SUSY FCNC at the LHC

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Flavour Physics at LHC run II

Outline

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    - Flavour-changing interactions in SUSY
    - R-parity conserving and violating SUSY models
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4. Other relevant flavour changing interactions in SUSY
    - Direct FCNC production @ LHC
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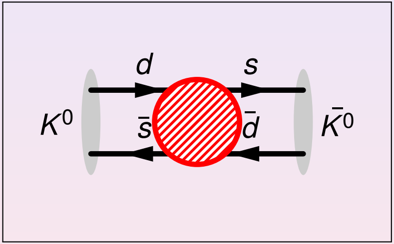
5. Conclusions

Introduction

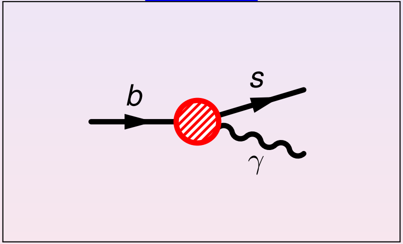
Flavour Changing Neutral Courrents (FCNC)

- FCNC are processes in which one up-type (or down-type) quark is converted into another one of the same type.

$K^0 - \bar{K}^0$



$b \to s\gamma$



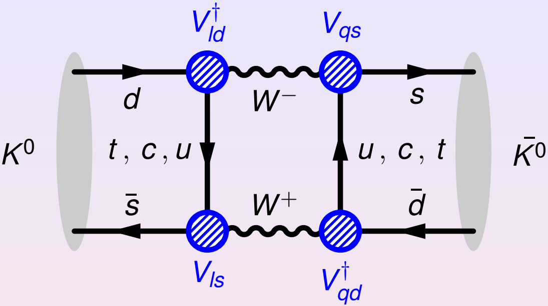
- Effect of mixing: Mass matrix

$$\begin{pmatrix} m_K^2 & A \\ A & m_K^2 \end{pmatrix} \Rightarrow \text{Diagonalize} \Rightarrow m^2_{K_{1,2}} = m_K^2 \pm A$$

- Mass difference $\Delta m_K \equiv |m_{K_1} - m_{K_2}|$: signal of FCNC

Standard Model

- FCNC absent at the tree-level
- Produced at one-loop by
    - charged currents
    - Cabibbo-Kobayashi-Maskawa mixing matrix (V)
- GIM Mechanism



S. L. Glashow, J. Iliopoulos and L. Maiani, Phys. Rev. **D2**, 1285–1292 (1970).

$\Rightarrow$ Unitarity of the CKM matrix: $\sum_q V_{qs} V^\dagger_{qd} = 0$

- Loop induced $\bigoplus$ GIM $\Longrightarrow$ FCNC processes have very small rates

New Physics (NP)

New Physics $\Longrightarrow$ New FCNC Sources

– Strong constraints from low energy data

- Ideal place to get indirect evidence of NP
- So far, most of experimental results on flavor observables are consistent with SM expectations and lead to strong indirect constraints on NP models
- Increase the sensitivity of flavour experiments & More precision on theoretical determination
- Here we will focus on some SUSY contributions to flavour observables

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⇓

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New Physics: Supersymmetry

Flavour-changing interactions in SUSY

- Minimal Flavor Violation (MFV) in the MSSM
  - FC phenomena is analogue to the SM case
    → supersymmetrization of the one-loop SM contributions
  - squarks are assumed to be aligned with quarks
  - originates from CKM matrix as the only source and proceeds via loop-contributions
  - the size is expected to be small
- Non Minimal Flavor Violation (NMFV) in the MSSM
  - Additional FC phenomena is due to misalignment between the rotations that diagonalize quark/squark sectors (beyond CKM)
  - arise at tree level
  - sizeable contributions are expected to occur

Flavour-changing interactions in SUSY

- Supersymmetry allows for flavour-mixing terms in the scalar-quark mass matrix
- Squark Mixing:

$$\mathcal{M}^2_{\tilde{q}} = \begin{pmatrix} M^2_Q + m^2_q + \cos 2\beta(T_3 - Q_q \sin\theta^2_W)M^2_Z & m_q(A - \mu\{\cot\beta, \tan\beta\}) \\ m_q(A - \mu\{\cot\beta, \tan\beta\}) & M^2_{U,D} + m^2_q + \cos 2\beta Q_q \sin\theta^2_W M^2_Z \end{pmatrix}$$

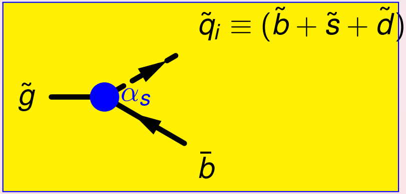
M^2_Q, A, $M^2_{U,D}$ are 3 × 3 matrices in generation space

- Flavour Mixing parameters

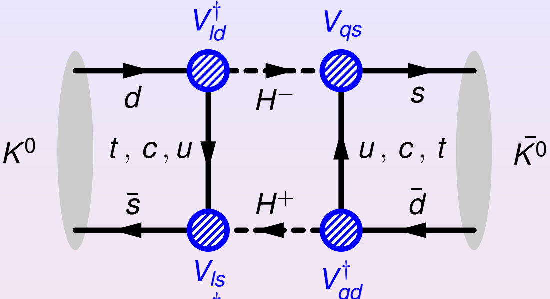
$$\delta_{ij} = \frac{\mathcal{M}^2_{ij}}{\mathcal{M}_{ii}\mathcal{M}_{jj}}$$

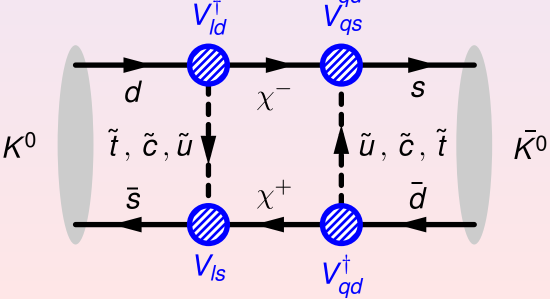
⇒ induces strong FCNC interactions!

SUSY-QCD tree-level gluino coupling



- ⇒ extra FCNC induced at one-loop and CKM by extra charged particles: $H^{\pm}$ and $\chi^{\pm}$





Constraints

- Limits from Low Energy Data

  F. Gabbiani *et. al.* **Nucl. Phys B** 477, 321 (1996)

  - $K^0\bar{K}^0$ ($d\bar{s} \leftrightarrow \bar{d}s$): $\Delta m_K \Longrightarrow \delta^d_{12}$
  - $D^0\bar{D}^0$ ($c\bar{u} \leftrightarrow \bar{c}u$): $\Delta m_D \Longrightarrow \delta^u_{12}$
  - $B^0\bar{B}^0$ ($b\bar{d} \leftrightarrow \bar{b}d$): $\Delta m_B \Longrightarrow \delta^d_{13}$

$$\boxed{\begin{array}{lcl} \delta_{12} & \lesssim & .1\,\sqrt{m_{\tilde{u}}\,m_{\tilde{c}}}/500\,\mathrm{GeV} \\ \delta_{13} & \lesssim & .098\,\sqrt{m_{\tilde{u}}\,m_{\tilde{t}}}/500\,\mathrm{GeV} \\ \delta_{23} & \lesssim & 8.2\,m_{\tilde{c}}\,m_{\tilde{t}}/(500\,\mathrm{GeV})^2 \end{array}}$$

- New *B*-data from Belle, Babar, LHC: additional constraints
- The Flavour-Changing terms are communicated from the up- to the down-sector by CKM e.g. M.Misiak *et. al.*, hep-ph/9703442

  Due to $SU(2)_L$ gauge invariance

$$\begin{array}{cccc} (M^d_{LL})^2 & = CKM^\dagger \times & (M^u_{LL})^2 & \times CKM \\ \nparallel & & \nparallel & \\ (M^d_{LL})^2_{\mathrm{DIAG}} & & \mathbb{1}\,\tilde{M}^2 & \end{array}$$

$\Rightarrow$ the bounds are transfered to the up-quark sector

$\Rightarrow$ top-charm FCNC are constrained by *b*-sector measurements.

