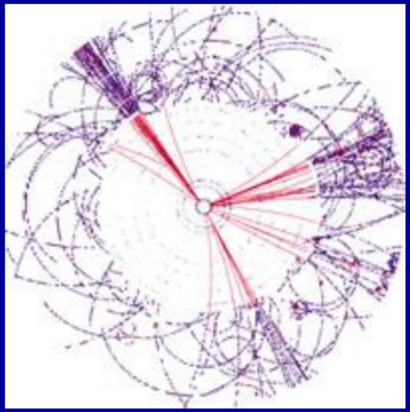
Quark Flavour Violating Bosonic Squark Decays



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Contents

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

1. Introduction

- ***Quark flavour conserving (QFC) fermionic squark decays, such as $\tilde{t}_{1,2} \to t\, \tilde{\chi}_i^0$ are usually assumed in the squark search analyss.***

- ***Here we study quark flavour violating (QFV) bosonic squark decays, such as $\tilde{u}_2 \to \tilde{u}_1\ h^0 / Z^0$, where the mass eigenstates $\tilde{u}_{1,2}$ are mixtures of scharm and stop quarks.***

- ***We point out that the branching ratios of such QFV bosonic squark decays can be very large due to the $\tilde{c}_R - \tilde{t}_{R/L}$ and $\tilde{t}_R - \tilde{t}_L$ mixing effects despite the very strong constraints on the QFV parameters from B meson data.***

- ***We show that such QFV bosonic squark decays $\tilde{u}_2 \to \tilde{u}_1\ h^0 / Z^0$ can play a very important role in the squark and gluino searches at LHC(14 TeV) and the squark searches at Lepton Colliders with E_{CM} = 1.5 TeV - 2 TeV.***

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 = 1TeV scale (SPA convention)) (α,β = 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

QFV parameters in our study are:

$M^2_{Q,23}$: $\tilde{c}_L - \tilde{t}_L$ mixing term

M^2_{U23} : $\tilde{c}_R - \tilde{t}_R$ mixing term

T_{U23} : $\tilde{c}_L - \tilde{t}_R$ mixing term

T_{U32} : $\tilde{c}_R - \tilde{t}_L$ mixing term

(Note) We work in the super-CKM basis of squarks.

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3. ***Constraints on the MSSM***

We respect the following 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 [arXiv:1202.4083].

(3) the constraints on the QFV parameters from the B physics experiments.

$$B(b \to s\,\gamma) \quad \Delta M_{Bs} \quad B(B_s \to \mu^+ \mu^-) \quad B(B_u^+ \to \tau^+ \nu)$$

(4) the constraints from the observed Higgs boson signal at LHC (allowing for theoretical uncertainty): 123 GeV < m_h^0 < 129 GeV.

(5) theoretical constraints from the vacuum stability conditions for the trilinear coupling matrices.

4. QFV bosonic squark decays

4.1 QFV Benchmark Scenario

We take the following scenario as our QFV benchmark scenario:

***These weak scale parameters are defined at Q = 1 TeV scale** (SPA convention).*

$(M_1, M_2, M_3) = (400, 800, 1000)$ GeV

$\mu = 2640$ GeV, $\tan\beta = 20$, $m_A(\text{pole}) = 1500$ GeV

$(M^2_{Q11}, M^2_{Q22}, M^2_{Q33}) = (2400\text{^}2, 2360\text{^}2, 1450\text{^}2)$ GeV^2

$(M^2_{U11}, M^2_{U22}, M^2_{U33}) = (2380\text{^}2, 780\text{^}2, 750\text{^}2)$ GeV^2

$(M^2_{D11}, M^2_{D22}, M^2_{D33}) = (2380\text{^}2, 2340\text{^}2, 2300\text{^}2)$ GeV^2

All of $T_{U\alpha\alpha}$ and $T_{D\alpha\alpha}$ are zero, except $T_{U33} = -2160$ GeV.

QFV parameters: $M^2_{U23} = 419\text{^}2$ GeV^2

$T_{U32} = -458$ GeV.

decoupling Higgs scenario

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

large $\tilde{c}_R - \tilde{t}_R$ mixing

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

h^0

Main features of the benchmark scenario

- *large QFC/QFV trilinear couplings of*

  $\tilde{t}_R - \tilde{t}_L - H_2^0$ / $\tilde{c}_R - \tilde{t}_L - H_2^0$

- *sizable scharm-stop mixing* ($\tilde{c}_R - \tilde{t}_R$ *mixing)*
- *large mass of either* $\tilde{t}_L$ *or* $\tilde{t}_R$
- *large mass of the CP-odd neutral Higgs boson* m_{A^0} *(= 1500 GeV) and large* $\tan\beta$ *(= 20).*

