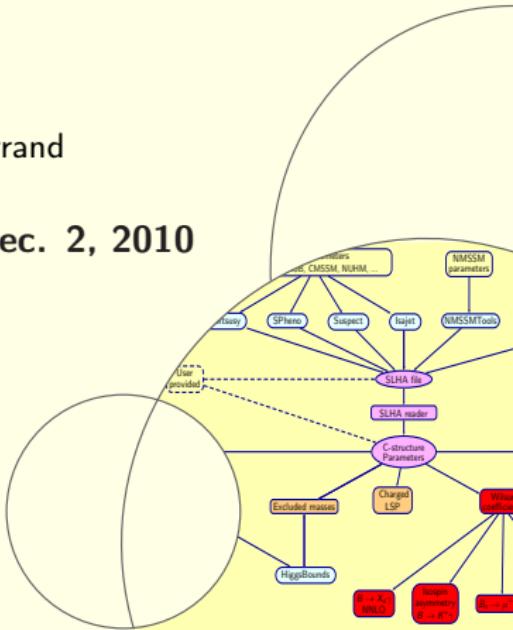


# Probing supersymmetry with flavour physics data

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CERN & LPC Clermont-Ferrand

LC10 Workshop – Frascati – Dec. 2, 2010



## Introduction

New physics appears as a necessity:

- cosmological problems: dark matter, dark energy
  - hierarchy problem in the Standard Model
  - unification of interactions
  - ...

The hope is that LHC will find something new!

- ## • New Physics!

Many theoretical models beyond the SM, within reach of the LHC, already exist in the market.



SUSY Constraints

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- Collider limits
  - Electroweak precision tests
  - The anomalous magnetic moment of the muon ( $g - 2)_\mu$
  - Flavour Physics
  - Cosmological constraints, in particular from the dark matter relic density



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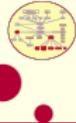
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## Motivations

# Flavour Physics

- sensitive to new physics effects
  - complementary to other searches
  - probes sectors inaccessible to direct searches
  - tests quantum structure of the SM at loop level
  - constrains parameter spaces of new physics scenarios
  - valuable data already available
  - promising experimental situation
  - consistency checks with direct observations



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In the following we consider supersymmetry as new physics scenario.



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SUSY models can be divided into two categories:

- R-parity conserving models
  - R-parity violating models



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R-parity conserving models can also be divided according to how SUSY breaks:

- mSUGRA  $\{m_0, m_{1/2}, A_0, \tan\beta, \text{sign}(\mu)\}$
- NUHM {mSUGRA parameters +  $M_A$  and  $\mu$ }
- AMSB  $\{m_0, m_{3/2}, \tan\beta, \text{sign}(\mu)\}$
- GMSB  $\{\Lambda, M_{\text{mess}}, N_5, c_{\text{grav}}, \tan\beta, \text{sign}(\mu)\}$

In these models, SUSY effects appear:

- in the sparticle loops
  - radiative and electroweak penguins
- in the charged Higgs mediated tree level decays (similar to 2HDM type II)
  - leptonic and semileptonic decays



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## Outline

## In this talk:

- ① Effective approach
  - ② Flavour Observables
    - Radiative penguin decays
    - Electroweak penguin decays
    - Neutrino modes
  - ③ SuperIso
  - ④ Conclusion



## Effective Hamiltonian

## A multi-scale problem

- new physics:  $1/\Lambda_{\text{NP}}$
  - electroweak interactions:  $1/M_W$
  - hadronic effects:  $1/m_b$
  - QCD interactions:  $1/\Lambda_{\text{QCD}}$

⇒ Effective field theory approach:

separation between low and high energies using Operator Product Expansion

- short distance: Wilson coefficients, computed perturbatively
  - long distance: local operators

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{\text{CKM}} \sum C_i(\mu) O_i(\mu)$$

New physics can show up in new operators or modified Wilson coefficients



## Effective Hamiltonian

### $b \rightarrow s\gamma$ operator set:

$$\left\{ \begin{array}{ll} O_1 = (\bar{s}_L \gamma_\mu T^a c_L)(\bar{c}_L \gamma^\mu T^a b_L) & O_2 = (\bar{s}_L \gamma_\mu c_L)(\bar{c}_L \gamma^\mu b_L) \\ \\ O_3 = (\bar{s}_L \gamma_\mu b_L) \sum_q (\bar{q} \gamma^\mu q) & O_4 = (\bar{s}_L \gamma_\mu T^a b_L) \sum_q (\bar{q} \gamma^\mu T^a q) \\ \\ O_5 = (\bar{s}_L \gamma_{\mu_1} \gamma_{\mu_2} \gamma_{\mu_3} b_L) \sum_q (\bar{q} \gamma^{\mu_1} \gamma^{\mu_2} \gamma^{\mu_3} q) & O_6 = (\bar{s}_L \gamma_{\mu_1} \gamma_{\mu_2} \gamma_{\mu_3} T^a b_L) \sum_q (\bar{q} \gamma^{\mu_1} \gamma^{\mu_2} \gamma^{\mu_3} T^a q) \\ \\ O_7 = \frac{e}{16\pi^2} m_b (\bar{s}_L \sigma^{\mu\nu} b_R) F_{\mu\nu} & O_8 = \frac{g}{16\pi^2} m_b (\bar{s}_L \sigma^{\mu\nu} T^a b_R) G_{\mu\nu}^a \end{array} \right.$$



## Wilson Coefficients

## Two main steps:

- Calculating  $C_i^{\text{eff}}(\mu)$  at scale  $\mu \sim M_W$  by requiring matching between the effective and full theories

$$C_i^{eff}(\mu) = C_i^{(0)eff}(\mu) + \frac{\alpha_s(\mu)}{4\pi} C_i^{(1)eff}(\mu) + \dots$$