Flavour-changing interactions in SUSY

- R-parity conserving SUSY models: MFV and NMFV
  - Provides elegant solutions to the dark matter and hierarchy problems.
  - Leads to natural GUT
- R-parity violating (RPV) SUSY:
  - RPV terms are allowed in the superpotential:

$$W = W_{MSSM} + \lambda_{ijk} L_i L_j \bar{E}_k + \lambda^{'}_{ijk} L_i Q_j \bar{D}_k + k_i L_i H_u + \lambda^{''}_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

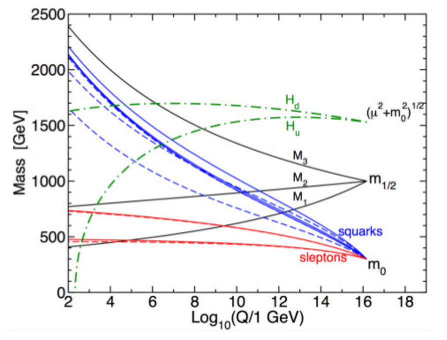
Lepton number violating Baryon number viol.

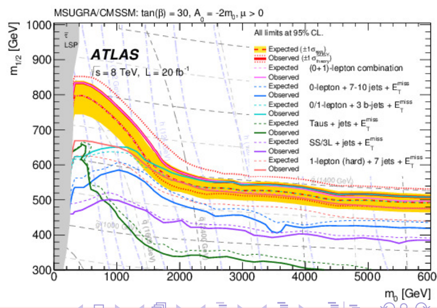
  - Resonant/associated single SUSY particle production is possible
  - Could explain large mixing angles and hierarchical masses of neutrinos
  - The lightest SUSY particle (LSP) is no longer stable
  - No dark matter candidate :-(
- Other non-minimal extensions exist, e.g. one extra Higgs (NMSSM), extra $U(1)$ groups ($Z^{'}$), extra neutrinos (see-saw models), etc.

Approaches for probing SUSY

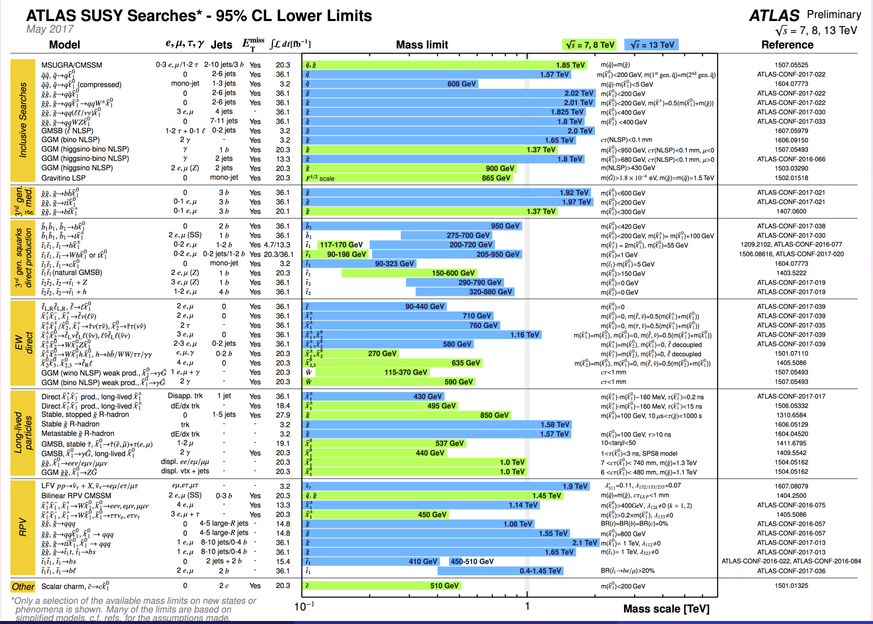
Most common approaches for probing SUSY:

- Concrete models: e.g. mSUGRA/CMSSM, GMSB:
  - easy interpretability as a full theory
  - but, rigid relationships of parameters, not necessarily realistic: all masses related to few parameters: m_0 , $m_{\frac{1}{2}}$, μ
- Simplified models: very reduced, accessible spectrum
  - focus on decay chains to which LHC is sensitive, easier to reinterpret
  - not a full SUSY model