Decoupling-Higgs scenarios with $m_{A^0} >> m_{h^0}$

The lightest Higgs boson h^0 *is SM-like!*

Physical masses in the benchmark QFV scenario

$$m_{h^0} = 124 GeV$$

$$m_{H^0} \cong m_{H^+} \cong m_{A^0} = 1500 GeV$$

$$m_{\tilde{g}}^{pole} = 1141 GeV$$

$$m_{\tilde{u}_1} = 605 GeV$$

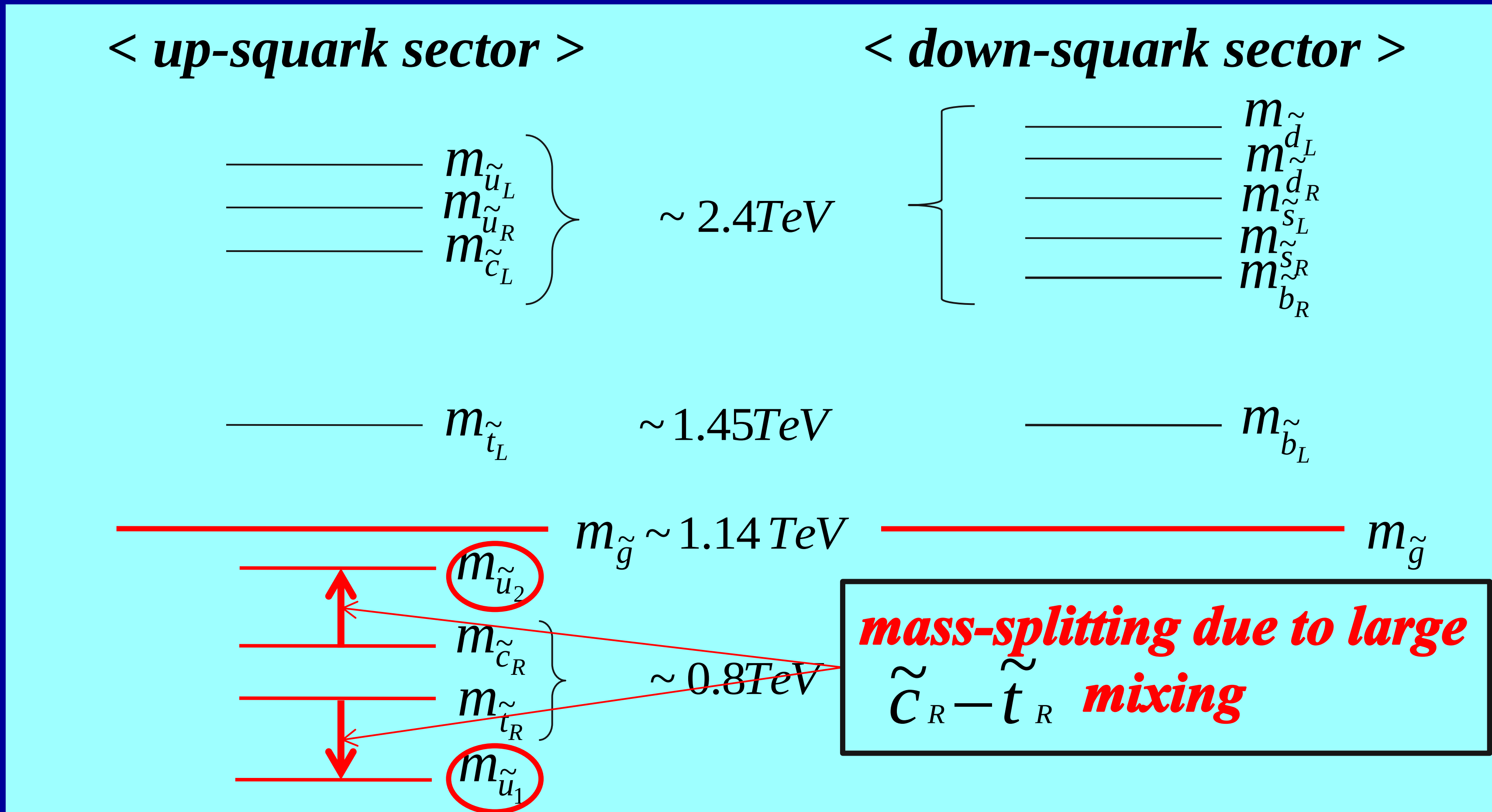
$$m_{\tilde{u}_2} = 861 GeV$$

$$m_{\tilde{u}_3} = 1477 GeV$$

- *CP-even lighter Higgs boson* ***h^0 is SM-like!***
- *its mass* ***m_{h^0} = 124 GeV is in the LHC "Higgs signal" range !*** :

123 < m_{h^0} < 129GeV.

Benchmark QFV scenario

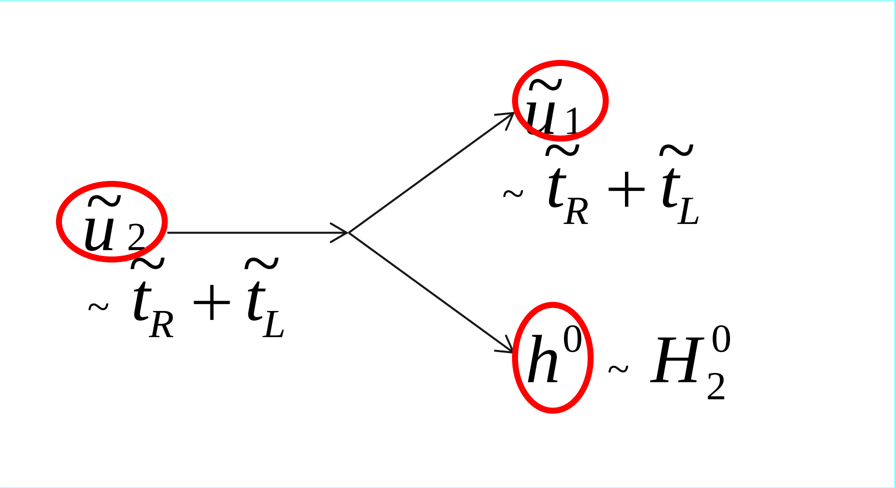


large mass splitting between $m_{\tilde{u}_1}$ ***and*** $m_{\tilde{u}_2}$ ***!***