- Evolving the  $C_i^{\text{eff}}(\mu)$  to scale  $\mu \sim m_b$  using the RGE:

$$\mu \frac{d}{d\mu} C_i^{eff}(\mu) = C_j^{eff}(\mu) \gamma_{ji}^{eff}(\mu)$$

driven by the anomalous dimension matrix  $\hat{\gamma}^{\text{eff}}(\mu)$ :

$$\hat{\gamma}^{eff}(\mu) = \frac{\alpha_s(\mu)}{4\pi} \hat{\gamma}^{(0)eff} + \frac{\alpha_s^2(\mu)}{(4\pi)^2} \hat{\gamma}^{(1)eff} + \dots$$



## Flavour Observables

### I) Radiative penguin decays

- inclusive branching ratio of  $B \rightarrow X_s \gamma$
  - isospin asymmetry of  $B \rightarrow K^* \gamma$

## II) Electroweak penguin decays

- branching ratio of  $B_s \rightarrow \mu^+ \mu^-$
  - inclusive branching ratio of  $B \rightarrow X_s \ell^+ \ell^-$
  - branching ratio of  $B \rightarrow K^* \mu^+ \mu^-$

### III) Neutrino modes

- branching ratio of  $B \rightarrow \tau\nu$
  - branching ratio of  $B \rightarrow D\tau\nu$
  - branching ratios of  $D_s \rightarrow \tau\nu/\mu\nu$
  - branching ratio of  $K \rightarrow \mu\nu$
  - double ratios of leptonic decays



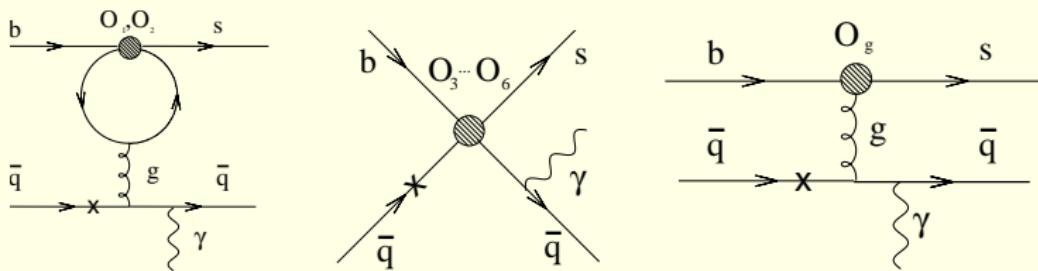
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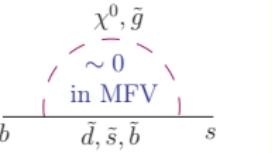
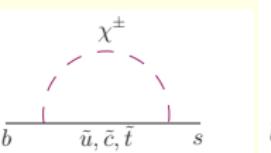
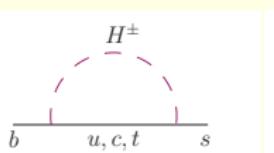
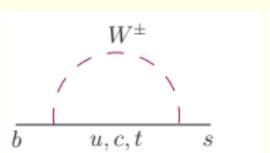
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## $b \rightarrow s\gamma$ transitions



## Contributing loops:



## First penguin ever observed!



## $b \rightarrow s\gamma$ transitions

- Charged Higgs loop always adds constructively to the SM penguin
- Chargino loops can add constructively or destructively
  - if constructive, great enhancement in the  $\text{BR}(b \rightarrow s\gamma)$ 
    - BR is the interesting observable
  - if destructive, other interesting observables
    - CP asymmetry

$$A_{CP} = \frac{\text{BR}(\bar{B} \rightarrow X_s \gamma) - \text{BR}(B \rightarrow X_s \gamma)}{\text{BR}(\bar{B} \rightarrow X_s \gamma) + \text{BR}(B \rightarrow X_s \gamma)}$$

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## Inclusive Branching ratio

$$\mathcal{B}[\bar{B} \rightarrow X_s \gamma]_{E_\gamma > E_0} = \mathcal{B}[\bar{B} \rightarrow X_c e \bar{\nu}]_{\text{exp}} \left| \frac{V_{ts}^* V_{tb}}{V_{cb}} \right|^2 \frac{6 \alpha_{\text{em}}}{\pi C} [P(E_0) + N(E_0)]$$

$$C = \left| \frac{V_{ub}}{V_{cb}} \right|^2 \frac{\Gamma[\bar{B} \rightarrow X_c e \bar{\nu}]}{\Gamma[\bar{B} \rightarrow X_u e \bar{\nu}]}$$



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$$\left\{ \begin{array}{lcl} P^{(0)}(\mu_b) & = & \left(C_7^{(0)\text{eff}}(\mu_b)\right)^2 \\ P_1^{(1)}(\mu_b) & = & 2C_7^{(0)\text{eff}}(\mu_b)C_7^{(1)\text{eff}}(\mu_b) \\ P_1^{(2)}(\mu_b) & = & \left(C_7^{(1)\text{eff}}(\mu_b)\right)^2 + 2C_7^{(0)\text{eff}}(\mu_b)C_7^{(2)\text{eff}}(\mu_b) \end{array} \right.$$

M. Misiak et al., Phys. Rev. Lett. 98 (2007)



## Inclusive Branching ratio

- Theoretical values for the SM:

