Impact of quark flavour violation on the decay $h^0(125GeV) \to c\bar{c}$ in the MSSM

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Contents

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

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 the most important issue in the present particle physics world!*

- *Here we study a possibility that it is the lightest Higgs boson h^0 of Minimal Supersymmetric Standard Model (MSSM) focusing on the width of the decay $h^0 \to c\bar{c}$.*

- *We compute the width at full one-loop level in the $\overline{DR}$ scheme in the MSSM with non minimal Quark Flavor Violation (QFV).*

- *We find that the difference of the MSSM and SM predictions for the width can be quite significant compared with expected experimental errors at future lepton colliders such as ILC.*

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 $Q = m_h$ 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

Key parameters in this study are:

QFV parameters: δ^{LL}_{23} , δ^{uRR}_{23} , δ^{uRL}_{23} , δ^{uLR}_{23}

QFC parameter: δ^{uRL}_{33}

$$\delta^{LL}_{23}\ (\sim M^2_{Q_{23}}) = (\tilde{c}_L - \tilde{t}_L \text{ mixing parameter})$$

$$\delta^{uRR}_{23}\ (\sim M^2_{U_{23}}) = (\tilde{c}_R - \tilde{t}_R \text{ mixing parameter})$$

$$\delta^{uRL}_{23}\ (\sim T_{U_{32}}) = (\tilde{c}_R - \tilde{t}_L \text{ mixing parameter})$$

$$\delta^{uLR}_{23}\ (\sim T_{U_{23}}) = (\tilde{c}_L - \tilde{t}_R \text{ mixing parameter})$$

$$\delta^{uRL}_{33}\ (\sim T_{U_{33}}) = (\tilde{t}_L - \tilde{t}_R \text{ mixing parameter})$$

3. *Constraints on the MSSM*

We respect the following experimental and theoretical constraints:

(1) the recent LHC limits on the masses of squarks, gluino, charginos and neutralinos.

(2) the constraint on (m_A, $\tan\beta$) from the recent MSSM Higgs boson search at LHC.

(3) the constraints on the QFV parameters from the B 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 at LHC (allowing for theoretical uncertainty): 122.7 GeV < m_h^0 < 127.6 GeV.

(5) theoretical constraints from the vacuum stability conditions for the QFC/QFV trilinear couplings T_{Uab}.

(6) The experimental limit on SUSY contributions to the electroweak ρ parameter $\Delta\rho(SUSY) < 0.0012$.

4. Benchmark QFV Scenario

Table 1: Reference QFV scenario: shown are the basic MSSM parameters at $Q = 125.5$ GeV $\simeq m_{h^0}$, except for m_{A^0} which is the pole mass (i.e. the physical mass) of A^0, with $T_{U33} = -2050$ GeV (corresponding to $\delta^{uRL}_{33} = -0.2$). All other squark parameters not shown here are zero.

large $\tilde{t}_L - \tilde{t}_R$ mixing scenario (large top-trilinear-coupling scenario)

M_1	M_2	M_3
250 GeV	500 GeV	1500 GeV

μ	$\tan\beta$	m_{A^0}
2000 GeV	20	1500 GeV

decoupling Higgs scenario

	$\alpha = 1$	$\alpha = 2$	$\alpha = 3$
$M^2_{Q\alpha\alpha}$	$(2400)^2$ GeV^2	$(2360)^2$ GeV^2	$(1850)^2$ GeV^2
$M^2_{U\alpha\alpha}$	$(2380)^2$ GeV^2	$(1050)^2$ GeV^2	$(950)^2$ GeV^2
$M^2_{D\alpha\alpha}$	$(2380)^2$ GeV^2	$(2340)^2$ GeV^2	$(2300)^2$ GeV^2

δ^{LL}_{23}	δ^{uRR}_{23}	δ^{uRL}_{23}	δ^{uLR}_{23}
0.05	0.2	0.03	0.06

Sizable QFV parameters

Physical masses in our benchmark scenario

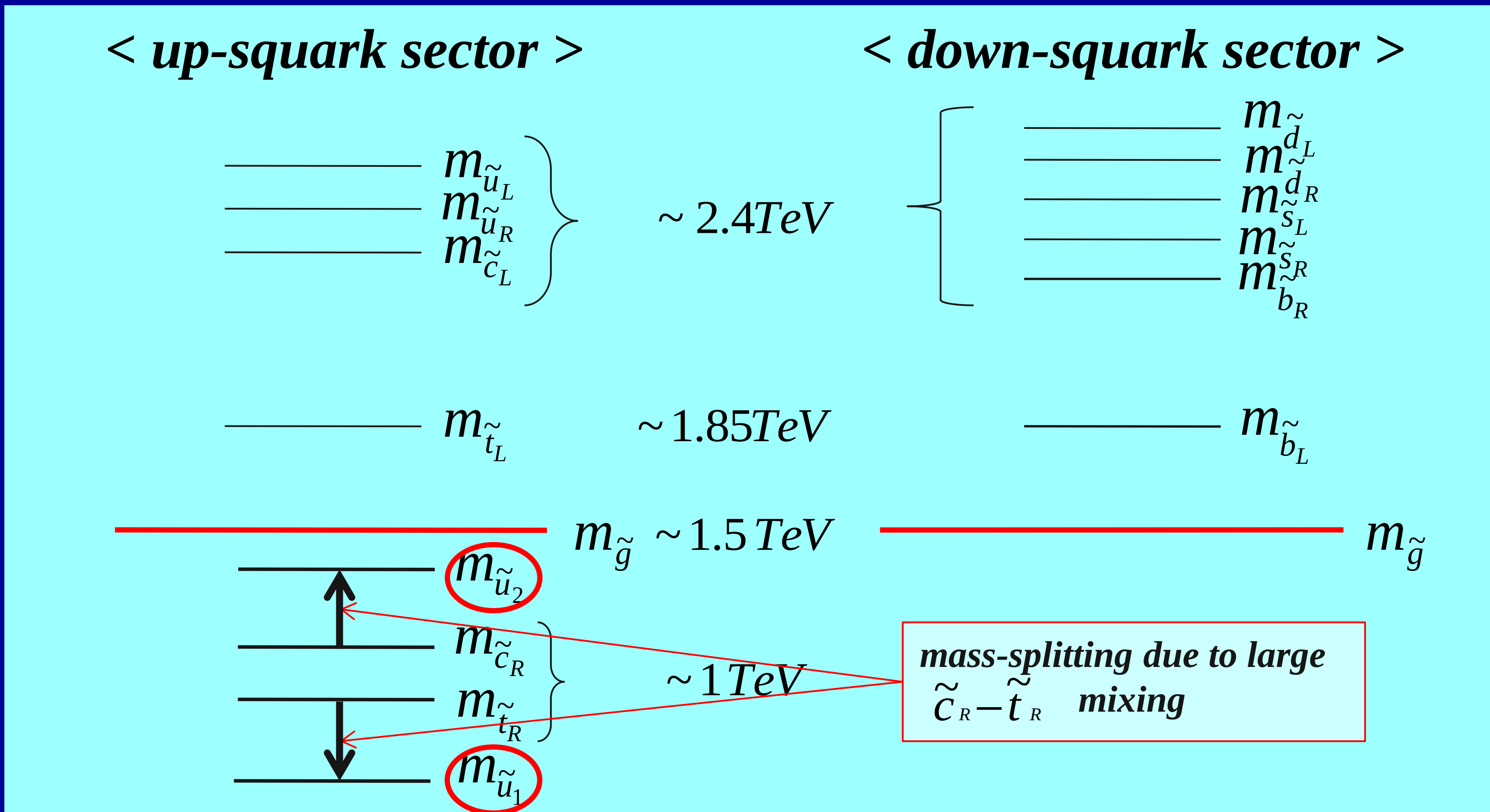
Table 2: Physical masses in GeV of the particles for the scenario of Table 1.