$B(\tilde{u}_2 \to \tilde{u}_1 h^0)$ ***could be sizable!***

In this large $\tilde{c}_R - \tilde{t}_R$ & $\tilde{t}_L - \tilde{t}_R$ & $\tilde{c}_R - \tilde{t}_L$ mixing scenario;

$$\tilde{u}_1 \sim \tilde{t}_R + \tilde{c}_R + \tilde{t}_L$$
$$\tilde{u}_2 \sim \tilde{c}_R + \tilde{t}_R + \tilde{t}_L$$
$$h^0 \sim H_2^0$$



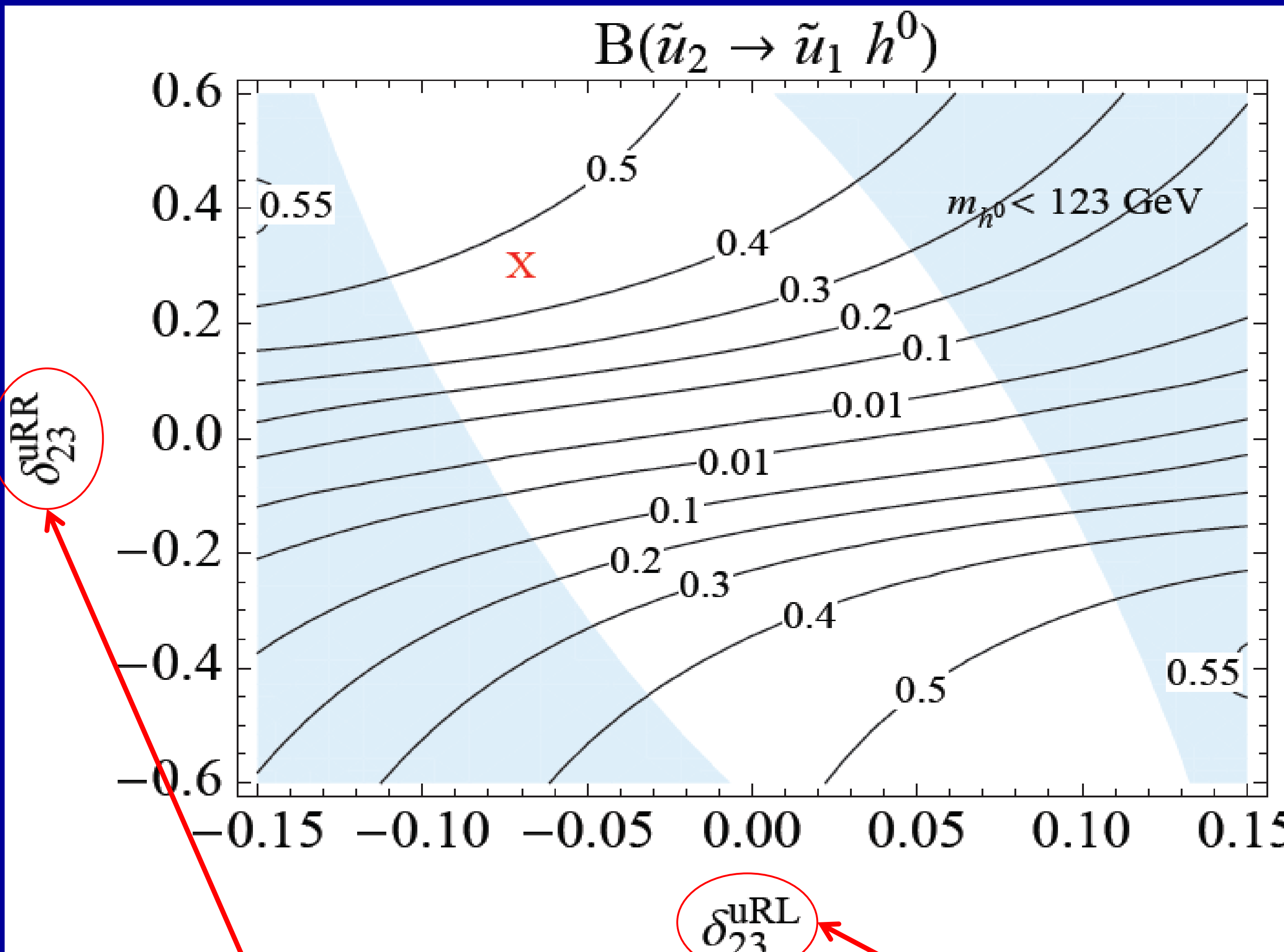
In our scenario "top trilinear coupling" ($\tilde{t}_L - \tilde{t}_R - H_2^0$ coupling) = T_{U33} is large!