NNLO (Misiak & Steinhauser '07):  $\mathcal{B}[\bar{B} \rightarrow X_s \gamma] = (3.15 \pm 0.23) \times 10^{-4}$

or (Becher & Neubert '07):  $\mathcal{B}[\bar{B} \rightarrow X_s \gamma] = (2.98 \pm 0.26) \times 10^{-4}$

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- Experimental values:

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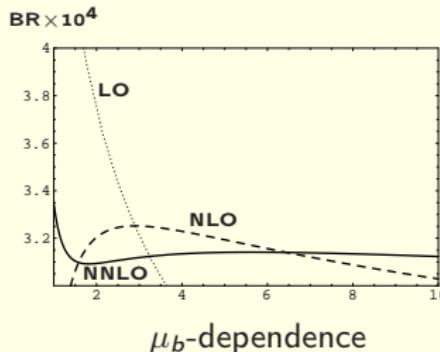
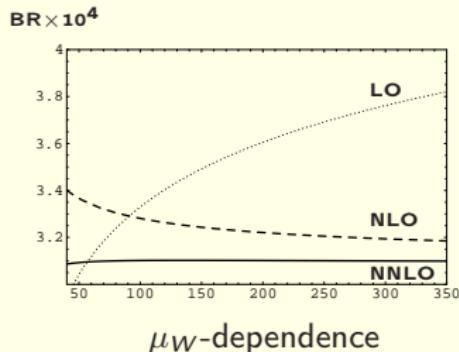
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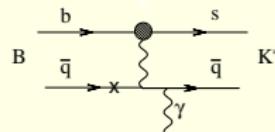
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Reduced scale dependence:



## Isospin Asymmetry

$$\Delta_{0-} \equiv \frac{\Gamma(\bar{B}^0 \rightarrow \bar{K}^{*0}\gamma) - \Gamma(B^- \rightarrow K^{*-}\gamma)}{\Gamma(\bar{B}^0 \rightarrow \bar{K}^{*0}\gamma) + \Gamma(B^- \rightarrow K^{*-}\gamma)}$$



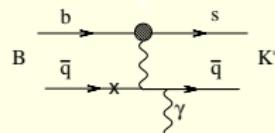
$$b_q = \frac{12\pi^2 f_B Q_q}{m_b T_1^{B \rightarrow K^*} a_2^c} \left( \frac{f_{K^*}^\perp}{m_b} K_1 + \frac{f_{K^*} m_{K^*}}{6\lambda_B m_B} K_2 \right)$$

HFAG 2010



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$$\Delta_{0-} = \text{Re}(b_d - b_u)$$

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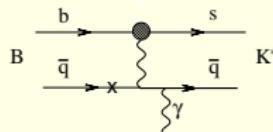
$$a_7^c = \textcolor{red}{C}_7 + \frac{\alpha_s(\mu) C_F}{4\pi} \left( C_1(\mu) G_1(s_p) + C_8(\mu) G_8 \right) + \frac{\alpha_s(\mu_h) C_F}{4\pi} \left( C_1(\mu_h) H_1(s_p) + C_8(\mu_h) H_8 \right)$$

HFAG 2010



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In the Standard Model:  $\Delta_{0-} \simeq 8\%$

Kagan and Neubert, Phys. Lett. B539 (2002)

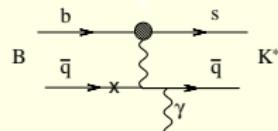
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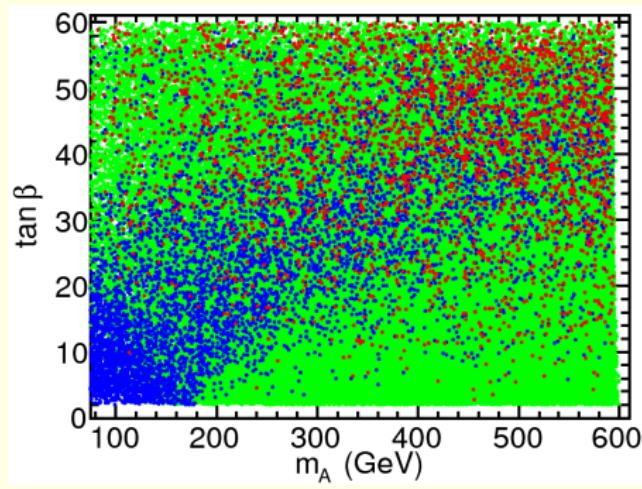
HFAG 2010

$$\Delta_{0-} = +0.052 \pm 0.026$$



## Results

## NUHM scenario



**blue**: branching ratio  
**red**: isospin asymmetry  
**green**: allowed



## Flavour observables

## II) Electroweak penguin decays

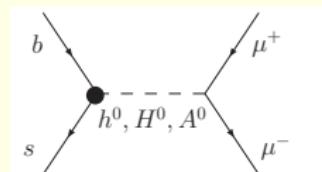
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  - forward-backward asymmetry in  $B \rightarrow X_s \ell^+ \ell^-$
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## II) Electroweak penguin decays

Branching ratio of  $B_s \rightarrow \mu^+ \mu^-$

$$\begin{aligned} \mathcal{B}(B_s \rightarrow \mu^+ \mu^-) &= \frac{G_F^2 \alpha^2}{64\pi^3} f_{B_s}^2 \tau_{B_s} M_{B_s}^3 |V_{tb} V_{ts}^*|^2 \sqrt{1 - \frac{4m_\mu^2}{M_{B_s}^2}} \\ &\times \left\{ \left( 1 - \frac{4m_\mu^2}{M_{B_s}^2} \right) M_{B_s}^2 |\textcolor{red}{C}_S|^2 + \left| \textcolor{red}{C}_P M_{B_s} - 2 \textcolor{red}{C}_A \frac{m_\mu}{M_{B_s}} \right|^2 \right\} \end{aligned}$$