$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{\chi}_3^0}$	$m_{\tilde{\chi}_4^0}$	$m_{\tilde{\chi}_1^+}$	$m_{\tilde{\chi}_2^+}$
260	534	2020	2021	534	2022

m_{h^0}	m_{H^0}	m_{A^0}	m_{H^+}
126.08	1498	1500	1501

$m_{\tilde{g}}$	$m_{\tilde{u}_1}$	$m_{\tilde{u}_2}$	$m_{\tilde{u}_3}$	$m_{\tilde{u}_4}$	$m_{\tilde{u}_5}$	$m_{\tilde{u}_6}$
1473	756	965	1800	2298	2301	2332

Benchmark QFV scenario



Main features of our scenario:

- *Large scharm-stop mixing terms* M^2_{Q23}, M^2_{U23}, T_{U23}, T_{U32}
- *Large QFV/QFC trilinear couplings* T_{U23}, T_{U32}, T_{U33}

The gluino loop contributions to the width $\Gamma(h^0 \to c\bar{c})$ *are enhanced!* *(see next page)*

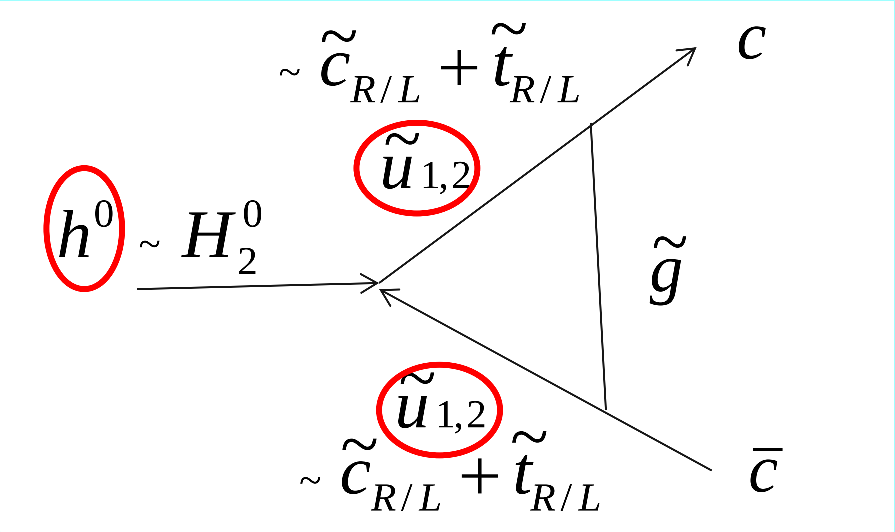
Large deviation of the MSSM prediction for $\Gamma(h^0 \to c\bar{c})$ *from the SM prediction!*

This makes it easier to discover the QFV SUSY effects in this decay $h^0 \to c\bar{c}$ *!*

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

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

$h^0 \sim H_2^0$



In our scenario "trilinear couplings" ($\tilde{c}_L - \tilde{t}_R - H_2^0$, $\tilde{c}_R - \tilde{t}_L - H_2^0$, $\tilde{t}_L - \tilde{t}_R - H_2^0$ **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!

5. $h^0 \rightarrow c$ cbar at full 1-loop level

- *We compute the width* $\Gamma(h^0 \rightarrow c\,\bar{c})$ *at full 1-loop level in the* $\overline{DR}$ *renormalization scheme in the MSSM with QFV.*

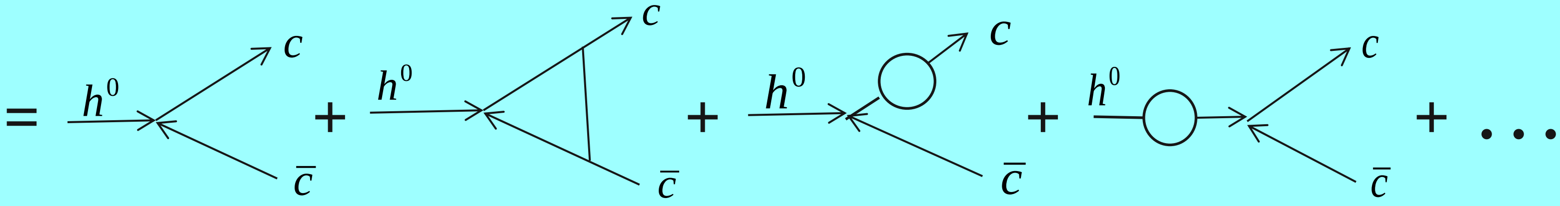
- *We take the normalization scale as Q =* m_{h^0}.

- *We study the normalization scale Q dependences of the width* $\Gamma(h^0 \rightarrow c\,\bar{c})^{full\,1-loop}$ *in the range* $m_{h^0}/2 < Q < 2m_{h^0}$.

For details, see Phys. Rev. D 91 (2015) 015007 [arXiv:1411.2840 [hep-ph]]

- ***Invariant decay amplitude*** $M_{inv}(h^0 \to c\,\bar{c})$:

$$M_{inv} = M^{tree} + M^{1\text{-}loop} + \ldots$$



$$M^{1\text{-}loop} = M^{SUSY\ QCD\text{-}loops} + M^{EW\text{-}loops}$$

$$= M(gluon\text{-}loop) + M(gluino\text{-}loop)$$

$$+ \quad M(\gamma / Z^0 / W^{\pm} / h^0 / H^0 / A^0 / H^{\pm} - \mathrm{loop})$$

$$+ \quad M(neutralino/chargino/squark\ \text{-}\ loop)$$

(Note) $M^{EW\text{-}loops}$ ***is small.***

(Note) In our benchmark scenario, M(gluino-loop) is significantly larger than M(gluon-loop):