$\tilde{u}_1 - \tilde{u}_2 - h^0$ **coupling is large!**

QFV branching ratio $B(\tilde{u}_2 \to \tilde{u}_1 h^0)$ can be large!

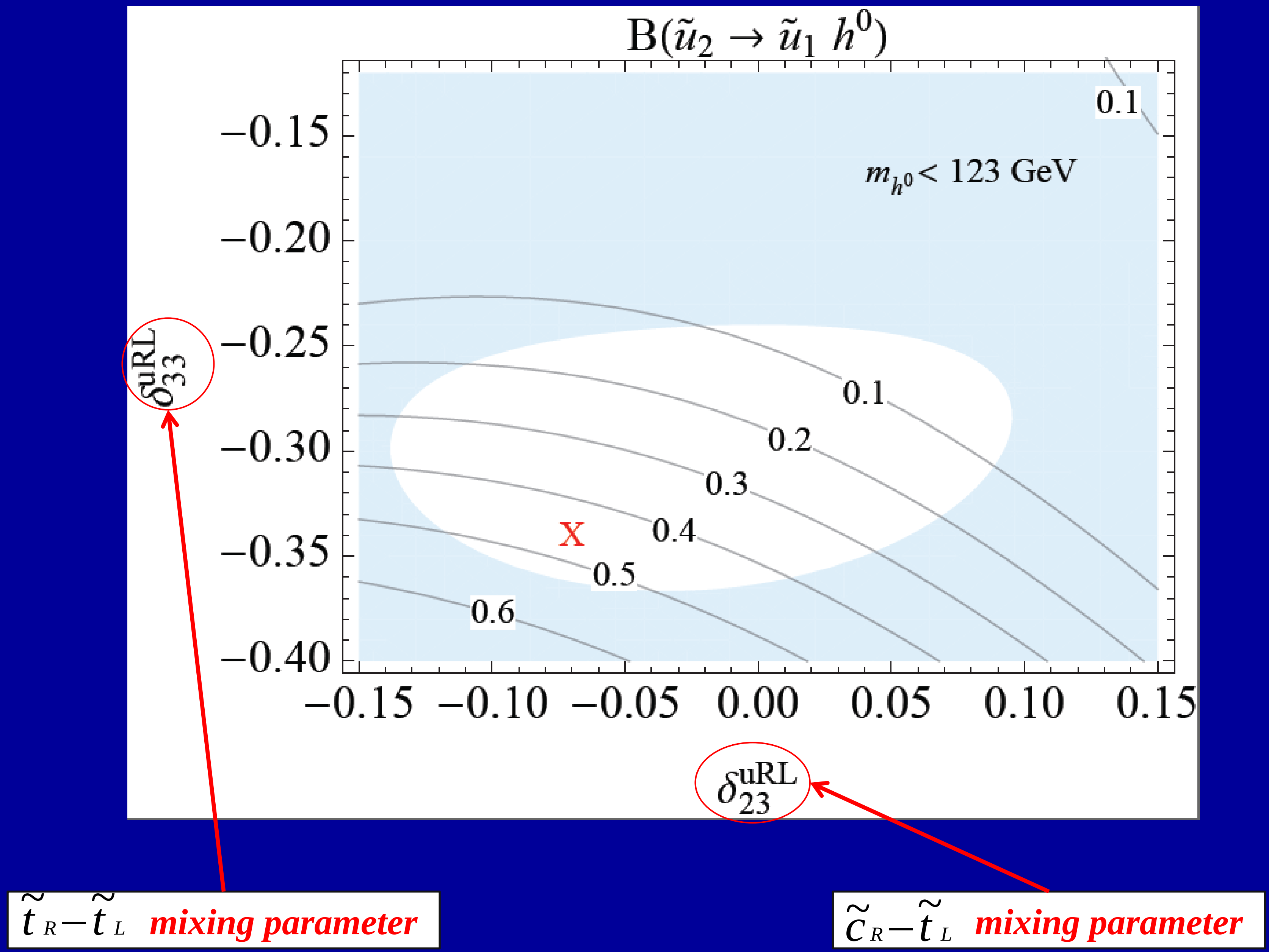
$$\delta^{uRR}_{\alpha\beta} \equiv M^2_{U\alpha\beta}/\sqrt{M^2_{U\alpha\alpha}M^2_{U\beta\beta}}\ ,$$

$$\delta^{uRL}_{\alpha\beta} \equiv (v_2/\sqrt{2})T_{U\beta\alpha}/\sqrt{M^2_{U\alpha\alpha}M^2_{Q\beta\beta}}\ .$$