Upper limit:  $\mathcal{B}(B_s \rightarrow \mu^+ \mu^-) < 4.3 \times 10^{-8}$  at 95% C.L.  
(CDF public note 9892)

SM predicted value:  $\mathcal{B}(B_s \rightarrow \mu^+ \mu^-)_{SM} \sim 3 \times 10^{-9}$

Interesting in the high  $\tan \beta$  regime, where the SUSY contributions can lead to an O(100) enhancement over the SM:

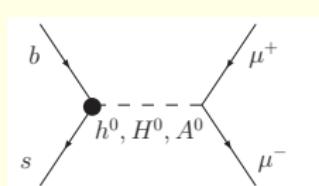
$$\mathcal{B}(B_s \rightarrow \mu^+ \mu^-)_{MSSM} \sim \frac{m_b^2 m_\mu^2 \tan^6 \beta}{M_A^4}$$



## II) Electroweak penguin decays

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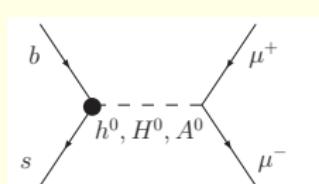
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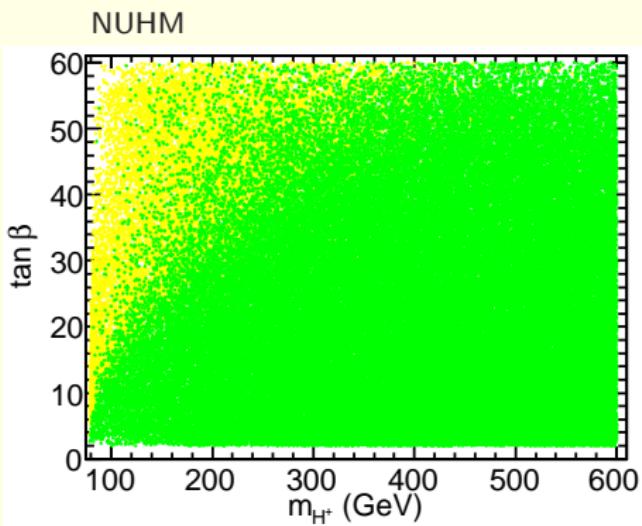
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$B_s \rightarrow \mu^+ \mu^-$



D. Eriksson, FM, O. Stål, JHEP 0811 (2008)



## II) Electroweak penguin decays

## Forward-backward asymmetry in $B \rightarrow K^* \mu^+ \mu^-$

### Interesting observable for NP searches

$$A_{FB}(q^2) = \frac{1}{d\Gamma/dq^2} \left[ \int_0^1 d(\cos\theta) \frac{d^2\Gamma}{dq^2 d(\cos\theta)} - \int_{-1}^0 d(\cos\theta) \frac{d^2\Gamma}{dq^2 d(\cos\theta)} \right]$$

$\theta$ : angle between  $B^0$  and  $\mu^+$  momenta in the dilepton system center of mass

$$q^2 = (p_{\mu^+} + p_{\mu^-})^2$$



## II) Electroweak penguin decays

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$$q^2 = (p_{\mu^+} + p_{\mu^-})^2$$

## Effective Hamiltonian:

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left( \sum C_i(\mu) \mathcal{O}_i(\mu) + \sum C_{Q_i}(\mu) Q_i(\mu) \right)$$

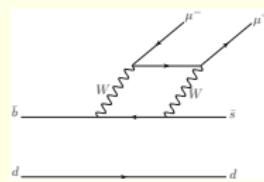
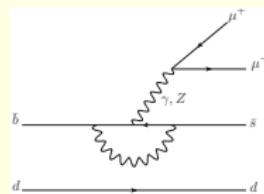
## Important operators:

$$\mathcal{O}_9 = \frac{e^2}{(4\pi)^2} (\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu \ell)$$

$$\mathcal{O}_{10} = \frac{e^2}{(4\pi)^2} (\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu\gamma_5\ell)$$

$$Q_1 = \frac{e^2}{16\pi^2} (\bar{s}_L^\alpha b_R^\alpha)(\bar{\ell}\ell)$$

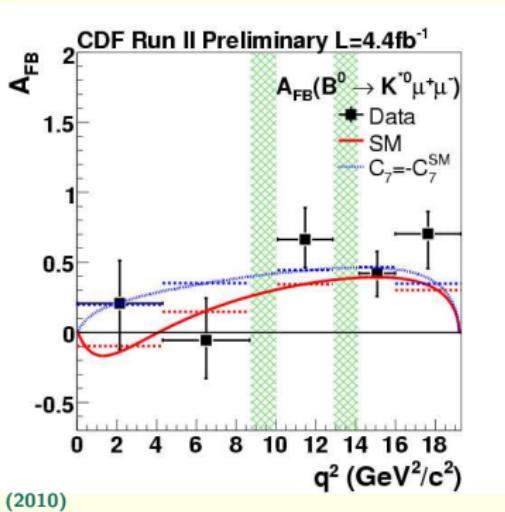
$$Q_2 = \frac{e^2}{16\pi^2} (\bar{s}_L^\alpha b_R^\alpha)(\bar{\ell}\gamma_5 \ell)$$