M(gluon-loop): M(gluino-loop) ~ 1 : 2

Main one-loop contributions with SUSY particles

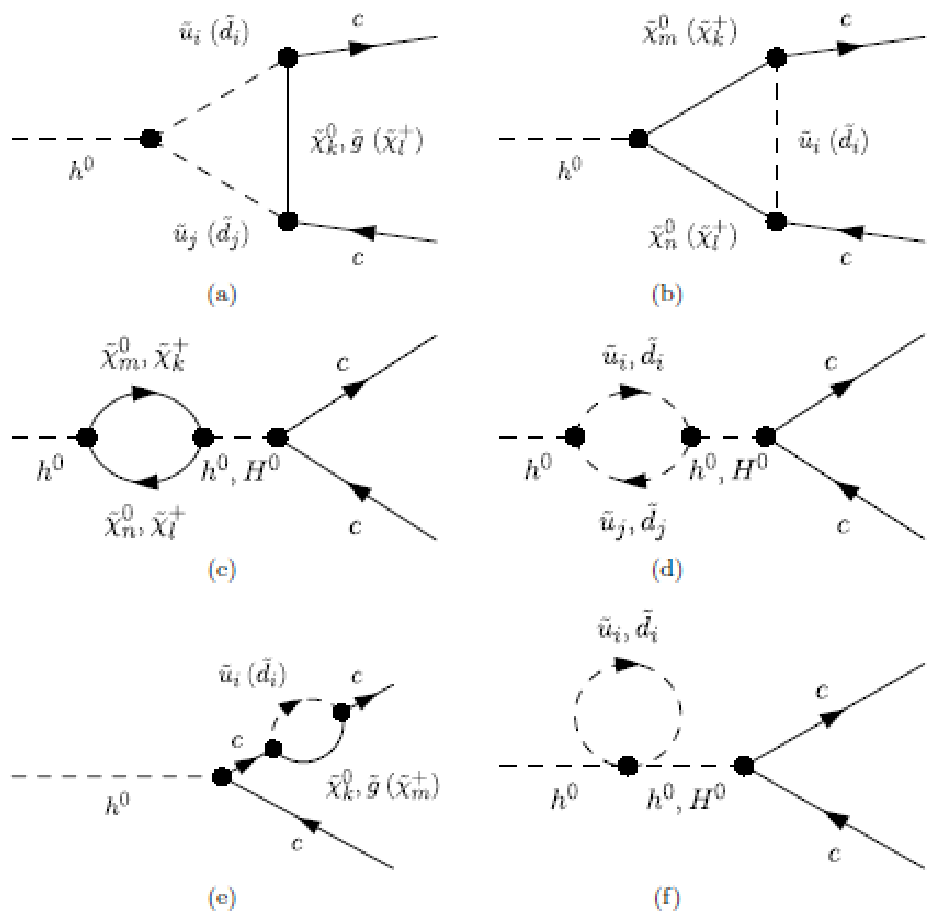


Figure 2: The main one-loop contributions with SUSY particles in $h^0 \to c\bar{c}$. The corresponding diagram to (e) with the self-energy contribution to the other charm quark is not shown explicitly.

- ***The decay width $\Gamma(h^0 \to c\bar{c})$:***

$$\Gamma(h^0 \to c\bar{c}) \sim |M_{inv}|^2$$

$$= (M^{tree} + M^{1\text{-}loop} + \ldots)^* (M^{tree} + M^{1\text{-}loop} + \ldots)$$

$$= |M^{tree}|^2 + 2\,Re(M^{tree\,*} M^{1\text{-}loop}) + \ldots$$

⇩

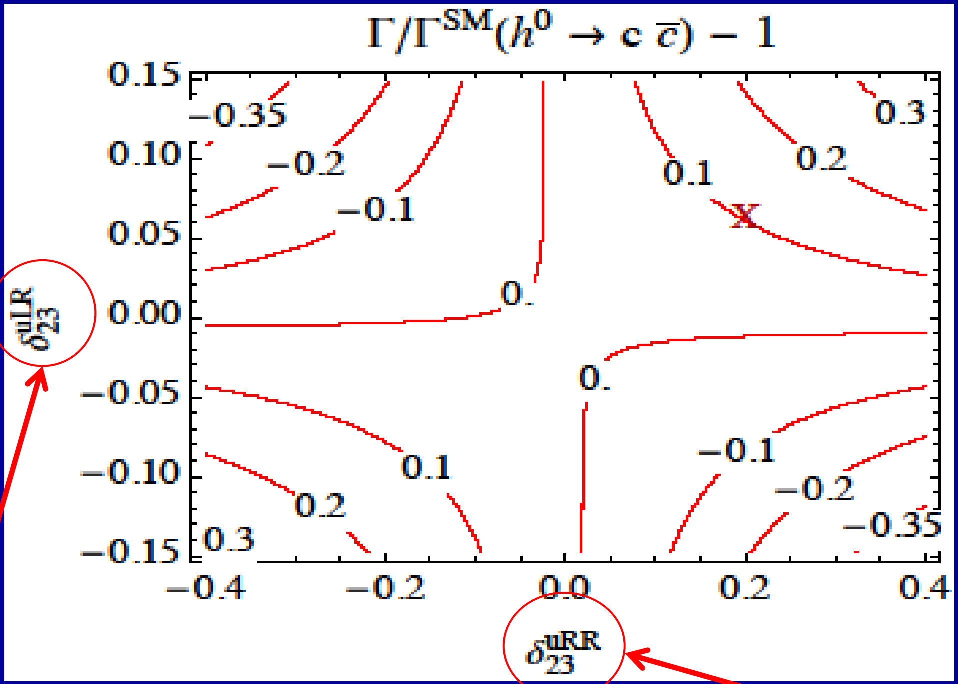
Each 1-loop diagram contributes to the width $\Gamma(h^0 \to c\bar{c})$ separately without interfering with each other!

(Note) We include real photon /gluon emissions in the width in order to cancel the IR divergences.

(Note) We improve gluon loop contribution by including gluonic α_s^2 contributions. (See Spira, hep-ph9705337)

5. Numerical results

Contour plot of the deviation of the MSSM prediction from the SM prediction
$\Gamma^{SM}(h^0 \to c\bar{c}) = 0.118 MeV$ *(PDG2014)* ***in*** δ_{23}^{uRR} - δ_{23}^{uLR} ***plane***