SUSY searches in simplified models



ATLAS SUSY Searches* - 95% CL Lower Limits

May 2017

ATLAS Preliminary

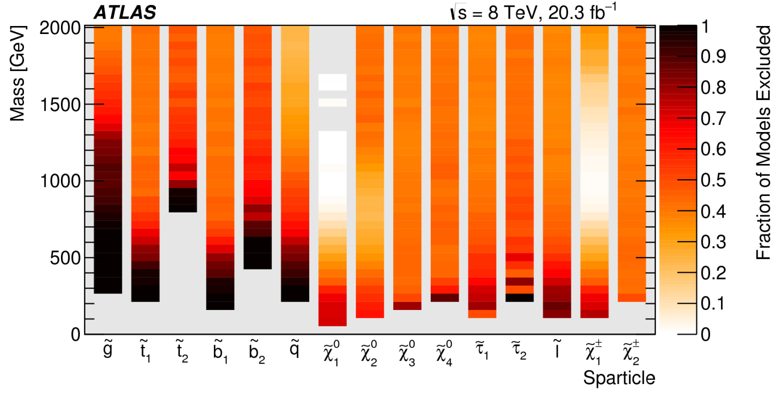
$\sqrt{s}$ = 7, 8, 13 TeV

🟩 $\sqrt{s}$ = 7, 8 TeV 🟦 $\sqrt{s}$ = 13 TeV

	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e,μ/1-2 τ	2-10 jets/3 b	Yes	20.3	$\tilde{q},\tilde{g}$ 1.85 TeV	m($\tilde{q}$)=m($\tilde{g}$)	1507.05525
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$	0	2-6 jets	Yes	36.1	$\tilde{q}$ 1.57 TeV	m($\tilde{\chi}^0_1$)<200 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	ATLAS-CONF-2017-022
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$ (compressed)	mono-jet	1-3 jets	Yes	3.2	$\tilde{q}$ 608 GeV	m($\tilde{q}$)-m($\tilde{\chi}^0_1$)<5 GeV	1604.07773
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0	2-6 jets	Yes	36.1	$\tilde{g}$ 2.02 TeV	m($\tilde{\chi}^0_1$)<200 GeV	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^\pm_1\to qqW^\pm\tilde{\chi}^0_1$	0	2-6 jets	Yes	36.1	$\tilde{g}$ 2.01 TeV	m($\tilde{\chi}^0_1$)<200 GeV, m($\tilde{\chi}^\pm$)=0.5(m($\tilde{\chi}^0_1$)+m($\tilde{g}$))	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\nu\nu)\tilde{\chi}^0_1$	3 e,μ	4 jets	-	36.1	$\tilde{g}$ 1.825 TeV	m($\tilde{\chi}^0_1$)<400 GeV	ATLAS-CONF-2017-030
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}^0_1$	0	7-11 jets	Yes	36.1	$\tilde{g}$ 1.8 TeV	m($\tilde{\chi}^0_1$) <400 GeV	ATLAS-CONF-2017-033
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	$\tilde{g}$ 2.0 TeV		1607.05979
	GGM (bino NLSP)	2 γ	-	Yes	3.2	$\tilde{g}$ 1.65 TeV	$c\tau$(NLSP)<0.1 mm	1606.09150
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	$\tilde{g}$ 1.37 TeV	m($\tilde{\chi}^0_1$)<950 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	13.3	$\tilde{g}$ 1.8 TeV	m($\tilde{\chi}^0_1$)>680 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	ATLAS-CONF-2016-066
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	$\tilde{g}$ 900 GeV	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale 865 GeV	m($\tilde{G}$)>1.8 × 10^{-4} eV, m($\tilde{g}$)=m($\tilde{q}$)=1.5 TeV	1502.01518
3rd gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{b}\tilde{\chi}^0_1$	0	3 b	Yes	36.1	$\tilde{g}$ 1.92 TeV	m($\tilde{\chi}^0_1$)<600 GeV	ATLAS-CONF-2017-021
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	Yes	36.1	$\tilde{g}$ 1.97 TeV	m($\tilde{\chi}^0_1$)<200 GeV	ATLAS-CONF-2017-021
	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{t}\tilde{\chi}^+_1$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.37 TeV	m($\tilde{\chi}^0_1$)<300 GeV	1407.0600
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_1$	0	2 b	Yes	36.1	$\tilde{b}_1$ 950 GeV	m($\tilde{\chi}^0_1$)<420 GeV	ATLAS-CONF-2017-038
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}^\pm_1$	2 e,μ (SS)	1 b	Yes	36.1	$\tilde{b}_1$ 275-700 GeV	m($\tilde{\chi}^0_1$)<200 GeV, m($\tilde{\chi}^\pm_1$)= m($\tilde{\chi}^0_1$)+100 GeV	ATLAS-CONF-2017-030
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}^\pm_1$	0-2 e,μ	1-2 b	Yes	4.7/13.3	$\tilde{t}_1$ 117-170 GeV 200-720 GeV	m($\tilde{\chi}^\pm_1$) = 2m($\tilde{\chi}^0_1$), m($\tilde{\chi}^0_1$)=55 GeV	1209.2102, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}^0_1$ or $t\tilde{\chi}^0_1$	0-2 e,μ	0-2 jets/1-2 b	Yes	20.3/36.1	$\tilde{t}_1$ 90-198 GeV 205-950 GeV	m($\tilde{\chi}^0_1$)=1 GeV	1506.08616, ATLAS-CONF-2017-020
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}^0_1$	0	mono-jet	Yes	3.2	$\tilde{t}_1$ 90-323 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)=5 GeV	1604.07773
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 150-600 GeV	m($\tilde{\chi}^0_1$)>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1 + Z$	3 e,μ (Z)	1 b	Yes	36.1	$\tilde{t}_2$ 290-790 GeV	m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2017-019
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1 + h$	1-2 e,μ	4 b	Yes	36.1	$\tilde{t}_2$ 320-880 GeV	m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2017-019
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0	Yes	36.1	$\tilde{\ell}$ 90-440 GeV	m($\tilde{\chi}^0_1$)=0	ATLAS-CONF-2017-039
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	36.1	$\tilde{\chi}^\pm_1$ 710 GeV	m($\tilde{\chi}^0_1$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	ATLAS-CONF-2017-039
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_2$, $\tilde{\chi}^+_1\to\tilde{\tau}\nu(\tau\tilde{\nu})$, $\tilde{\chi}^0_2\to\tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1	$\tilde{\chi}^\pm_1$ 760 GeV	m($\tilde{\chi}^0_1$)=0, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	ATLAS-CONF-2017-035
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	36.1	$\tilde{\chi}^\pm_1,\tilde{\chi}^0_2$ 1.16 TeV	m($\tilde{\chi}^\pm_1$)=m($\tilde{\chi}^0_2$), m($\tilde{\chi}^0_1$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	ATLAS-CONF-2017-039
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to W\tilde{\chi}^0_1Z\tilde{\chi}^0_1$	2-3 e,μ	0-2 jets	Yes	36.1	$\tilde{\chi}^\pm_1,\tilde{\chi}^0_2$ 580 GeV	m($\tilde{\chi}^\pm_1$)=m($\tilde{\chi}^0_2$), m($\tilde{\chi}^0_1$)=0, $\tilde{\ell}$ decoupled	ATLAS-CONF-2017-039
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to W\tilde{\chi}^0_1h\tilde{\chi}^0_1$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde{\chi}^\pm_1,\tilde{\chi}^0_2$ 270 GeV	m($\tilde{\chi}^\pm_1$)=m($\tilde{\chi}^0_2$), m($\tilde{\chi}^0_1$)=0, $\tilde{\ell}$ decoupled	1501.07110
	$\tilde{\chi}^0_2\tilde{\chi}^0_3$, $\tilde{\chi}^0_{2,3}\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}^0_{2,3}$ 635 GeV	m($\tilde{\chi}^0_2$)=m($\tilde{\chi}^0_3$), m($\tilde{\chi}^0_1$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}^0_2$)+m($\tilde{\chi}^0_1$))	1405.5086
	GGM (wino NLSP) weak prod., $\tilde{\chi}^0_1\to\gamma\tilde{G}$	1 e,μ + γ	-	Yes	20.3	$\tilde{W}$ 115-370 GeV	$c\tau$<1 mm	1507.05493
	GGM (bino NLSP) weak prod., $\tilde{\chi}^0_1\to\gamma\tilde{G}$	2 γ	-	Yes	20.3	$\tilde{W}$ 590 GeV	$c\tau$<1 mm	1507.05493
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}^\pm_1$ 430 GeV	m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)~160 MeV, τ($\tilde{\chi}^\pm_1$)=0.2 ns	ATLAS-CONF-2017-017
	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}^\pm_1$ 495 GeV	m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)~160 MeV, τ($\tilde{\chi}^\pm_1$)<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 850 GeV	m($\tilde{\chi}^0_1$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	3.2	$\tilde{g}$ 1.58 TeV		1606.05129
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	$\tilde{g}$ 1.57 TeV	m($\tilde{\chi}^0_1$)=100 GeV, τ>10 ns	1604.04520
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}^0_1\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}^0_1$ 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}^0_1\to\gamma\tilde{G}$, long-lived $\tilde{\chi}^0_1$	2 γ	-	Yes	20.3	$\tilde{\chi}^0_1$ 440 GeV	1<τ($\tilde{\chi}^0_1$)<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}$, $\tilde{\chi}^0_1\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}^0_1$ 1.0 TeV	7 <$c\tau$($\tilde{\chi}^0_1$)< 740 mm, m($\tilde{g}$)=1.3 TeV	1504.05162
	GGM $\tilde{g}\tilde{g}$, $\tilde{\chi}^0_1\to Z\tilde{G}$	displ. vtx + jets	-	-	20.3	$\tilde{\chi}^0_1$ 1.0 TeV	6 <$c\tau$($\tilde{\chi}^0_1$)< 480 mm, m($\tilde{g}$)=1.1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau + X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu$,$e\tau$,$\mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$ 1.9 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q},\tilde{g}$ 1.45 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to W\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to ee\nu, e\mu\nu, \mu\mu\nu$	4 e,μ	-	Yes	13.3	$\tilde{\chi}^\pm_1$ 1.14 TeV	m($\tilde{\chi}^0_1$)>400GeV, $\lambda_{12k}\neq0$ (k = 1, 2)	ATLAS-CONF-2016-075
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to W\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to\tau\tau\nu_e, e\tau\nu_\tau$	3 e,μ + τ	-	Yes	20.3	$\tilde{\chi}^\pm_1$ 450 GeV	m($\tilde{\chi}^0_1$)>0.2×m($\tilde{\chi}^\pm_1$), $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqq$	0	4-5 large-R jets	-	14.8	$\tilde{g}$ 1.08 TeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to qqq$	0	4-5 large-R jets	-	14.8	$\tilde{g}$ 1.55 TeV	m($\tilde{\chi}^0_1$)=800 GeV	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to qqq$	1 e,μ	8-10 jets/0-4 b	-	36.1	$\tilde{g}$ 2.1 TeV	m($\tilde{\chi}^0_1$)= 1 TeV, $\lambda_{112}\neq0$	ATLAS-CONF-2017-013
	$\tilde{g}\tilde{g}$, $\tilde{g}\to\tilde{t}_1t$, $\tilde{t}_1\to bs$	1 e,μ	8-10 jets/0-4 b	-	36.1	$\tilde{g}$ 1.65 TeV	m($\tilde{t}_1$)= 1 TeV, $\lambda_{323}\neq0$	ATLAS-CONF-2017-013
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$	0	2 jets + 2 b	-	15.4	$\tilde{t}_1$ 410 GeV 450-510 GeV		ATLAS-CONF-2016-022, ATLAS-CONF-2016-084
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\ell$	2 e,μ	2 b	-	36.1	$\tilde{t}_1$ 0.4-1.45 TeV	BR($\tilde{t}_1\to be/\mu$)>20%	ATLAS-CONF-2017-036
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}^0_1$	0	2 c	Yes	20.3	$\tilde{c}$ 510 GeV	m($\tilde{\chi}^0_1$)<200 GeV	1501.01325

**Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.*

pMSSM: 19 parameters (R_p-conserving)



MSUGRA	pMSSM
$m_{\tilde{g}} > 1.85$ TeV	50% of models with $m_{\tilde{g}} > 1.4$ TeV allowed
$m_{\tilde{q}} > 1.85$ TeV	50% of models with $m_{\tilde{q}} > 0.6$ TeV allowed
$m_{\chi_1^+} > 0.71$ TeV	50% of models with $m_{\chi_1^+} > 0.1$ TeV allowed

pMSSM scans provide powerful way to reinterpret existing searches in context of full SUSY models

New Physics Beyond the SM at the LHC

There are few anomalies show in data hinting the need of new physics

$B_s \to \mu^+\mu^- \quad \sim \quad 2\sigma$

$B \to D^{(*)}\tau\nu \quad \sim \quad 4\sigma$

$B_s \to K^* l^+ l^- \ (R_{K^*}) \quad \sim \quad 2.1 - 2.5\sigma$

$h \to \mu\tau \quad \sim \quad 2\sigma$ (Run1) - No excess any more

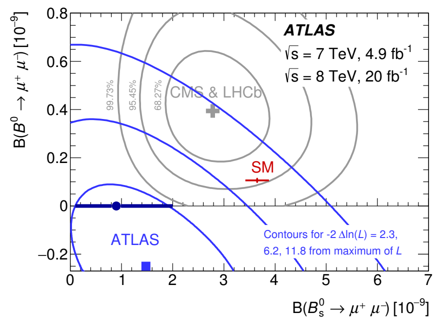
(B anomalies – See talks by Mescia, Martinez-Vidal, Kosnik and Capdevila on Wednesday, May 24)

(LFV – See talk by Fiorini on Monday, May 22)

How SUSY could accomodate these results?

$B_s \to \mu^+\mu^-$

ATLAS, Eur. Phys. J. C 76 (2016) 513, arXiv:1604.04263

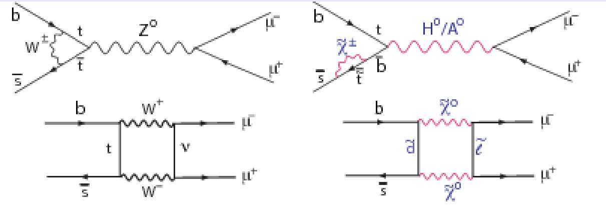


- ATLAS is consistent with the LHCb and CMS
- ATLAS consistency with SM is 2.0
- Room for NP destructively interfering with the SM

- CMS and LHCb observation: $BR(B^0_d \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4})\times 10^{-10}, BR(B^0_s \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6})\times 10^{-9}$
- ATLAS: $BR(B^0_d \to \mu^+\mu^-) < 4.2 \times 10^{-10}\,, 95\% C.L.,$
  $BR(B^0_s \to \mu^+\mu^-) < 3 \times 10^{-9}\,, 95\% C.L.,$
  $BR(B^0_s \to \mu^+\mu^-) = (0.9^{+1.1}_{-0.8}) \times 10^{-9}$

Rare decays: $B_s \to \mu^+\mu^-$

SM SUSY



- SM prediction accurate: Bobeth, arXiv:1405.4907

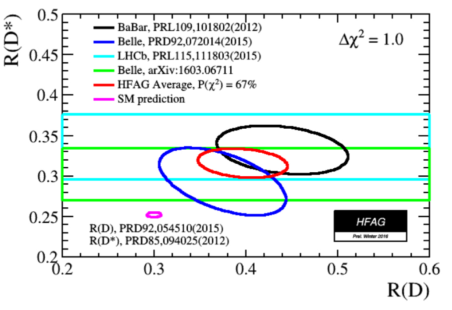
$$BR(B_s^0 \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$$

- SUSY
  - Enhancement by a factor of order $\tan^6 \beta$
  - Implications on the viability of SUSY (constrained and unconstrained models): Arbey, Battaglia, et al.
    - BR in the MSSM does not deviate from its SM prediction
    - LHC results remove 10% of the scan points in the CMSSM and a few % in the pMSSM
  - Room for NP (SUSY) opened

$B \to D^{(*)}\tau\nu$

$$R(D) = \frac{BR(\bar{B}^0 \to D^+\tau^-\bar{\nu}_\tau)}{BR(\bar{B}^0 \to D^+l^-\bar{\nu}_l)}, \quad R(D^*) = \frac{BR(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{BR(\bar{B}^0 \to D^{*+}l^-\bar{\nu}_l)}$$

PRL 115, 111803 (2015)

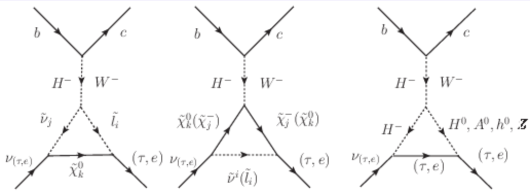


- The combined results disagree with the SM expectations at $\sim 4\sigma$
- In the SM, the only difference between the numerator and the denominator is the lepton mass
- Sensitive test to NP at tree level
- Inconsistent with Type II THDM ...
- SUSY has the potential to explain recent data

