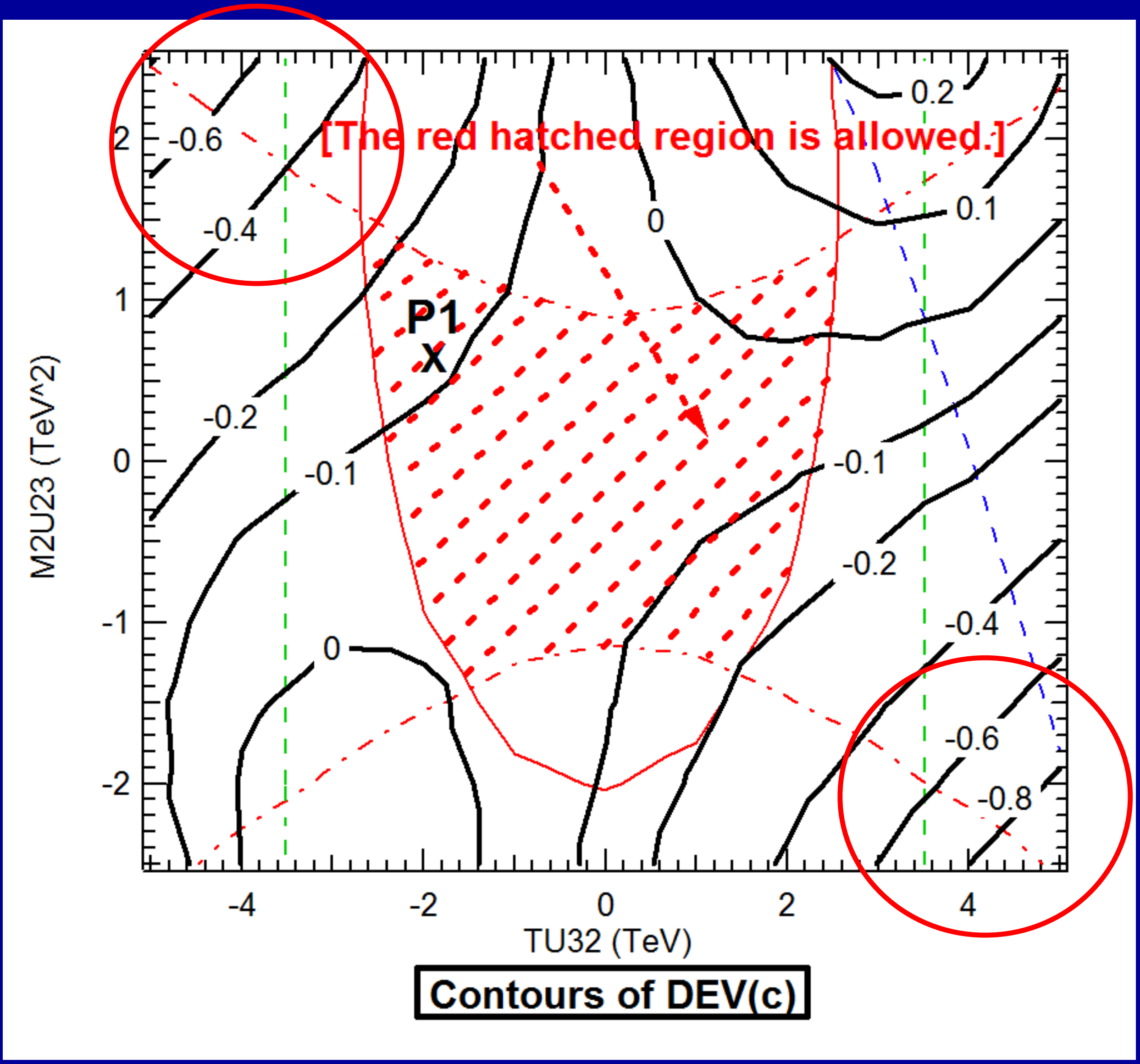
The interference term between the tree diagram and the gluino one-loop diagram can be very large (positive and negative) for large T_{U32}*M^2_{U23}, which can lead to even NEGATIVE width $\Gamma(h^0 \to c\,\bar{c})$ at one-loop level !

In this case perturbation theory breaks down!