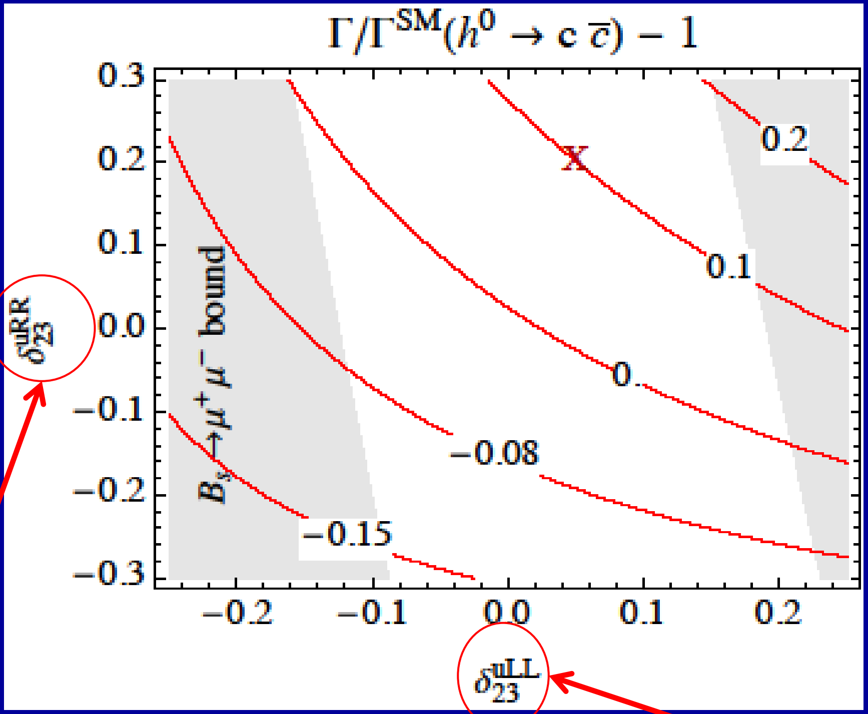
$\tilde{c}_L - \tilde{t}_R$ ***mixing parameter***

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

- The MSSM prediction $\Gamma(h^0 \to c\bar{c})^{full1-loop}$ ***is very sensitive to the QFV parameters*** δ_{23}^{uRR} - δ_{23}^{uLR} ***!***

- The deviation of the MSSM prediction from the SM prediction can be very large (as large as ~ - 35%)!

Contour plots of the deviation of the MSSM prediction from the SM prediction in δ^{uLL}_{23} – δ^{uRR}_{23} plane



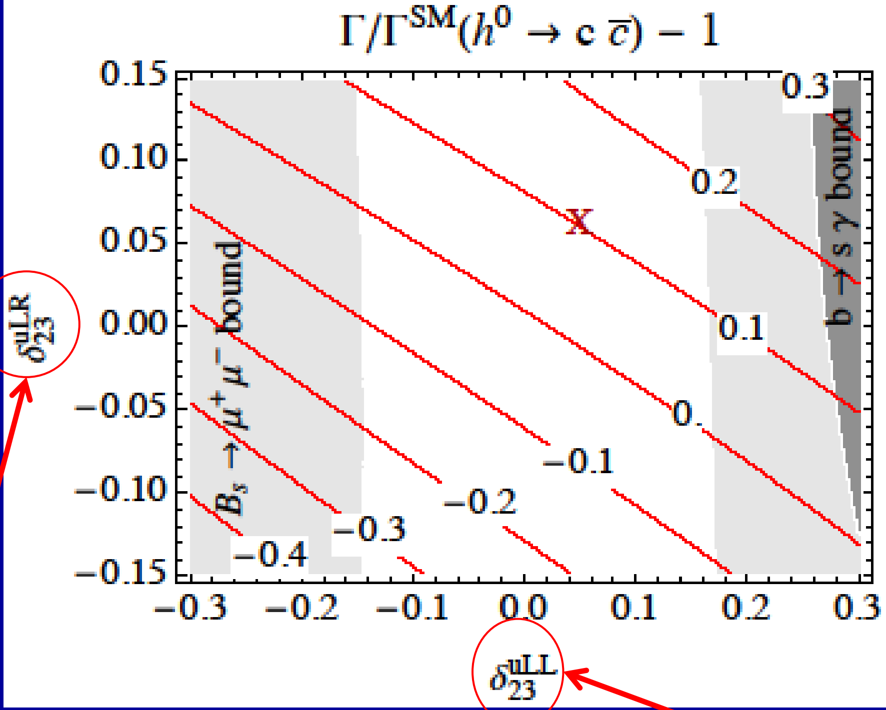
$\tilde{c}_R - \tilde{t}_R$ ***mixing parameter***

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

- The MSSM prediction $\Gamma(h^0 \to c\,\bar{c})^{full1-loop}$ is very sensitive to the QFV parameters δ^{uLL}_{23} – δ^{uRR}_{23} !

- The deviation of the MSSM prediction from the SM prediction can be very large (as large as ~ 20%)!

Contour plots of the deviation of the MSSM prediction from the SM prediction in δ_{23}^{uLL} – δ_{23}^{uLR} plane



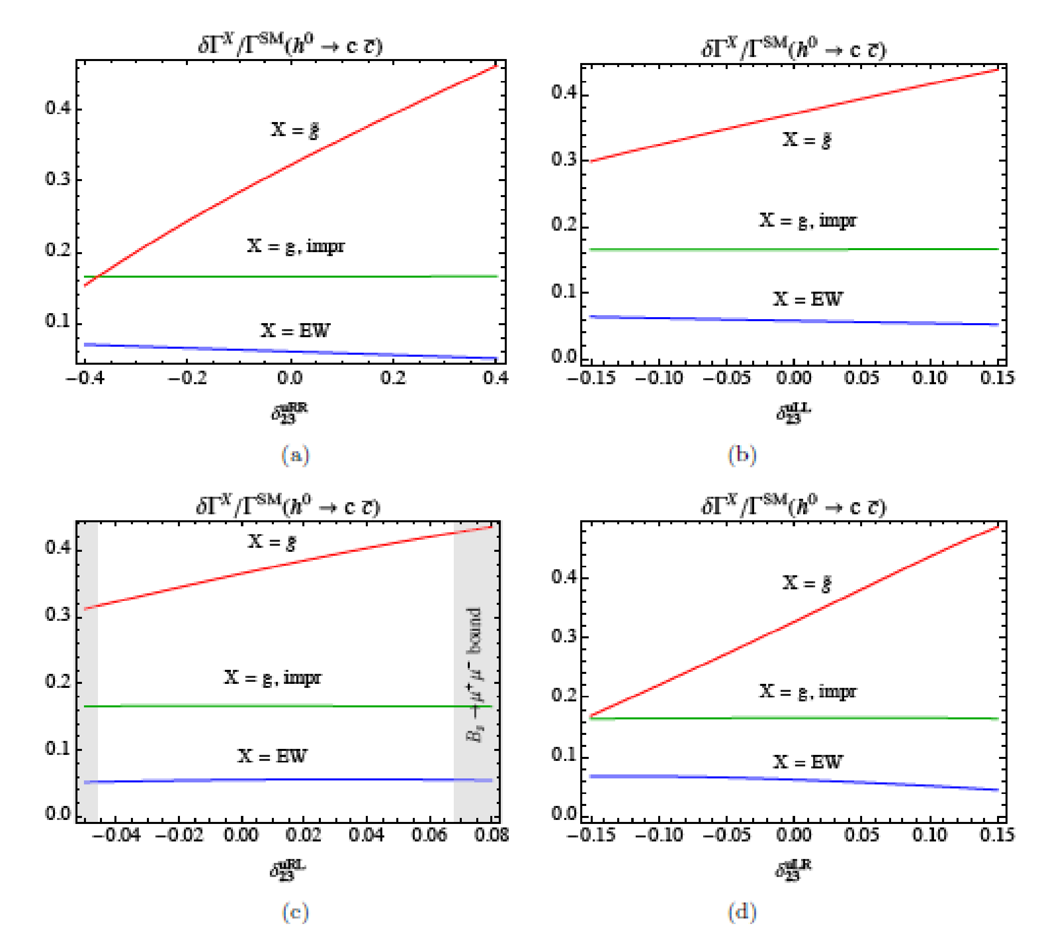
$\tilde{c}_L - \tilde{t}_R$ ***mixing parameter***