Boubaa et al, 1604.0341

$B \to D^{(*)}\tau\nu$

SUSY

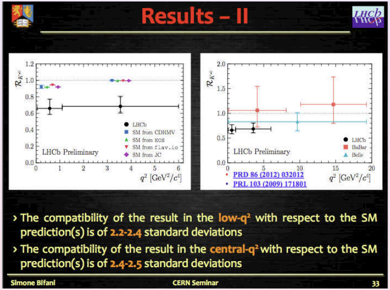


What needed to solve the anomaly? (Xiao-Gang He, SUSY 2016)

- Exp: More precise measurements!
- Theor: New Physics modify charged current interaction... in a way that
  a) The first two and third generations interact differently;
  b) Have P-parity conserving and violating ones differently!
  THDM-II cannot explain both
  SUSY OK (clear signal), Boubaa et al, 1604.0341.
- This is a striking hint of violation of the lepton flavour universality which clearly needs also to be checked in other modes.

$B \to K^* l^+ l^- \ (R_{K^*})$

- Experimental: At present no serious problems at colliders
  Deviations $2-3\sigma$ appear from time to time:
  - LHCb: CERN seminar 18/04/2017:



Results – II

› The compatibility of the result in the low-q² with respect to the SM prediction(s) is of 2.2-2.4 standard deviations

› The compatibility of the result in the central-q² with respect to the SM prediction(s) is of 2.4-2.5 standard deviations

Simone Bifani CERN Seminar 33

$$\mathcal{R}_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu-)}{\mathcal{B}(B^0 \to K^{*0}e^+e-)} =$$

$$\begin{cases} 0.660^{+0.110}_{-0.070} \pm 0.024 & \text{low } q^2 \\ 0.685^{+0.113}_{-0.069} \pm 0.047 & \text{central } q^2 \end{cases}$$

- SM prediction: 1
  (Lepton Flavour Universality)
- Papers explanation:
  NP: $Z^{'}$, leptoquarks

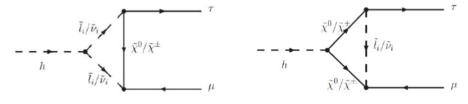
- ? SUSY with RPV:
  R_p-violation superpotential: $W = ... + \lambda^{'}_{ijk} L_i Q_j \bar{D}_k + ...$
  ???... sfermions behave as leptoquarks... (Work in progress)

LFV Higgs decay $h \to \mu\tau$?

- The CMS and ATLAS collaborations reported the first signal of LFV Higgs $h \to \mu\tau$ (Run1)

$$BR(h \to \mu\tau) = 8.4^{+3.9}_{3.7} \times 10^{-3} \text{ (CMS)}$$
$$BR(h \to \mu\tau) = (7.7 \pm 6.2) \times 10^{-3} \text{ (ATLAS)}$$

- The SM predicts no tree-level LFV Higgs coupling
- MSSM: loop processes mediated by charginos or neutralinos.



- However, SUSY models with non-zero family mixing in the sleptons also result in enhancement in other LFV processes such as $\mu \to e\gamma$, $\tau \to e\gamma$, and $\tau \to \mu\gamma$ $\Rightarrow$ Important correlation between observables
- Run2: The limits can be used to constrain the corresponding flavour violating Yukawa couplings, absent in the standard model.

Other relevant flavour changing interactions in SUSY

Model Setup

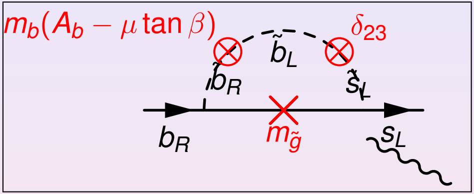
- Generic Minimal Supersymmetric Standard Model
- Scan over the parameters space:
  - ⇒ works done some years ago
  - ⇒ similar to present pMSSM scenarious
  - ⇒ updated
- Flavour violation terms only in the Left-Left sector
  - ⇒ Naturally generated by Renormalization Group Equations
  - ⇒ (results similar with Right-Right and Left-Right mixing)

$B(b \to s\gamma)$

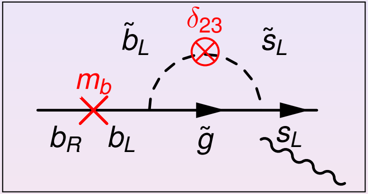
Borzumati **ZPC63** (1994) 291, hep-ph/9310212; Borzumati, Greub, Hurt, Wyler, **PRD62** (2000) 075005, hep-ph/9911245.

[True for Left-Left mixing only!]

- FCNC SUSY-QCD contribution:



Leading, Double insertion



Sub-Leading, Single insertion

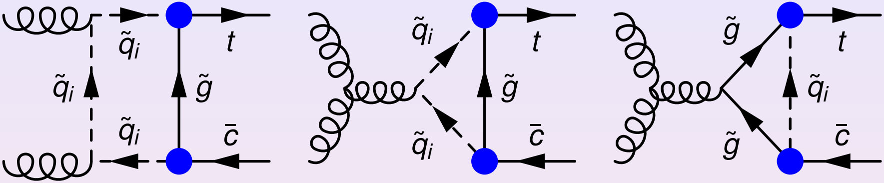
- The Feynman Amplitude:

$$A^{SUSY-QCD}(b \to s\gamma) \sim \delta_{23} \frac{m_b(A_b - \mu \tan\beta)}{M^2_{SUSY}} \times \frac{1}{m_{\tilde{g}}}$$

- Similar coupling structure in $pp \to t\bar{c}$ $(\sim m_t(A_t - \mu/\tan\beta))$ but different in $Hqq^{'}$ $(\sim \mu)$
- Relevant interplay between observables

Direct FCNC production @ LHC

$\boxed{pp[gg] \to tc}$



- Some previous works

  J.J. Lui *et al.*, **Nucl. Phys. B** 705 (2005) 3, hep-ph/0404099
  G. Eilam, M. Frank, I. Turan, **Phys.Rev.D74** (2006) 035012, hep-ph/0601253
  J. Guasch, W. Hollik, S.P., J. Sola, **Nucl. Phys. Proc. Suppl.** 157 (2006) 152, hep-ph/0601218

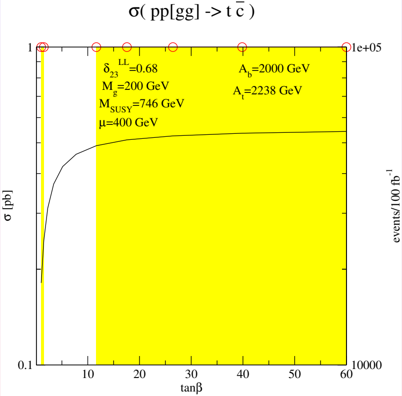
- Leading terms from Left-Left sector: similar structure to $b \to s\gamma$

$$A(gg \to t\bar{c}) \sim \delta_{23} \frac{m_t(A_t - \mu/\tan\beta)}{M^2_{SUSY}} \times \frac{1}{m_{\tilde{g}}}$$

- Large rates $\Longrightarrow$ Large δ_{23} and Large $(A_t - \mu/\tan\beta)$
  - high sensitivity to A_t