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

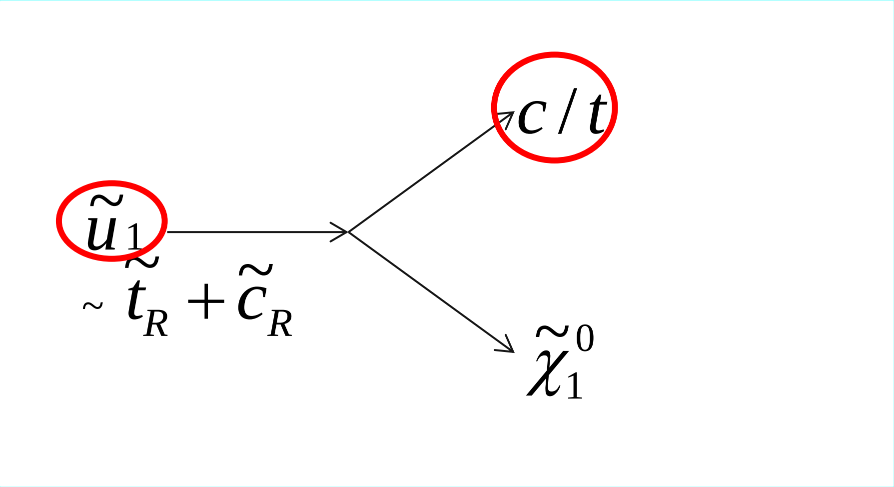
$\tilde{c}_R - \tilde{t}_L$ ***mixing parameter***



$B(\tilde{u}_2 \to \tilde{u}_1\ h^0)$
$m_{h^0} < 123$ GeV
0.1
0.1
0.2
0.3
0.4
0.5
0.6
X
−0.15
−0.20
−0.25
−0.30
−0.35
−0.40
−0.15 −0.10 −0.05 0.00 0.05 0.10 0.15
δ_{33}^{uRL}
δ_{23}^{uRL}
$\tilde{t}_R - \tilde{t}_L$ *mixing parameter*
$\tilde{c}_R - \tilde{t}_L$ *mixing parameter*

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

$\tilde{u}_1 \sim \tilde{t}_R + \tilde{c}_R + \tilde{t}_L$



QFV BR $B(\tilde{u}_1 \to c/t\ \tilde{\chi}_1^0)$ ***can be large!***

QFV BR $B(\tilde{u}_2 \to \tilde{u}_1 h^0 \to c/t\ h^0\ \tilde{\chi}_1^0)$ ***can be large!***

4.2 Impact of squark generation mixing

Squark & gluino decay branching ratio in our QFV benchmark scenario

Table 4 Two-body decay branching ratios of $\tilde{u}_2$, $\tilde{u}_1$ and gluino in scenario A of Table 1. The charge conjugated processes have the same branching ratios and are not shown explicitly.

$B(\tilde{u}_2 \to \tilde{u}_1 h^0)$	0.47
$B(\tilde{u}_2 \to \tilde{u}_1 Z^0)$	0.01
$B(\tilde{u}_2 \to c\tilde{\chi}_1^0)$	0.43
$B(\tilde{u}_2 \to t\tilde{\chi}_1^0)$	0.09
$B(\tilde{u}_1 \to c\tilde{\chi}_1^0)$	0.36
$B(\tilde{u}_1 \to t\tilde{\chi}_1^0)$	0.64
$B(\tilde{g} \to \tilde{u}_2 \bar{c})$	0.12
$B(\tilde{g} \to \tilde{u}_2 \bar{t})$	0.01
$B(\tilde{g} \to \tilde{u}_1 \bar{c})$	0.09
$B(\tilde{g} \to \tilde{u}_1 \bar{t})$	0.27

QFV squark decay BR $B(\tilde{u}_2 \to \tilde{u}_1 h^0)$ ***can be very large (~50%) !***

QFV squark decay BR $B(\tilde{u}_1 \to c/t\ \tilde{\chi}_1^0)$ ***can be very large simultaneously!***

5. Impact on squark signals at LHC

Example of QFV squark signal at LHC

Gluino pair production and the QFV squark bosonic decay can lead to

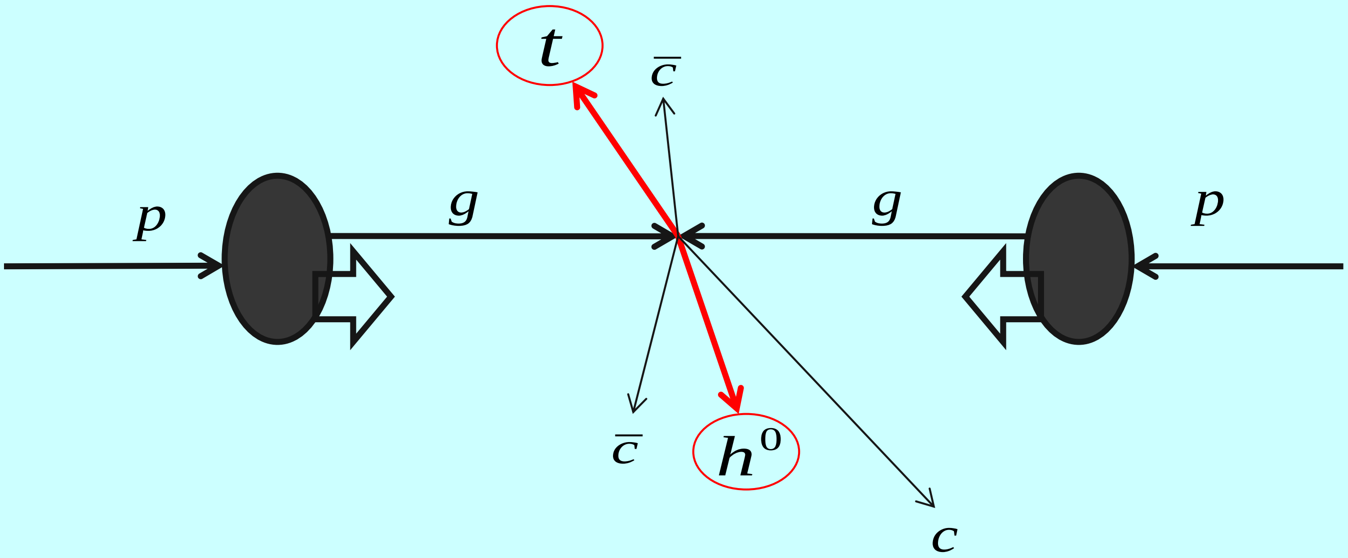
QFV squark signature at LHC :