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

- ***The MSSM prediction*** $\Gamma(h^0 \longrightarrow c\,\bar{c})^{full1-loop}$ ***is very sensitive to the QFV parameters*** δ_{23}^{uLL} – δ_{23}^{uLR} ***!***

- ***The deviation of the MSSM prediction from the SM prediction can be very large (as large as ~ - 30%)!***

QFV parameter dependences of one-loop $\tilde{g}$, improved g, and EW contributions to $\Gamma(h^0 \to c\,\bar{c})^{full1-loop}$



- *The gluino loop contribution* $\delta\Gamma^{\tilde{g}}$ *is sensitive to the QFV parameters!*
- *The gluino loop contribution* $\delta\Gamma^{\tilde{g}} / \Gamma^{SM}$ *can be very large (up to 45%)!*

Comment on QFC SUSY contributions

If we switch off all the QFV parameters in our benchmark QFV scenario, then the MSSM prediction becomes nearly equal to the SM prediction!:

$$\Gamma(h^0 \to c\,\bar{c})^{QFCMSSM} = 0.116\,MeV$$

$$\Gamma(h^0 \to c\,\bar{c})^{SM} = 0.118\,MeV$$

The QFC supersymmetric contributions change the width $\Gamma(h^0 \to c\,\bar{c})$ by only ~ -1.5% compared to the SM value.

7. Theoretical and Experimental Errors

(a) $\Delta\Gamma^{SM}/\Gamma^{SM}(h^0 \to c\bar{c}) \approx$ **6%**

See; arXiv:1310.8361: Higgs WG Report Snowmass2013

arXiv:1307.1347: Report of the LHC Higgs Cross Section Working Group

arXiv:1311.6721v3: Phys. Rev. D 89 (2014) 033006

arXiv:1404.0319: Lepage-Mackenzie-Peskin

(b) $\Delta\Gamma^{MSSM}/\Gamma^{MSSM}(h^0 \to c\bar{c}) \approx$ **6%**

(for our benchmark QFV scenario)

* *uncertainties due to error of charm quark mass* $m_c(m_c)^{\overline{MS}}$: ≈5.2%

$m_c(m_c)^{\overline{MS}} = 1.275 \pm 0.025\,\text{GeV}$ (at 68% CL) (PDG2013)

* *uncertainties due to error of QCD coupling* $\alpha_s(m_Z)^{\overline{MS}}$: ≈2%

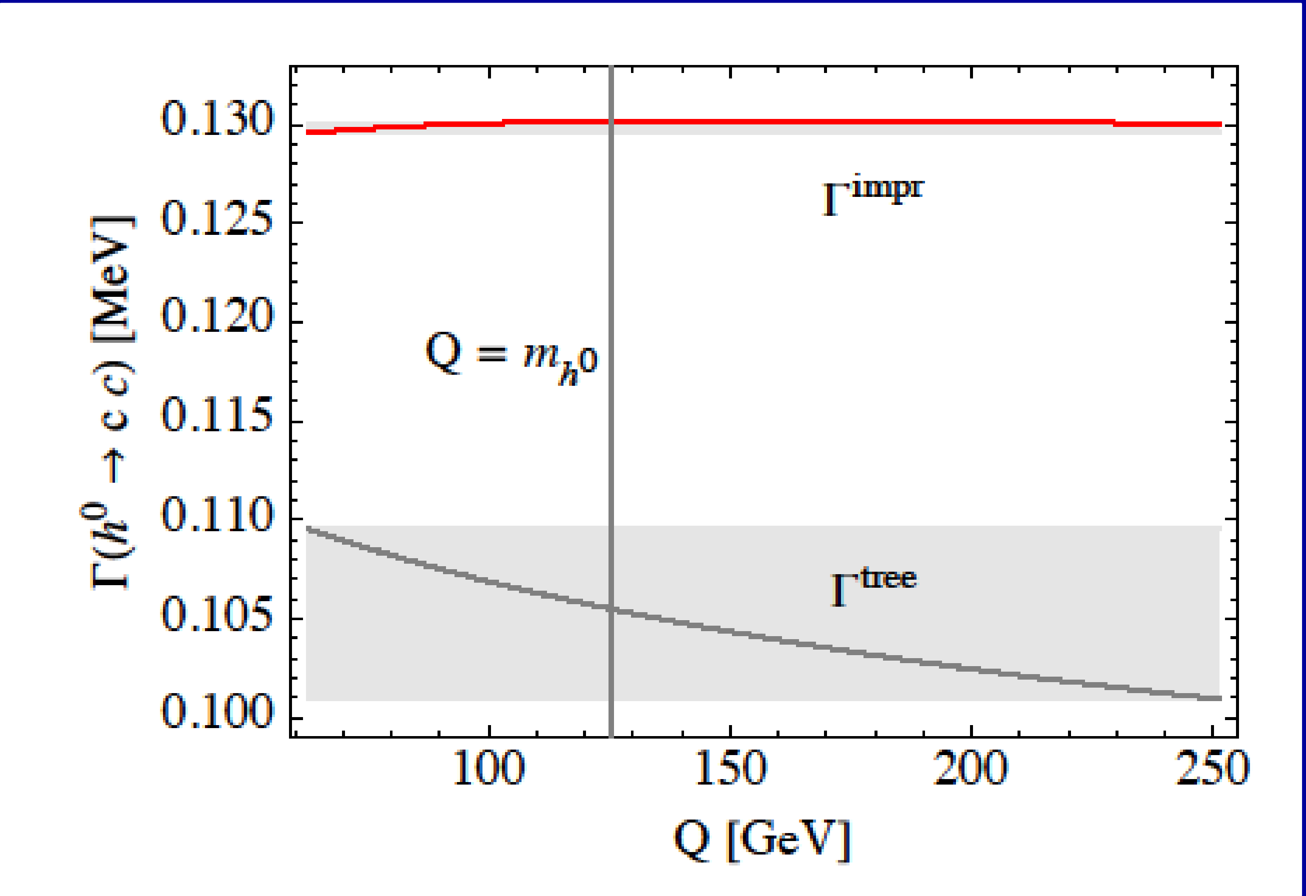
$\alpha_s(m_Z)^{\overline{MS}} = 0.1185 \pm 0.0006$ (at 68% CL) (ICHEP2014)

* *uncertainties due to errors of the other SM input parameters, such as* $m_b(m_b)^{\overline{MS}}$*, are negligible.*

* *uncertainties due to renormalization scale Q dependences of the width:* ≈0.5%

(see next plot)

The renormalization scale Q dependence of the MSSM width in the range $m_{h^0}/2 < Q < 2m_{h^0}$



The renormalization scale Q dependence of the MSSM width is small; it results in ~ 0.5% theoretical uncertainties.