$pp[gg] \rightarrow t\bar{c}$

$$\sigma(pp[gg] \rightarrow t\bar{c}) \sim (\delta_{23})^2 \frac{m_t^2(A_t - \mu/\tan\beta)^2}{M_{SUSY}^4} \frac{1}{m_{\tilde{g}}^2}$$



$BR^{exp}(b \rightarrow s\gamma) \sim (2.1 - 4.5) \times 10^{-4}$ (within 3σ)

- For small $\tan\beta$ there are no restrictions from $b \rightarrow s\gamma$ and σ increases as $\sim A_t^2$
  - $\Rightarrow$ $\sigma^{max}(pp[gg] \rightarrow t\bar{c} + \bar{t}c) \simeq 1$ pb and $\sim 10^5$ events for 100 fb^{-1}
- Cross-section decay significantly with M_{SUSY} and very fast with $M_{\tilde{g}}$
  - $\Rightarrow$ For $M_{\tilde{g}} \sim 500$ GeV: $\sigma^{max}(pp[gg] \rightarrow tc) \simeq 0.04$ pb
  - $\Rightarrow$ Cross-sections ~ 0.5 pb possible
  - $\Rightarrow$ $\sim 100,000$ events$/100$ fb^{-1} for $t\bar{c} + \bar{t}c$ processes

$\sigma^{SM}(pp[gg] \rightarrow t\bar{c}) \sim 3.6 \times 10^{-7}$ pb → 6 orders of magnitude larger than SM!

Comparison with Higgs FCNC

- Take parameters of maximum $\sigma(pp \to h \to t\,c)$: Large M_{SUSY} and $m_{\tilde{g}}$

$$M_{SUSY} \simeq m_{\tilde{g}} \simeq 880\,\mathrm{GeV}, \mu \simeq -700\,\mathrm{GeV}, \delta_{23} \simeq 10^{-0.1} \simeq 0.79$$

$$\sigma(pp \to H^0 \to t\bar{c} + \bar{t}c) \simeq 2.5 \times 10^{-3}\text{ pb}\ \ [\tan\beta = 5]$$

$$\boxed{\sigma(pp[gg] \to t\bar{c}) \simeq 1.8 \times 10^{-3}\text{ pb}}$$

$\Rightarrow$ Same order of magnitude as Higgs-mediated FCNC !?

Higgs FCNC @ LHC

$$\begin{aligned}
\sigma(pp \to h \to q\,q') &\equiv \sigma(pp \to hX)B(h \to q\,q') \\
&\equiv \sigma(pp \to hX)\frac{\Gamma(h \to q\,\bar{q}' + \bar{q}\,q')}{\sum_i \Gamma(h \to X_i)} \quad (qq' \equiv bs \text{ or } tc)\,.
\end{aligned}$$

- Computation:
  - $\sigma(pp \to hX)$: HIGLU and HQQ packages

    M. Spira, hep-ph/9510347; `http://people.web.psi.ch/~spira/higlu/`, and `...~spira/hqq/`.
  - $\Gamma(h \to X)$: FCNC FCHDECAY

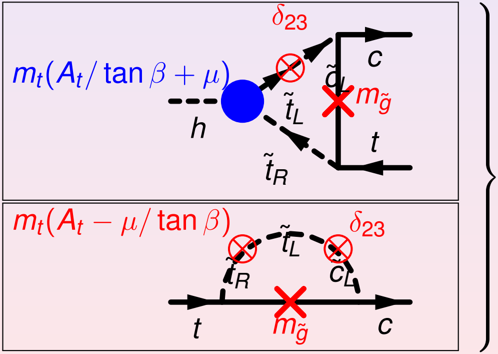
    S. Béjar, J. Guasch; `http://fchdecay.googlepages.com`
  - $\Gamma(h \to q\bar{q}')$: SUSY-QCD contributions
    - Don't assume alignment
    - Exact diagonalization of 6 × 6 squark mass matrix
    - Assume mixing only in the LL sector
- SM values:

$$\begin{aligned}
BR(H^{SM} \to b\bar{s}) &\lesssim 10^{-7} \quad (m_H < 2M_W) \\
&\lesssim 10^{-10} \quad (m_H > m_t)
\end{aligned}
\qquad \Bigg| \qquad
BR(H^{SM} \to t\bar{c}) \lesssim 10^{-13}$$

Leading contributions

- Diagrams with a chirality flip are enhanced by $m_{\tilde{g}}$: mass-insertion approximation

$H \to tc$



- The terms proportional to A_t cancel in the sum.

  J.Guasch, P.Häfliger, M.Spira

  PRD68 115001, 2003, hep-ph/0305101

- Equivalent structure for *bs*-channel

Leading contributions

- We can write an effective Lagrangian:

$$G_{Hqq'} \sim \delta_{23} \frac{m_{\tilde{g}}\,\mu}{M^2_{SUSY}} \left\{ \begin{array}{cc} \cos(\beta-\alpha_{\rm eff}) & (h^0) \\ \sin(\beta-\alpha_{\rm eff}) & (H^0) \\ 1 & (A^0) \end{array} \right. \xrightarrow[\alpha_{\rm eff}\to\beta-\pi/2]{M_{A^0}\gg M_Z} \left. \begin{array}{cc} 0 & (h^0) \\ 1 & (H^0) \\ 1 & (A^0) \end{array} \right\}$$

D. A. Demir, Phys. Lett. **B571**, 193–208 (2003), `hep-ph/0303249`.

- Different coupling structure in Hqq' ($\sim \mu$) and $bs\gamma$ ($\sim A_b - \mu\tan\beta$)
  $\Rightarrow$ Possibility of small contribution to $A(b \to s\gamma)$ and large contribution to $BR(H \to qq')$
- Numerical results $BR(h \to qq')$

  Find the maximum BR: MSSM parameter space scan:

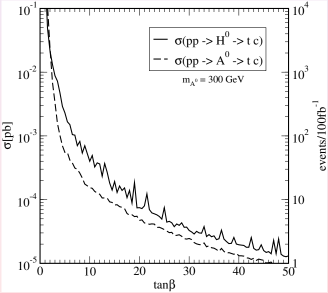
  $\boxed{BR(h \to bs) \lesssim 10^{-3}}$ $\boxed{BR(h \to tc) \sim 10^{-3}}$

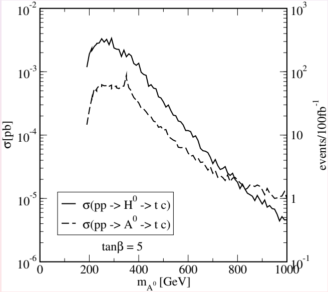
  $\Longrightarrow$ several orders of magnitude larger than in the SM!!