## II) Electroweak penguin decays

## Forward-backward asymmetry in $B \rightarrow K^* \mu^+ \mu^-$

Of particular interest, the position of the zero point:  $A_{FB}(q_0^2) = 0$



The value of  $q_0^2$  is very robust with respect to hadronic uncertainties

NP can modify the  $q_0^2$  value or even suppress the zero point



## Flavour observables

### III) Neutrino modes

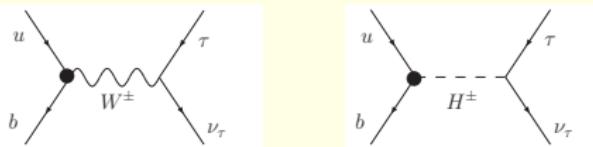
- branching ratio of  $B \rightarrow \tau\nu$
  - branching ratio of  $B \rightarrow D\tau\nu$
  - branching ratios of  $D_s \rightarrow \tau\nu/\mu\nu$
  - branching ratio of  $K \rightarrow \mu\nu$
  - double ratios of leptonic decays



### III) Neutrino modes

#### Branching ratio of $B \rightarrow \tau\nu$

Tree level process, mediated by  $W^\pm$  and  $H^\pm$ , higher order corrections from sparticles



$$\mathcal{B}(B \rightarrow \tau\nu) = \frac{G_F^2 |V_{ub}|^2}{8\pi} m_\tau^2 f_B^2 m_B \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 \left|1 - \left(\frac{m_B^2}{m_{H^+}^2}\right) \frac{\tan^2 \beta}{1 + \epsilon_0 \tan \beta}\right|^2$$

$$\epsilon_0 = -\frac{2\alpha_s}{3\pi} \frac{\mu}{m_{\tilde{g}}} H_2 \left( \frac{m_Q^2}{m_{\tilde{g}}^2}, \frac{m_D^2}{m_{\tilde{g}}^2} \right), \quad H_2(x, y) = \frac{x \ln x}{(1-x)(x-y)} + \frac{y \ln y}{(1-y)(y-x)}$$

Large uncertainty from  $V_{ub}$  and sensitive to  $f_B$

Also used:

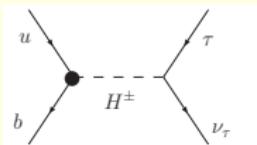
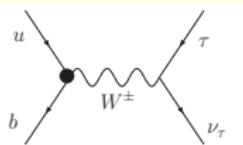
$$R_{\tau\nu_\tau}^{\text{MSSM}} = \frac{\text{BR}(B_u \rightarrow \tau\nu_\tau)_{\text{MSSM}}}{\text{BR}(B_u \rightarrow \tau\nu_\tau)_{\text{SM}}} = \left[1 - \left(\frac{m_B^2}{m_{H^+}^2}\right) \frac{\tan^2 \beta}{1 + \epsilon_0 \tan \beta}\right]^2$$



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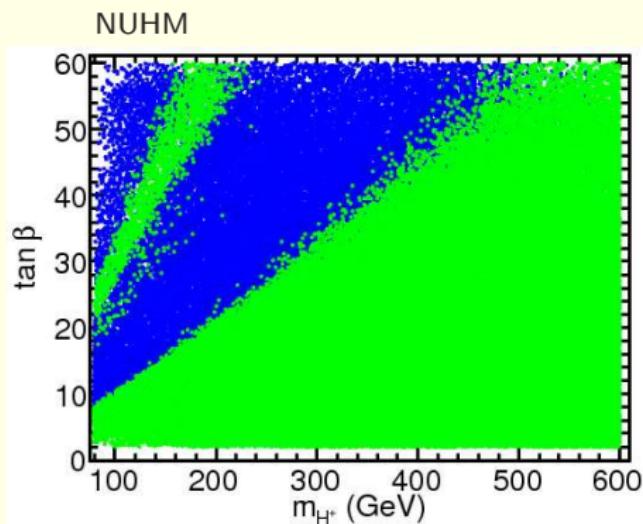
$$R_{\tau\nu\tau}^{\text{MSSM}} = \frac{\text{BR}(B_u \rightarrow \tau\nu_\tau)_{\text{MSSM}}}{\text{BR}(B_u \rightarrow \tau\nu_\tau)_{\text{SM}}} = \left[ 1 - \left( \frac{m_B^2}{m_{H^+}^2} \right) \frac{\tan^2 \beta}{1 + \epsilon_0 \tan \beta} \right]^2$$



$$B \rightarrow \tau \nu$$

SM:  $\mathcal{B}(B \rightarrow \tau\nu) = (1.01 \pm 0.26) \times 10^{-4}$

HFAG 2010:  $\mathcal{B}(B \rightarrow \tau\nu) = (1.64 \pm 0.34) \times 10^{-4}$



D. Eriksson, FM, O. Stål, JHEP 0811 (2008)

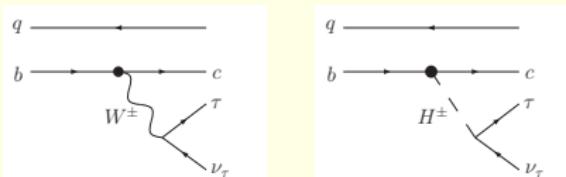
$$|V_{ub}^{comb}| = (3.95 \pm 0.35) \times 10^{-3}$$



## Charged Higgs mediated observables

## Branching ratio of $B \rightarrow D\tau\nu$

Another tree level process:



$$\frac{d\Gamma(B \rightarrow D\ell\bar{\nu})}{dw} = \frac{G_F^2 |V_{cb}|^2 m_B^5}{192\pi^3} \rho_V(w) \left[ 1 - \frac{m_\ell^2}{m_B^2} \left| 1 - \frac{t(w)}{(m_b - m_c)} \frac{m_b}{m_{H^+}^2} \frac{\tan^2 \beta}{1 + \epsilon_0 \tan \beta} \right|^2 \rho_S(w) \right]$$