(c) $\Delta\Gamma^{DATA} / \Gamma^{DATA}(h^0 \to c\bar{c}) \approx$ ***3% (5.6%)***

(at ILC (500GeV) with 1600 fb-1 (500 fb-1))

See; ILC Higgs White Paper, arXiv:1310.0763
J. Tian and K. Fujii, PoS(EPS-HEP2013) 316, arXiv:1311.6528

The deviation of the MSSM prediction from the SM width can be very large (as large as ~ 35%) as shown above!

Such a large deviation can be observed at ILC (500GeV), even if we take into account the theoretical uncertainties of the predictions!

(Note) A measurement of the width $\Gamma(h^0 \to c\bar{c})$ *at LHC (even at HL-LHC) is very difficult due to the difficulty in charm-tagging.*

8. Conclusion

- *We have calculated the width of the SM like Higgs boson decay h -> c cbar at full one-loop level (in the DRbar renorm. scheme) in the MSSM with non minimal QFV.*

- *The QFV effect (i.e. scharm-stop mixing effect) on the width can be quite large despite the very strong constraints on QFV from the B meson data.*

- *The deviation of the MSSM prediction from the SM width can be strongly enhanced (up tp ~ 35%) by the QFV effect!*

- *The deviation of the MSSM prediction from SM width can be quite significant compared with the expected experimental errors at ILC(500GeV), even if we take into account the theoretical uncertainties of the predictions!*

- ***Therefore, we have a good chance to discover the QFV SUSY effect in this decay h -> c cbar at ILC!***

- *Our analysis suggests the following:*

  PETRA/TRISTAN discovered virtual Z^0 effect for the first time.

  Similarly, ILC could discover virtual SUSY effects for the first time!

END

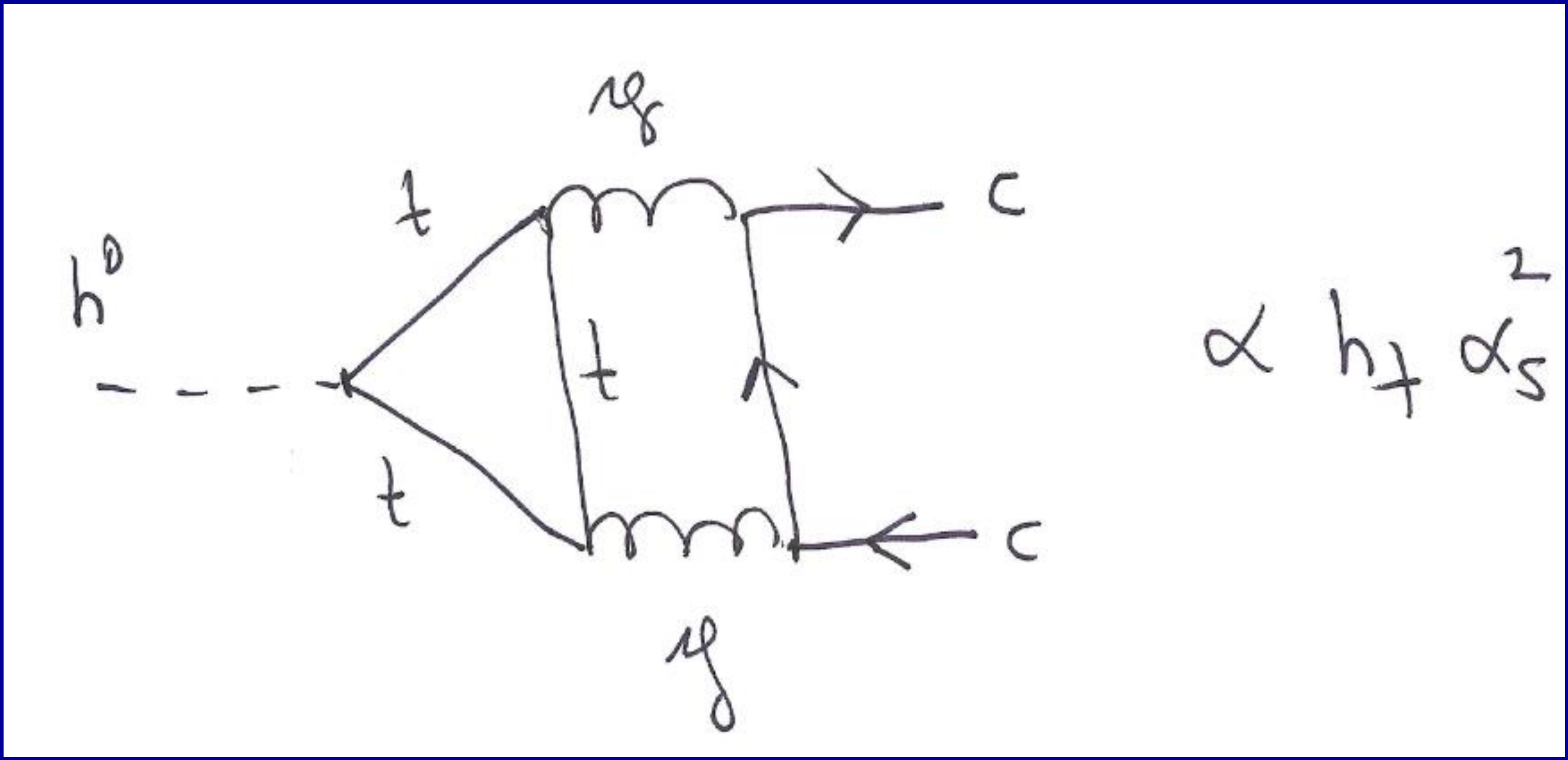
Backup Slides

Constraints on the MSSM parameters from B meson data and Higgs boson mass

Table 4: Constraints on the MSSM parameters from the B-physics experiments relevant mainly for the mixing between the second and the third generations of squarks and from the data on the h^0 mass. The fourth column shows constraints at 95% CL obtained by combining the experimental error quadratically with the theoretical uncertainty, except for m_{h^0}.