$$pp \to \tilde{g}\tilde{g}X \to (\bar{\tilde{u}}_1 t)(\tilde{u}_2 \bar{c})X \to (\bar{\tilde{u}}_1 t)(\tilde{u}_1 h^0 \bar{c})X$$

$$\to (\bar{c}\tilde{\chi}_1^0 t)(c\tilde{\chi}_1^0 h^0 \bar{c})X \;(= tc\,\bar{c}\bar{c}h^0 E_T^{mis} X)$$

' top-quark + 3 jets + h^0 + missing-E_T + beam-jets'

Example of QFV squark signal at LHC



' top-quark + 3 jets + h^0 + missing-E_T + beam-jets'

QFV bosonic squark decay signal rates at LHC

In our scenario;

- gluino prod. cross section is significant:

  $\sigma(pp \to \tilde{g}\tilde{g}X)$ ~ 150 fb at LHC(14 TeV)!

- $B(\tilde{g} \to \tilde{u}_2 c/t)$ can be large (~ 25 %)!

↓

We can expect copious production of $\tilde{u}_2$ from gluino prod. and decays at LHC(14 TeV)!

↓

QFV bosonic squark decay signal rates can be significant at LHC(14 TeV)!

QFV bosonic squark decay signal rates can be significant at LHC(14 TeV) in our QFV benchmark scenario !:

$$\sigma(pp \to \tilde{g}\tilde{g}X \to t\,c\,\bar{c}\bar{c}h^0 E_T^{mis} X) = 4\,fb$$

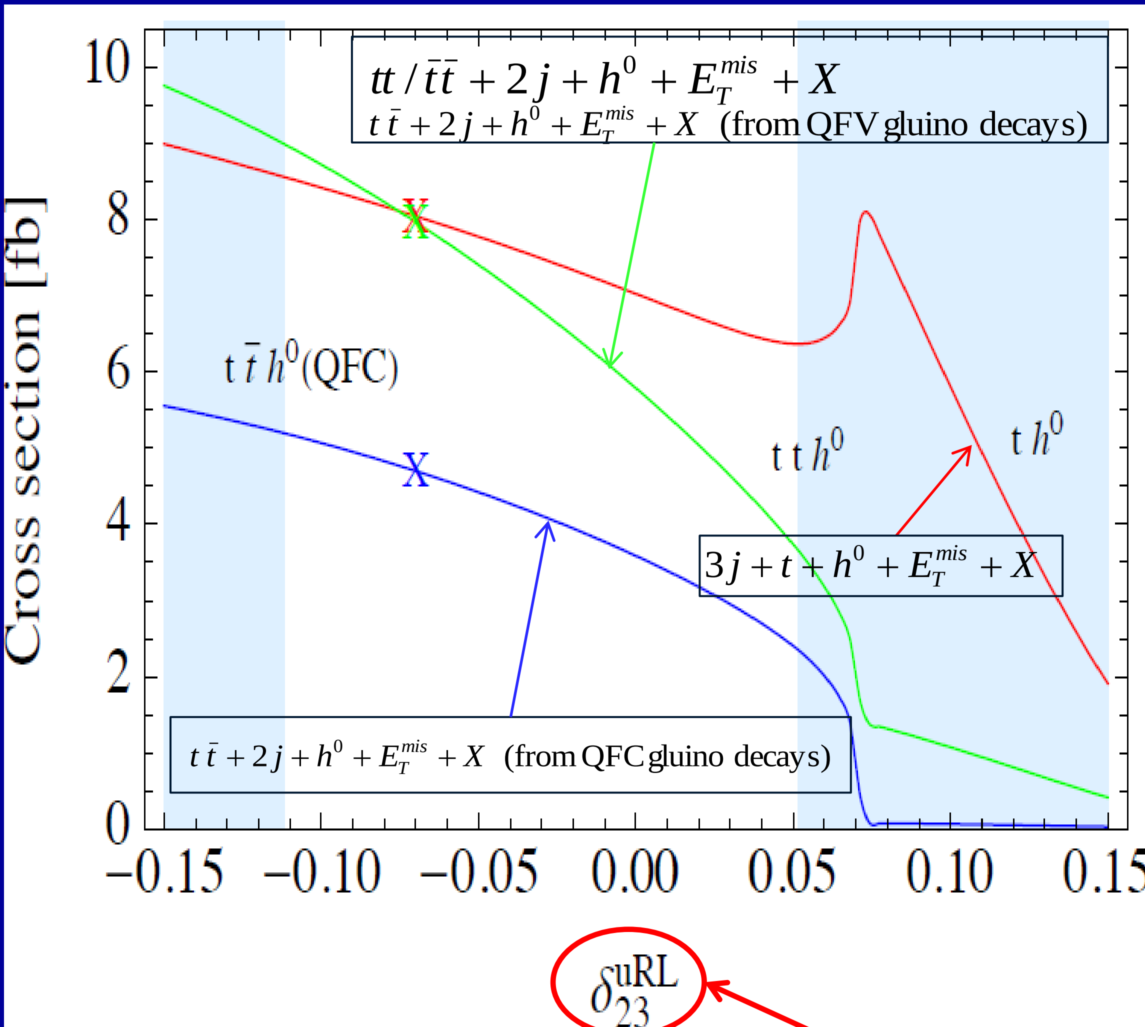
$$\sigma(pp \to \tilde{g}\tilde{g}X \to \bar{t}\,\bar{c}\,cch^0 E_T^{mis} X) = 4\,fb$$