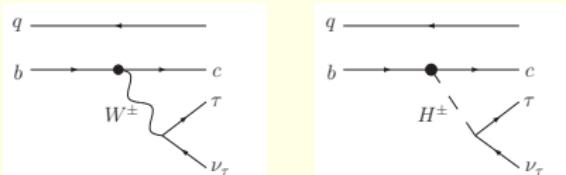
$w \equiv v_B : v_D$      $\rho v$  and  $\rho s$ : vector and scalar Dalitz density contributions



# Charged Higgs mediated observables

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$w = v_B \cdot v_D$        $\rho_V$  and  $\rho_S$ : vector and scalar Dalitz density contributions

- Depends on  $V_{cb}$ , which is known to better precision than  $V_{ub}$
- Larger branching fraction than  $B \rightarrow \tau\nu$
- Experimentally challenging due to the presence of neutrinos in the final state

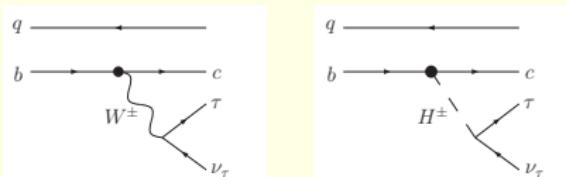
Interesting observables:  $\mathcal{B}(B^- \rightarrow D^0 \tau^- \nu)$  and  $\frac{\mathcal{B}(B^- \rightarrow D^0 \tau^- \nu)}{\mathcal{B}(B^- \rightarrow D^0 e^- \nu)}$



## Charged Higgs mediated observables

### Branching ratio of $B \rightarrow D\tau\nu$

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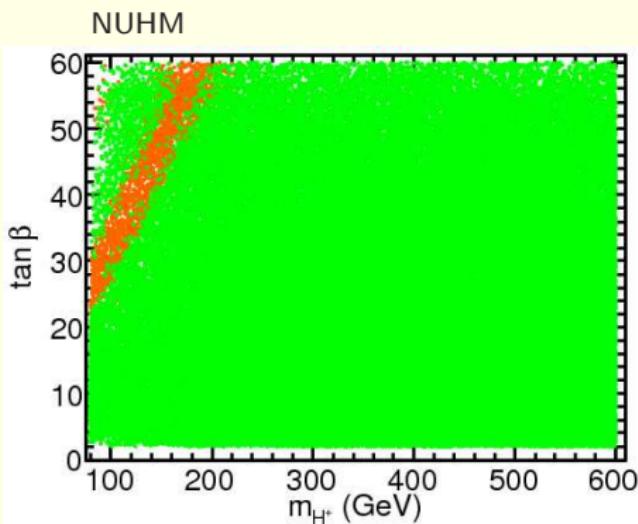
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$$\text{SM: } \frac{\mathcal{B}(B^- \rightarrow D^0 \tau^- \nu)}{\mathcal{B}(B^- \rightarrow D^0 e^- \nu)} = 0.30 \pm 0.02$$

$$\text{PDG 2010: } \frac{\mathcal{B}(B^- \rightarrow D^0 \tau^- \nu)}{\mathcal{B}(B^- \rightarrow D^0 e^- \nu)} = 0.416 \pm 0.117 \pm 0.052$$



D. Eriksson, FM, O. Stål, JHEP 0811 (2008)

### III) Neutrino modes

Branching ratio of  $D_s \rightarrow \ell\nu$

Tree level process similar to  $B \rightarrow \tau\nu$

$$\mathcal{B}(D_s \rightarrow \ell \nu) = \frac{G_F^2}{8\pi} |V_{cs}|^2 f_{D_s}^2 m_\ell^2 M_{D_s} \tau_{D_s} \left(1 - \frac{m_\ell^2}{M_{D_s}^2}\right)^2 \times \left[1 + \left(\frac{1}{m_c + m_s}\right) \left(\frac{M_{D_s}}{m_{H^+}}\right)^2 \left(m_c - \frac{m_s \tan^2 \beta}{1 + \epsilon_0 \tan \beta}\right)\right]^2 \text{ for } \ell = \mu, \tau$$

- Competitive with and complementary to analogous observables
  - Dependence on only one lattice QCD quantity
  - Interesting if lattice calculations eventually prefer  $f_{D_s} < 250$  MeV
  - Promising experimental situation (BES-III)