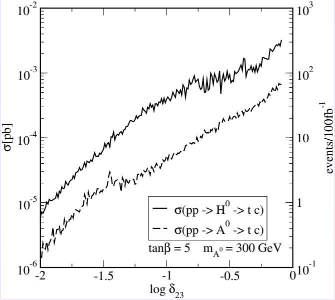
Combination with production

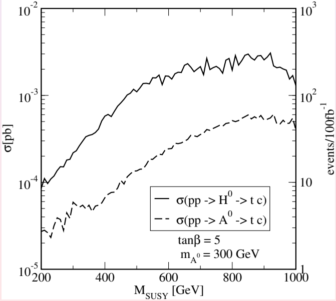
Combined analysis $\sigma(pp \to h \to tc)$

- Only H^0/A^0 possible
- Large at small $\tan\beta$
- differences at small M_{A^0}:
  - Near threshold for $H^0 \to \tilde{q}_1\tilde{q}_1$
  - not possible for A^0









The best situation

- Maximum at maximal δ_{23}
- Maximum at maximal M_{SUSY}

$M_{A^0} = 300\,\mathrm{GeV}, \tan\beta = 5$

h	H^0	A^0
$\sigma(pp \to h \to t\,c)$	2.4×10^{-3} pb	5.8×10^{-4} pb
events/100 fb^{-1}	240	58
$B(h \to tc)$	1.9×10^{-3}	5.7×10^{-4}
$\Gamma(h \to X)$	$0.41\,\mathrm{GeV}$	$0.39\,\mathrm{GeV}$
δ_{23}	0.79	0.83
$m_{\tilde{q}}$	$880\,\mathrm{GeV}$	$850\,\mathrm{GeV}$
A_t	$-2590\,\mathrm{GeV}$	$2410\,\mathrm{GeV}$
μ	$-700\,\mathrm{GeV}$	$-930\,\mathrm{GeV}$
$B(b \to s\gamma)$	4.13×10^{-4}	4.47×10^{-4}

$\tan\beta$	4	3	2
$\sigma(pp \to H^0 \to tc)$	5 fb	9 fb	20 fb
events/100 fb^{-1}	500	900	2000

$\Rightarrow$ increases fast at low $\tan\beta$

$\Rightarrow$ several thousand events could be produced

Comparison with direct FCNC production

- Not taking parameters of maximum $\sigma(pp \to h \to t\,c)$: small $m_{\tilde{g}}$

$$m_{\tilde{g}} \simeq 200\,\mathrm{GeV}, M_{SUSY} \simeq 800\,\mathrm{GeV}, |\mu| \simeq 700\,\mathrm{GeV}, \delta_{23} \simeq 0.7$$

$$\sigma(pp \to H^0 \to t\bar{c} + \bar{t}c) \simeq 10^{-3}\ \mathrm{pb}\ \ [\tan\beta = 5]$$

$$\boxed{\sigma(pp[gg] \to t\bar{c}) \simeq 0.5\ \mathrm{pb}}$$

⇒ 2-3 orders of magnitude larger than Higgs-mediated FCNC

SUSY FCNC at the LHC

- Effects at LHC: $\boxed{\sigma(pp[gg] \to t\bar{c})}$, $\sigma(pp \to h \to t\bar{c})$
- Direct production is competitive to Higgs-mediated processes

  ⇒ **Direct process can give much larger rates**

Parameter	Higgs-mediated	Direct production
$\tan\beta$	Decreases fast	insensitive
M_{A^0}	Decreases fast	insensitive
M_{SUSY}	Prefers large	Decreases fast
A_t	insensitive	very sensitive
δ_{23}	Moderate	Moderate

- Left-Left flavour mixing gives large rates
- Experimental issues:
  - Signal: single top-quark + light c-jet

    ⇒ Evidence of new physics

CONCLUSIONS

FCNC processes can be a helpful signature of SUSY physics at the LHC

- FCNCs are part of SUSY
- Constrained by low energy data
- Constrained by B-anomalies and LFV at the LHC
  - The results remove ONLY between 10% – 2% of the scan points in general SUSY models
- Room for NP (SUSY) opened
- Run II data expected to increase precisions ...

Some works

- $H \to bs$, $H \to tc$ MSSM

  A. M. Curiel, M. J. Herrero, W. Hollik, F. Merz, S. P., Phys. Rev. D **69** (2004) 075009 [hep-ph/0312135].

  A. M. Curiel, M. J. Herrero, D. Temes, Phys. Rev. D **67** (2003) 075008 [hep-ph/0210335].

- $H \to bs + b \to s\gamma$

  S. Béjar, F. Dilmé, J. Guasch and J. Solà, JHEP **0408** (2004) 018 [hep-ph/0402188].

  T. Hahn, W. Hollik, J.I. Illana, S. P., hep-ph/0512315.

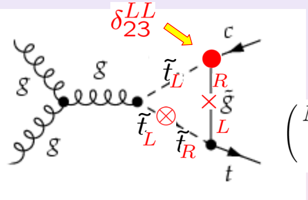
- $pp \to H$ + $H \to bs$ + $H \to tc$ + $b \to s\gamma$

  S. Béjar, J. Guasch, J. Solà, JHEP **0510** (2005) 113, hep-ph/0508043

- ...

Leading terms

Typical behavior of the cross-section



``stop'' mass matrix:

$$\begin{pmatrix} M_{\tilde{Q}}^2 + \mathcal{O}(M_Z^2) & \boxed{m_t \, M_{LR}^t} \\ \boxed{m_t \, M_{LR}^t} & M_{\tilde{Q}}^2 + \mathcal{O}(M_Z^2) \end{pmatrix}$$

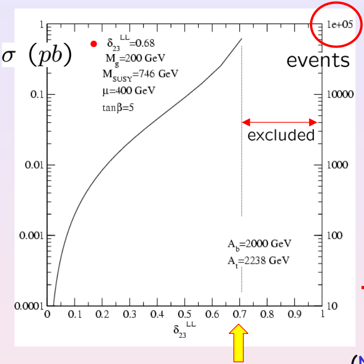
Amplitude:

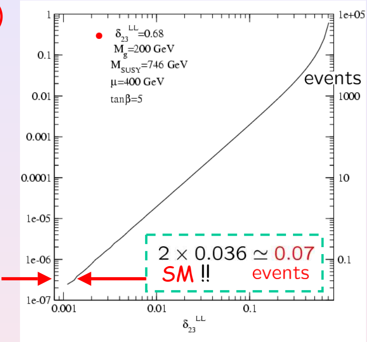
$$(M_{LR}^t = A_t - \mu/\tan\beta)$$

$$A(pp[gg] \to t\bar{c}) \sim \delta_{23}^{LL} \times \frac{m_t(A_t - \mu/\tan\beta)}{M_{SUSY}^2} \times \frac{1}{m_{\tilde{g}}}$$

$$(\sigma \sim |A(pp[gg] \to t\bar{c})|^2)$$

$$\boxed{\sigma(pp[gg]\to t\bar{c}) \sim \left(\delta^{LL}_{23}\right)^2 \frac{m_t^2(A_t-\mu/\tan\beta)^2}{M^4_{SUSY}}\frac{1}{M^2_{\tilde{g}}}}$$





$\delta^{LL}_{23} \simeq 0.7$

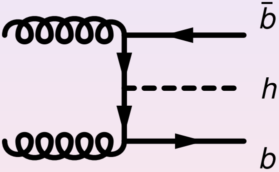
(Not even a single event in the SM for the entire lifetime of the LHC !!)