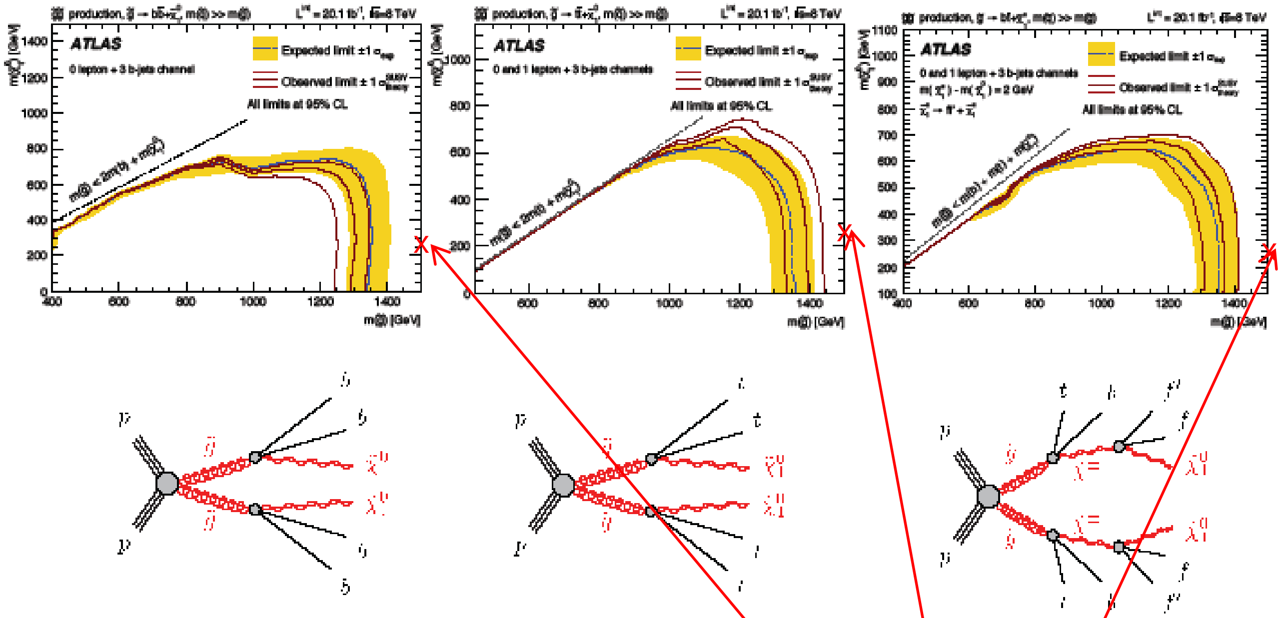
Observable	Exp. data	Theor. uncertainty	Constr. (95%CL)
ΔM_{B_s} [ps^{-1}]	17.768 ± 0.024 (68% CL) [53]	± 3.3 (95% CL) [54,55]	17.77 ± 3.30
$10^4 \times \mathrm{B}(b \to s\gamma)$	3.40 ± 0.21 (68% CL) [39]	± 0.23 (68% CL) [56]	3.40 ± 0.61
$10^6 \times \mathrm{B}(b \to s\, l^+ l^-)$ ($l = e$ or μ)	$1.60\,^{+0.48}_{-0.45}$ (68% CL) [57]	± 0.11 (68% CL) [58]	$1.60\,^{+0.97}_{-0.91}$
$10^9 \times \mathrm{B}(B_s \to \mu^+\mu^-)$	2.9 ± 0.7 (68%CL) [59–61]	± 0.23 (68% CL) [62]	2.90 ± 1.44
$10^4 \times \mathrm{B}(B^+ \to \tau^+\nu)$	1.15 ± 0.23 (68% CL) [63–65]	± 0.29 (68% CL) [63]	1.15 ± 0.73
m_{h^0} [GeV]	125.03 ± 0.30 (68% CL)(CMS) [2], 125.36 ± 0.41 (68% CL)(ATLAS) [1]	± 2 [52]	125.15 ± 2.48

Example of gluonic α_s^2 contributions



Gluino mass limit from LHC(7/8 TeV)

ATLAS ≥ 3 b-tags, 0,1 leptons

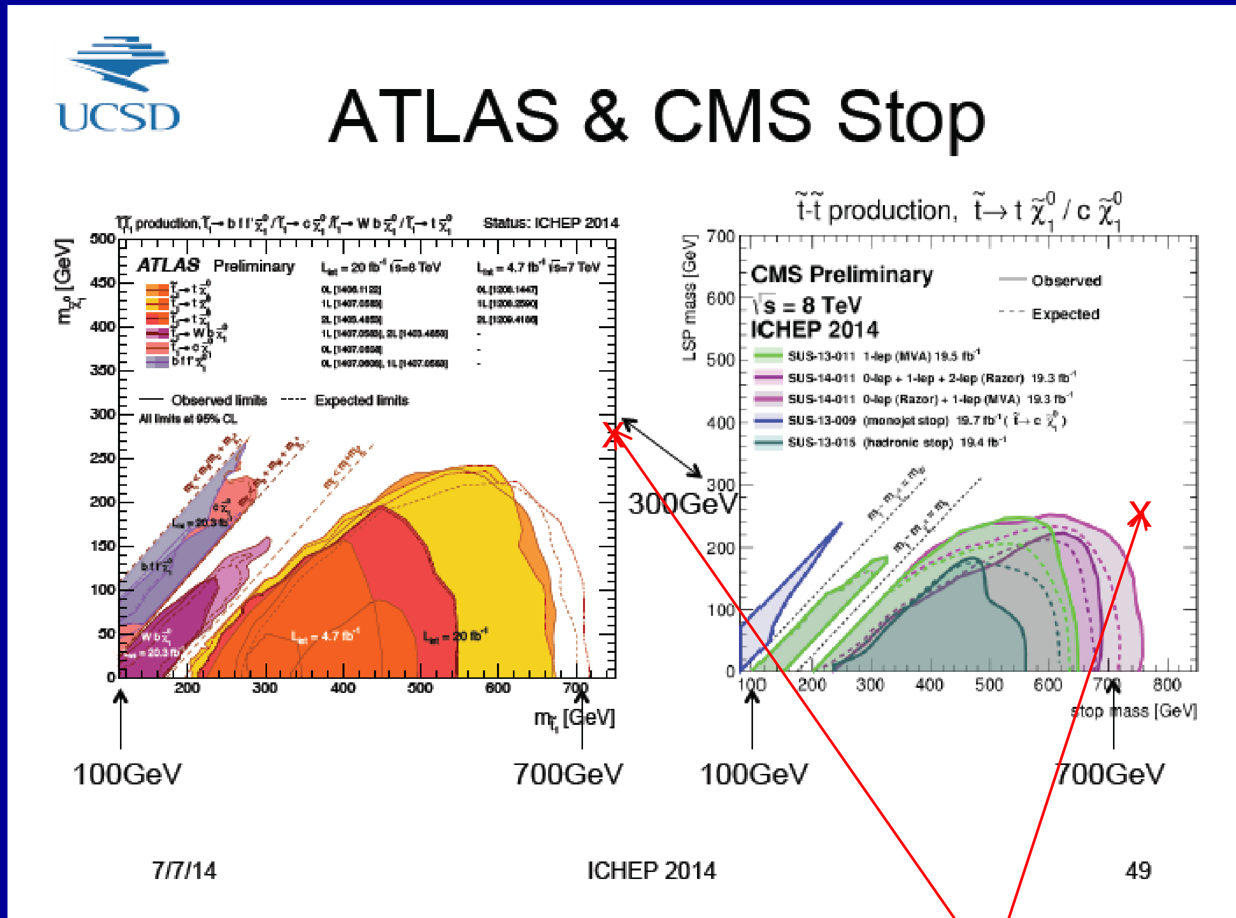


arXive: 1405.7875

7/7/14 ICHEP 2014 60

Our benchmark QFV scenario: $(m_{\tilde{g}}, m_{\tilde{\chi}_1^0}) = (1473, 260)\,\text{GeV}$