Sensitive to  $f_{D_s}$  and  $m_s/m_c$



$D_s \rightarrow \ell\nu$ 

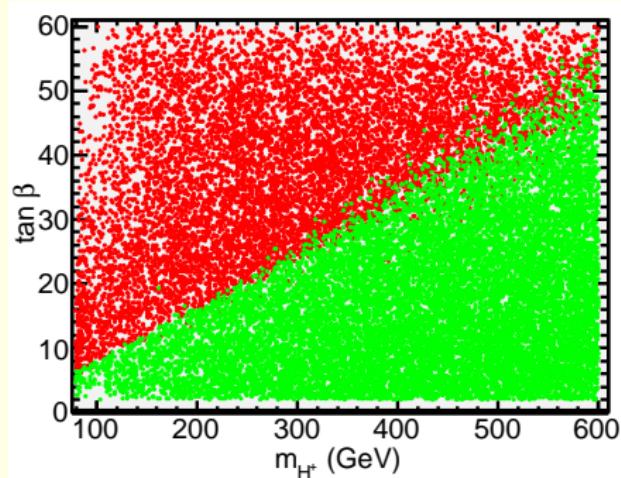
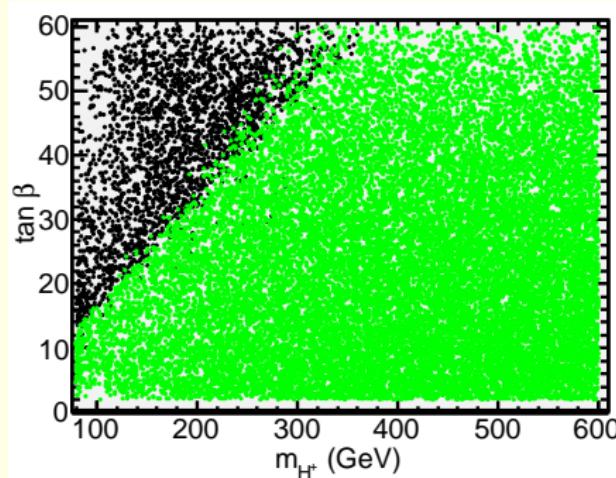
SM:  $\mathcal{B}(D_s \rightarrow \tau\nu) = (4.82 \pm 0.14) \times 10^{-2}$

HFAG 2010:  $\mathcal{B}(D_s \rightarrow \tau\nu) = (5.38 \pm 0.32) \times 10^{-2}$

$\mathcal{B}(D_s \rightarrow \mu\nu) = (4.98 \pm 0.14) \times 10^{-3}$

$\mathcal{B}(D_s \rightarrow \mu\nu) = (5.81 \pm 0.43) \times 10^{-3}$

## NUHM parameter space

 $D_s \rightarrow \tau\nu_\tau$  $D_s \rightarrow \mu\nu_\mu$ 

A.G. Akeroyd, FM, JHEP 0904, 121 (2009)

$f_{D_s} = 241 \pm 3 \text{ MeV}$

$m_s/m_c \approx 0.08$



# Charged Higgs mediated observables

## Branching ratio of $K \rightarrow \mu\nu$

Tree level process similar to  $B \rightarrow \tau\nu$

Two observables are considered:

$$\frac{\Gamma(K \rightarrow \mu\nu)}{\Gamma(\pi \rightarrow \mu\nu)} = \left| \frac{V_{us}}{V_{ud}} \right|^2 \frac{f_K^2 m_K}{f_\pi^2 m_\pi} \left( \frac{1 - m_\ell^2/m_K^2}{1 - m_\ell^2/m_\pi^2} \right)^2 \times \left( 1 - \frac{m_{K^+}^2}{M_{H^+}^2} \left( 1 - \frac{m_d}{m_s} \right) \frac{\tan^2 \beta}{1 + \epsilon_0 \tan \beta} \right)^2 (1 + \delta_{\text{em}})$$

$$R_{\ell 23} = \left| \frac{V_{us}(K_{\ell 2})}{V_{us}(K_{\ell 3})} \times \frac{V_{ud}(0^+ \rightarrow 0^+)}{V_{ud}(\pi_{\ell 2})} \right| = \left| 1 - \frac{m_{K^+}^2}{M_{H^+}^2} \left( 1 - \frac{m_d}{m_s} \right) \frac{\tan^2 \beta}{1 + \epsilon_0 \tan \beta} \right|$$

Large uncertainty from  $f_K/f_\pi$

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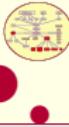
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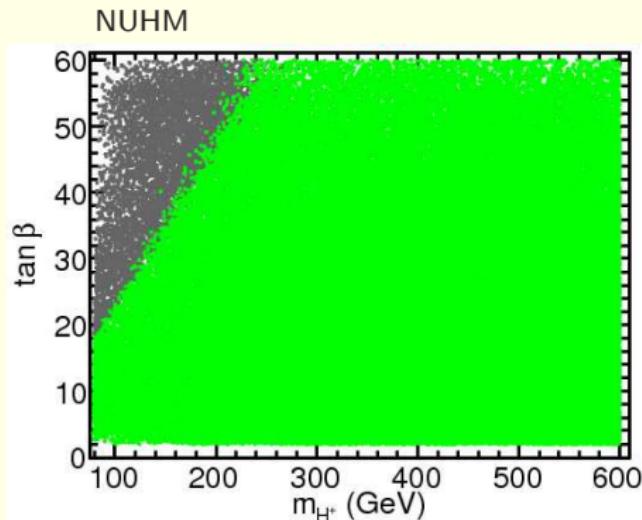


Large uncertainty from  $f_K/f_\pi$



$$K \rightarrow \mu\nu$$

Flavianet:  $R_{\ell 23} = 1.004 \pm 0.007$



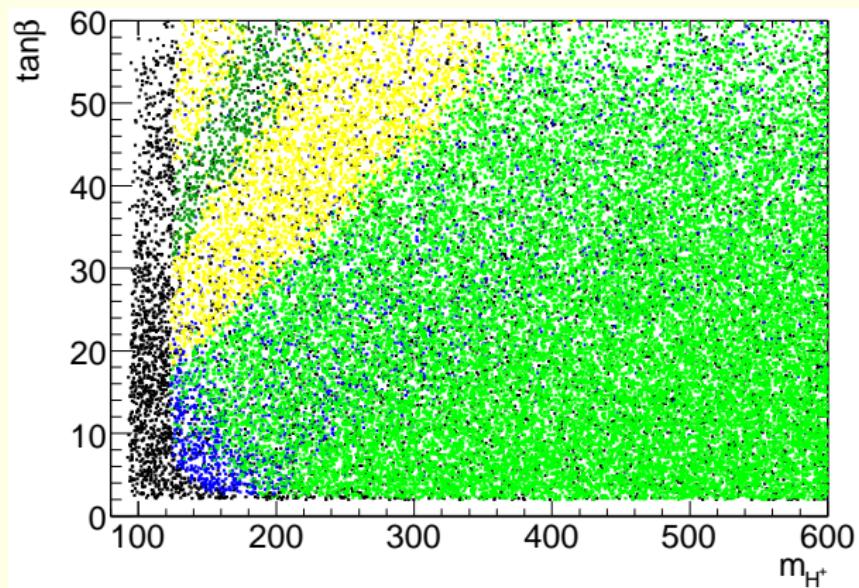
D. Eriksson, FM, O. Stål, JHEP 0811 (2008)