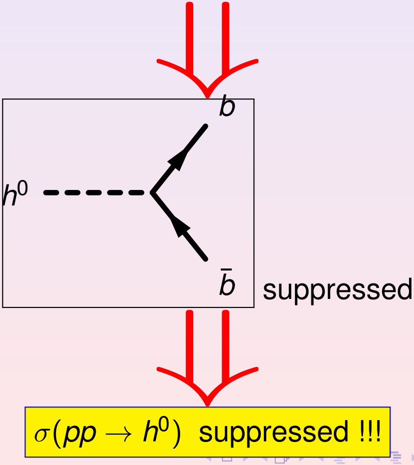
$(\sigma_{SM} = 3.6 \times 10^{-7}\, pb)$

⇒ only the presence of new physics could be an explanation for these events, if they are ever detected

Combination with production

- At large $\tan\beta$ the main production channel for h^0 is associated production: $\sigma(pp- > h^0 b\bar{b})$





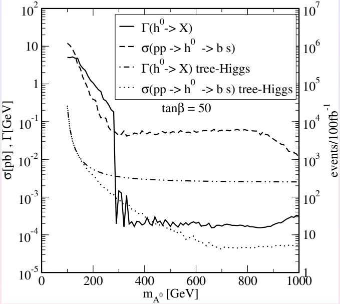
$BR(h^0 \to bs)$ enhanced

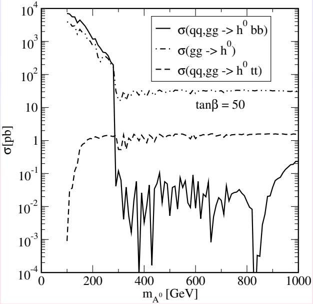
suppressed

$\sigma(pp \to h^0)$ suppressed !!!

Combined analysis $\sigma(pp \to h \to qq')$

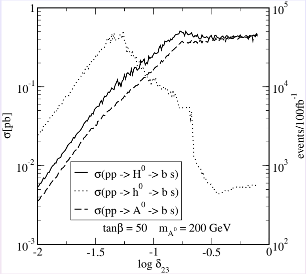
$\sigma(pp \to h \to bs)$

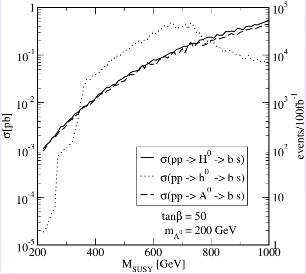




- Maximized production rates for h^0
- $M_{A^0} < 300\,\mathrm{GeV}$: enhancement of $\sigma(pp \to h^0)$ dominates
- $M_{A^0} > 300\,\mathrm{GeV}$: supression of $\Gamma(h^0 \to X)$ dominates

Combined analysis $\sigma(pp \to h \to bs)$





- h^0: Maximum attained for small δ_{23}, $M_{SUSY} \sim 700\,\mathrm{GeV}$
  - $\Rightarrow$ Larger $\delta_{23} \Rightarrow$ smaller μ $(b \to s\gamma)$
  - $\Rightarrow$ Small $M_{SUSY} \Rightarrow$ small δ_{23} $(b \to s\gamma)$
- H^0/A^0: Maximum at large M_{SUSY}
  - $\Rightarrow$ Large $M_{SUSY} \Longrightarrow$ small $B(b \to s\gamma) \Longrightarrow$ larger δ_{23} allowed

    - Large $\delta_{23} \Rightarrow \mu$ has to decrease to obtain acceptable $B(b \to s\gamma) \Rightarrow BR(H^0/A^0 \to bs)$ can not grow.
- Maximun values: $\sigma(pp \to h \to bs) \sim 0.4pb$ and 10^4 events/$100fb^{-1}$

Finding the maximum

- Define: $\delta_{33}^{LR} = \frac{m_t(A_t - \mu/\tan\beta)}{M_{SUSY}^2}$
- $\sigma = (\delta_{23})^2(\delta_{33}^{LR})^2$ =constant defines an hyperbola in the $\delta_{23} - \delta_{33}^{LR}$ plane
- Mass (approximation):

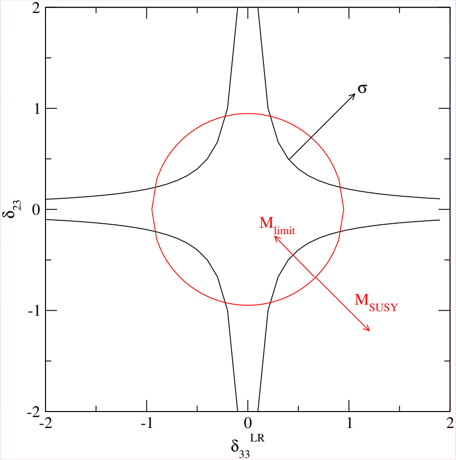
$$m_{\tilde{q}}^2 = M_{SUSY}^2 \left(\begin{array}{c|ccc} & c_L & t_L & t_R \\ \hline c_L & 1 & \delta_{23} & 0 \\ t_L & \delta_{23} & 1 & \delta_{33}^{LR} \\ t_R & 0 & \delta_{33}^{LR} & 1 \end{array} \right)$$

- lightest mass:

$$m_q^2 = M_{SUSY}^2 \left(1 - \sqrt{(\delta_{23})^2 + (\delta_{33}^{LR})^2} \right) > M_{\mathrm{limit}}^2 \; .$$

Experimental limit defines a circle in $\delta_{23} - \delta_{33}^{LR}$ plane:

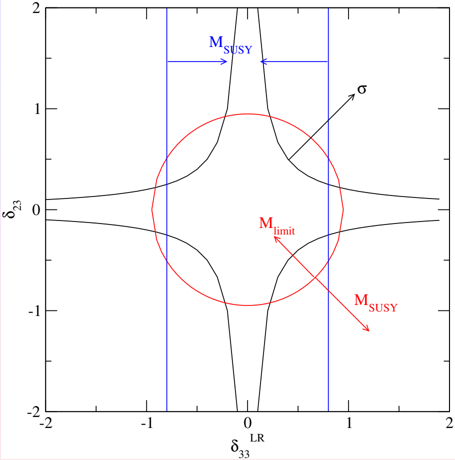
$$(\delta_{23})^2 + (\delta_{33}^{LR})^2 < \left(1 - \frac{M_l^2}{M_{SUSY}^2} \right)^2 \equiv R^2$$



Maximum at:

$$\delta_{23} = \delta_{33}^{LR} = \frac{R}{\sqrt{2}} = \frac{1}{\sqrt{2}}\left(1 - \frac{M_l^2}{M_{SUSY}^2}\right) \to \frac{1}{\sqrt{2}} \ .$$

$$M_{SUSY} \to \infty$$



non-colour breaking vacua: $|A_t| \sim< 3M_{SUSY}$

$$|\delta_{33}^{LR}| <\sim \frac{3m_t}{M_{SUSY}}$$

The maximum is obtained when:

- the diagonal: $\delta_{23} = \delta_{33}^{LR}$
- the limit mass circle
- the limit from A_t

cross in a single point

Exact equations

$$\begin{aligned}
\delta_{23} &= \delta_{33}^{LR} \\
\delta_{33}^{LR} &= \frac{m_t\,(3M_{SUSY} - \mu/\tan\beta)}{M_{SUSY}^2} \\
(\delta_{23})^2 + (\delta_{33}^{LR})^2 &= \left(1 - \frac{M_l^2}{M_{SUSY}^2}\right)^2
\end{aligned}$$

setting:

$m_t = 175\,\mathrm{GeV}$, $M_l = 150\,\mathrm{GeV}$, $\mu = 400\,\mathrm{GeV}$, $\tan\beta = 5$ (by $b \to s\gamma$)

$$\boxed{\begin{aligned}
\delta_{33}^{LR} = \delta_{23} &= 0.678525 \\
M_{SUSY} &= 746.082\,\mathrm{GeV} \\
A_t &= 2238.25\,\mathrm{GeV}
\end{aligned}}$$