$$\sigma(pp \to \tilde{g}\tilde{g}X \to tt\bar{c}\bar{c}h^0 E_T^{mis} X) = 2\,fb$$

$$\sigma(pp \to \tilde{g}\tilde{g}X \to \bar{t}\bar{t}cch^0 E_T^{mis} X) = 2\,fb$$

For LT=300 fb^{-1} we expect 1200, 1200, 600, 600 events for these QFV signal rates.

Signal cross sections (fb)



In Fig. 7(a) we show the cross sections for $pp \to \tilde g\tilde g X \to 3j + t + h^0 + \not{E}_T + X$ and $pp \to \tilde g\tilde g X \to 2j + 2t + h^0 + \not{E}_T + X$ in scenario A as a function of δ_{23}^{uRL}. The red solid line corresponds to the pure QFV final state $3j + t + h^0 + \not{E}_T + X$. The green solid line corresponds to the pure QFV final state $tt/\bar t\bar t + 2j + h^0 + \not{E}_T + X$ plus the final state $t\bar t + 2j + h^0 + \not{E}_T + X$ coming from the QFV gluino decays. Note that the number of the $tt/\bar t\bar t$ final state events is exactly equal to the number of the $t\bar t$ final state events coming from the QFV gluino decays due to the Majorana nature of the gluino. The blue solid line corresponds to the QFC events $t + \bar t + 2j + h^0 + \not{E}_T + X$ coming from the QFC gluino decays.

$\tilde c_R - \tilde t_L$ ***mixing parameter***

$$m_{\tilde{g}}^{pole} = 1141 GeV$$

$$m_{\tilde{u}_1} = 605 GeV$$

$$m_{\tilde{u}_2} = 861 GeV$$

$$m_{\tilde{u}_3} = 1477 GeV$$

- ***The strongly interacting sparticles produced at LHC (14 TeV) are practically only*** $\tilde{u}_{1,2}$ ***and*** $\tilde{g}$ ***in this scenario.***

- ***In case the QFV squark (*** $\tilde{u}_{1,2}$ ***) decay signals could not be observed due to significant BG at LHC(14 TeV), then we need LC(1.5-2.0 TeV) for the discovery of such squarks*** $\tilde{u}_{1,2}$ ***!!!***

6. QFV squark signals at LC

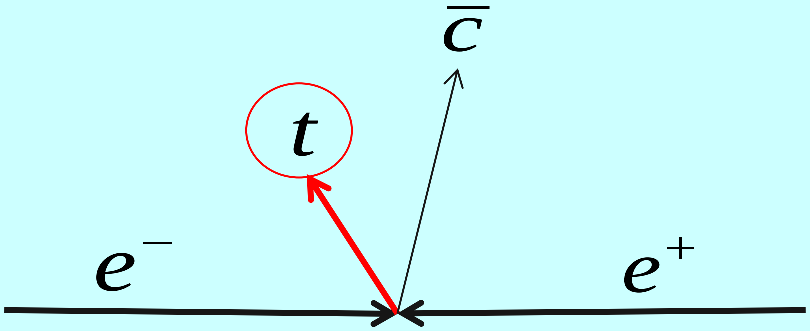
Example of QFV fermionic squark decay signal at LC

$$e^+ e^- \to \tilde{u}_1 \, \overline{\tilde{u}}_1 \to (t \, \tilde{\chi}_1^0)(\bar{c} \, \tilde{\chi}_1^0) \; (= t \, \bar{c} \, E_T^{mis})$$

⇓

' top-quark + charm-jet + missing-E_T '

Example of QFV fermionic squark decay signal at LC



' top-quark + charm-jet + missing-E_T '