STOP mass limit from LHC(7/8 TeV)



Our benchmark QFV scenario:

$$(m_{\tilde{u}_1}, m_{\tilde{\chi}_1^0}) = (756, 260)\,\mathrm{GeV}$$

$$(m_{\tilde{u}_2}, m_{\tilde{\chi}_1^0}) = (965, 260)\,\mathrm{GeV}$$

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

From Hewett's talk at LCWS2013

Study of the pMSSM (Neutralino/Gravitino LSP)

Scan with Linear Priors

Perform large scan over Parameters

$100\ \text{GeV} \leq m_{sfermions} \leq 4\ \text{TeV}$

$50\ \text{GeV} \leq |M_1, M_2, \mu| \leq 4\ \text{TeV}$

$400\ \text{GeV} \leq M_3 \leq 4\ \text{TeV}$

$100\ \text{GeV} \leq M_A \leq 4\ \text{TeV}$

$1 \leq \tan\beta \leq 60$

$|A_{t,b,\tau}| \leq 4\ \text{TeV}$

($1\ \text{ev} \leq m_G \leq 1\ \text{TeV}$) (log prior)

Subject these points to Constraints from:

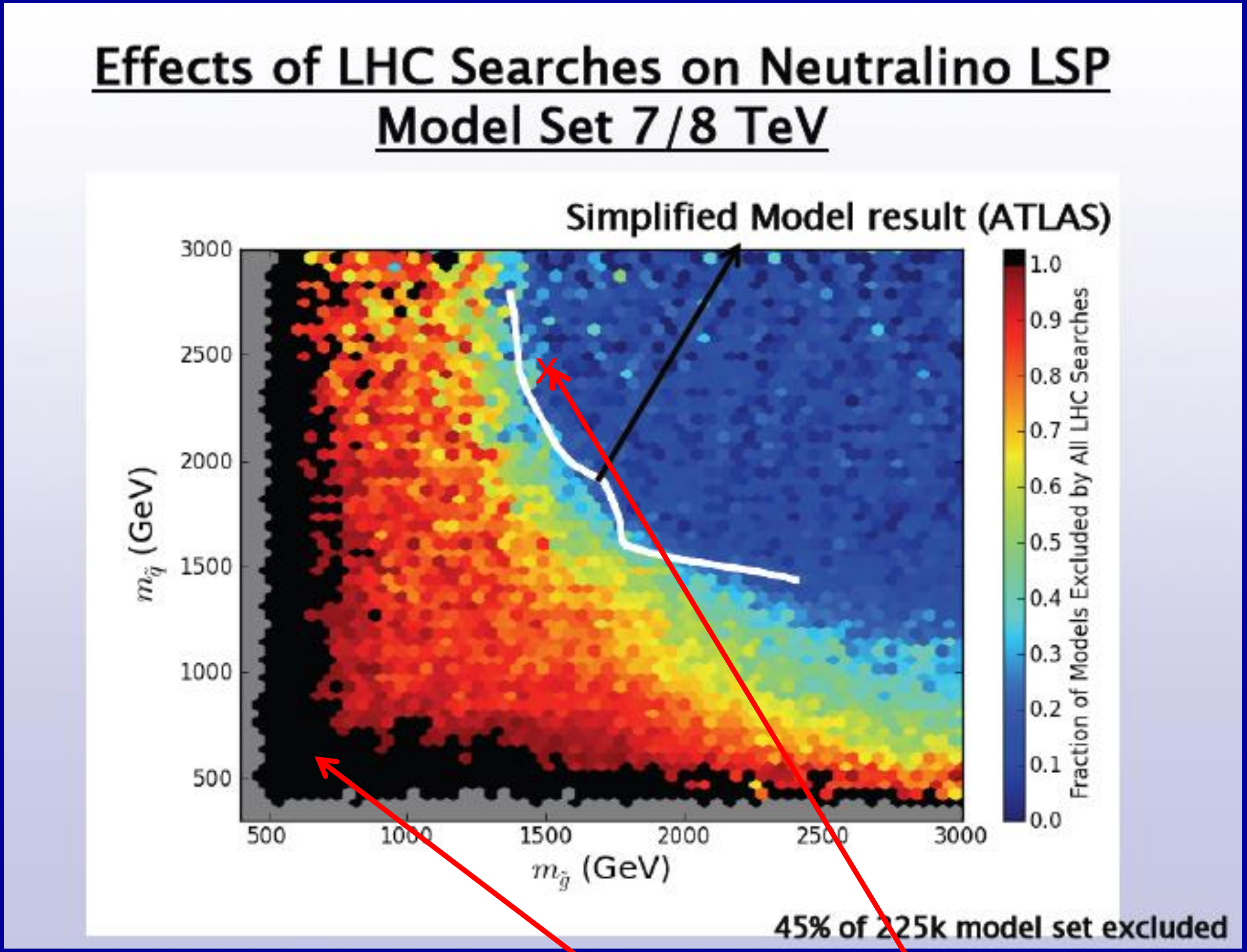
- Flavor physics
- EW precision measurements
- Collider searches
- Cosmology

~225,000 models survive constraints for each LSP type!

ATLAS MET-based SUSY Analyses @ 7/8/14 TeV

- Apply the general LHC SUSY MET-based searches to our model sets
- We (almost) exclusively follow the ATLAS analysis suite as closely as possible with fast MC (modified versions of PGS, Pythia, SoftSUSY, SDECAY, HDECAY)
- Generate signal events for every model for all 85 SUSY processes (~10^{13} events!) & scale to NLO with Prospino
- Validated our results with ATLAS benchmark models
- We combine the various signal regions (as ATLAS does) for ~ 35 analyses: and we quote the coverage for each as well as the combined result..
- This approach is CPU intensive!!

Squark - gluino mass limit from LHC(7/8 TeV)



Black area is an excluded region in pMSSM = (MSSM with MFV)

Our benchmark QFV scenario: $(m_{\tilde{g}}, m_{\tilde{q}}) \approx (1473, 2400)\,\mathrm{GeV}$

$m_{\tilde{q}}$ ***= (degenerate mass of 1st & 2nd generation squarks)***

14 TeV LHC pMSSM Coverage for 0.3 & 3 ab^{-1}

Jets+MET Analysis (ATLAS European Strategy Study)
Stop search (ATLAS Snowmass study)