A large deviation of $\Gamma(h^0 \to c\,\bar{c})$ 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($h^0 \to c\,\bar{c}$) can be unnaturally large. So, we show only the results with a deviation from the SM up to ~ +/-60%.

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

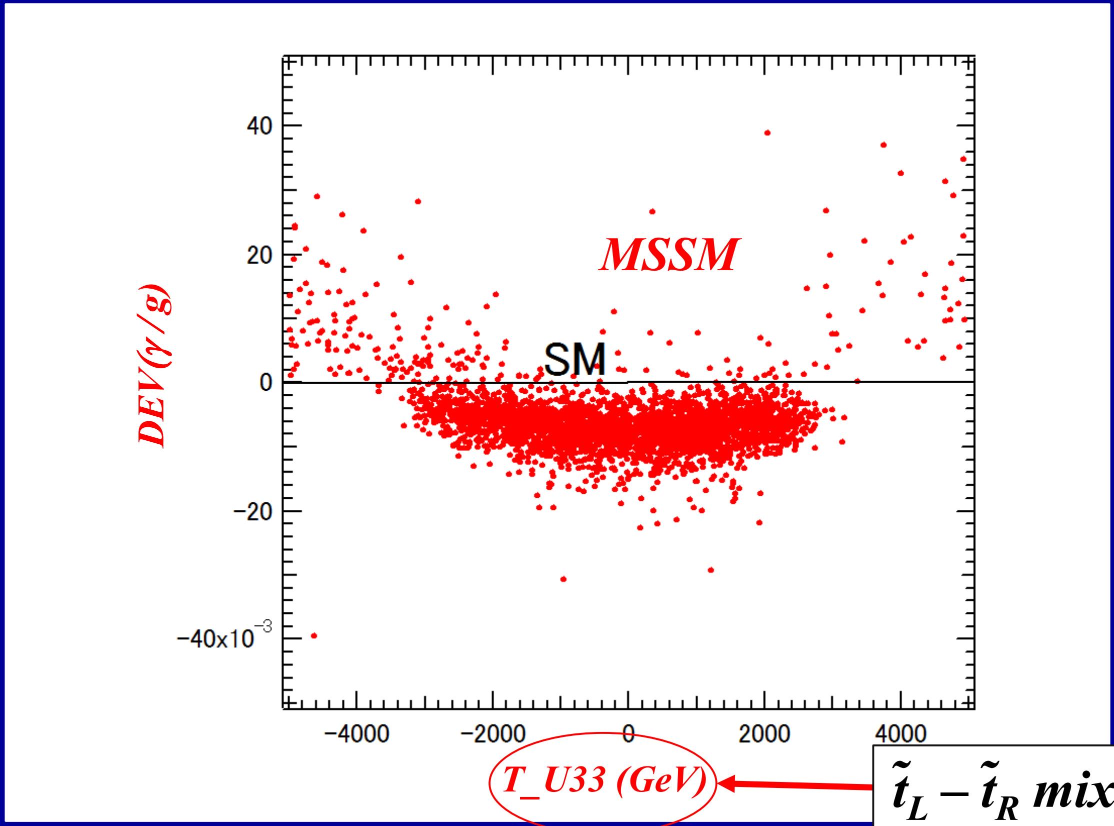


Effect of Resummation of the bottom Yukawa coupling at large $\tan\beta$

As for $\Gamma(h^0 \to b\,\bar{b})$ & $\Gamma(h^0 \to b\,\bar{s}\,/\,s\,\bar{b})$, *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 [hepph]].

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



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

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

- $DEV(\gamma/g)$ can be as large as ~ +4% for large T_{U33} !

8. Conclusion

- *We have studied the decays*

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

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

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

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

  * BR(h^0 -> $b\bar{s}$ / $s\bar{b}$) can be as large as ~ 0.15%!

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

* *DEV(h^0 -> $\gamma\gamma$) and DEV(h^0 -> g g) can be sizable simultaneously! :*
  DEV(h^0 -> $\gamma\gamma$) can be as large as ~ ±1%,
  DEV(h^0 -> g g) can be as large as ~ ±4%.

* *The deviation of the width ratio Γ(h^0 -> $\gamma\gamma$)/ Γ(h^0 -> g g) from the SM value can be as large as ~ -4% to +8% .*

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

- *All of these large deviations in the h^0 (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)!*