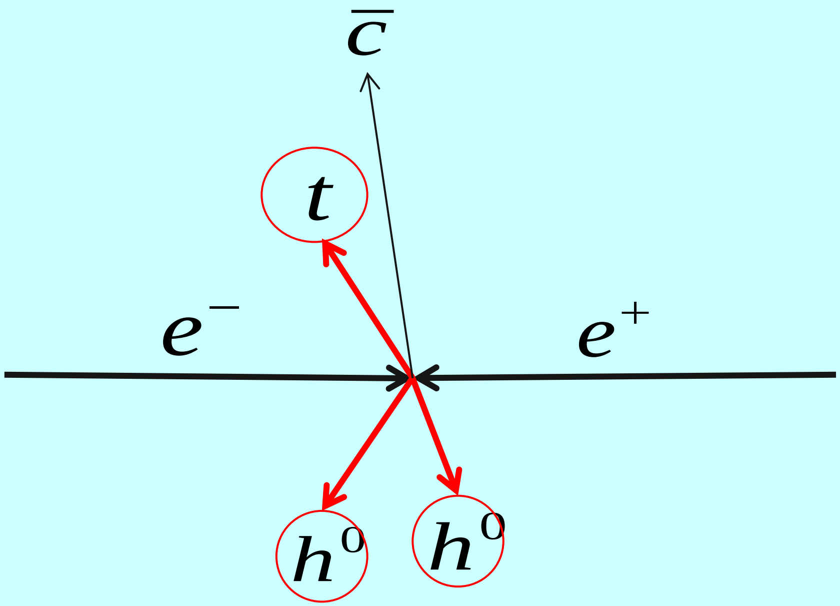
Example of QFV bosonic squark decay signal at LC

$$e^+ e^- \to \tilde{u}_2 \, \bar{\tilde{u}}_2 \to (\tilde{u}_1 h^0)(\bar{\tilde{u}}_1 h^0)$$

$$\to (t \, \tilde{\chi}_1^0 h^0)(\bar{c} \, \tilde{\chi}_1^0 h^0) \; (= t \, \bar{c} \, h^0 h^0 E_T^{mis})$$

‘ ***top-quark + charm-jet + 2h^0 + missing-E$_T$***‘

Example of QFV bosonic squark decay signal at LC



‘ top-quark + charm-jet + 2h^0 + missing-E_T ‘

7. Conclusion

- *We have shown that QFV bosonic squark decay branching ratios such as* $B(\tilde{u}_2 \to \tilde{u}_1 h^0)$ *can be very large (up to ~50%) due to the* $\tilde{c}_R - \tilde{t}_{R/L}$ *and* $\tilde{t}_R - \tilde{t}_L$ *mixings despite the very strong constraints from B meson data.*
- *This can result in remarkable QFV squark signal events, such as*

$$pp \to \tilde{g}\tilde{g}X \to tc\,\bar{c}\bar{c}h^0 + E_T^{mis} + \textit{beam-jets}$$

with a significant rate at LHC(14 TeV).

- *Our analysis suggests that one should take into account the possibility of important contributions from QFV bosonic squark decays* $\tilde{u}_2 \to \tilde{u}_1 h^0$ *in the search for squarks and gluinos and in the determination of the MSSM parameters at LHC(14 TeV).*

- ***In case the QFV squark ($\tilde{u}_{1,2}$) decay signals could not be observed due to significant BG at LHC(14 TeV), then we need LC(1.5-2.0 TeV) for the discovery of such squarks $\tilde{u}_{1,2}$!!!***

END

Backup Slides

Possible signatures from the decays of $\tilde{u}_2$ into h^0 and Z^0 at LHC

Table 9: Possible final states containing at least one Higgs boson h^0 expected from the decays of $\tilde{u}_2$ into h^0 and Z^0. t denotes top-quark or anti-top-quark; j denotes a $c/\bar{c}$-quark jet; $\not{E}_T$ is missing transverse energy due to the two LSP neutralinos $\tilde{\chi}_1^0$ in the final state; X contains only the beam jets. Note that in general the states with h^0 replaced by Z^0 are also possible. We also give the corresponding cross sections in scenario A, in case they exceed 1 fb. We indicate by "QFV" the final states which are explicitely QFV.

processes	final states containing h^0	
$pp \to \tilde{u}_2\bar{\tilde{u}}_2X$	$2j + h^0 + \not{E}_T + X$ (1.5 fb)	
	$j + t + h^0 + \not{E}_T + X$ (2.8 fb);	QFV
	$2t + h^0 + \not{E}_T + X$	
	$2j + 2h^0 + \not{E}_T + X$	
	$j + t + 2h^0 + \not{E}_T + X$ (1 fb);	QFV
	$2t + 2h^0 + \not{E}_T + X$	
	$2j + h^0 + Z^0 + \not{E}_T + X$	
	$j + t + h^0 + Z^0 + \not{E}_T + X$;	QFV
	$2t + h^0 + Z^0 + \not{E}_T + X$	

processes	final states containing h^0	
$pp \to \tilde{g}\tilde{g}X$	$4j + h^0 + \not{E}_T + X$ (2 fb)	
	$3j + t + h^0 + \not{E}_T + X$ (8 fb);	QFV
	$2j + 2t + h^0 + \not{E}_T + X$ (13 fb);	8 fb QFV
	$4j + 2h^0 + \not{E}_T + X$	
	$3j + t + 2h^0 + \not{E}_T + X$;	QFV
	$2j + 2t + 2h^0 + \not{E}_T + X$	
	$4j + h^0 + Z^0 + \not{E}_T + X$	
	$3j + t + h^0 + Z^0 + \not{E}_T + X$;	QFV
	$2j + 2t + h^0 + Z^0 + \not{E}_T + X$	