$$f_K/f_\pi = 1.189 \pm 0.007$$



## Combined constraints

## NUHM scenario



black: direct constraints

**blue:**  $\mathcal{B}(B \rightarrow X_s \gamma)$

**yellow:**  $\mathcal{B}(B \rightarrow \tau\nu)$

dark green:  $\mathcal{B}(B \rightarrow D\tau\nu)$

green: allowed

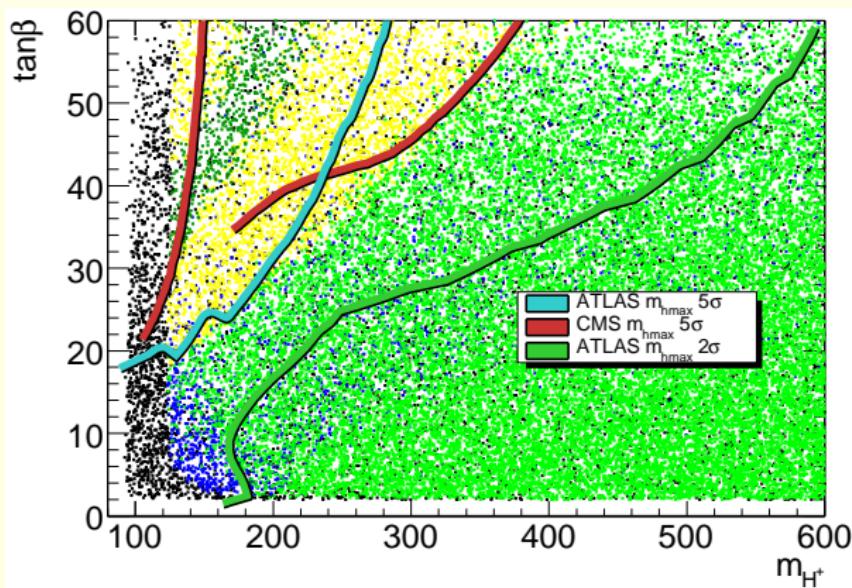
D. Eriksson, FM, O. Stål, JHEP 0811 (2008)



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## Combined constraints

NUHM scenario



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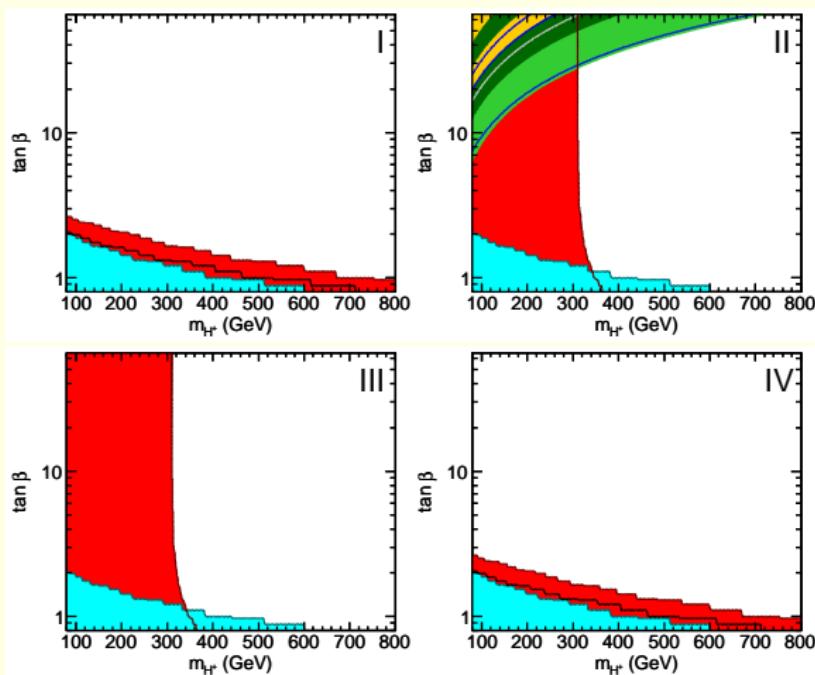
green: allowed

D. Eriksson, FM, O. Stål, JHEP 0811 (2008)



## Combined constraints

## THDM (Types I–IV)



Red:  $b \rightarrow s\gamma$   
 Cyan:  $\Delta M_{B_d}$   
 Blue:  $B_u \rightarrow \tau\nu_\tau$   
 Yellow:  $B \rightarrow D\ell\nu_\ell$   
 Gray:  $K \rightarrow \mu\nu_\mu$   
 Green:  $D_s \rightarrow \tau\nu_\tau$   
 Dark green:  $D_s \rightarrow \mu\nu_\mu$

FM, O. Stål, Phys. Rev. D81 (2010)



### III) Neutrino modes

#### Double ratios of leptonic decays

For example:

$$R = \left( \frac{\text{BR}(B_s \rightarrow \mu^+ \mu^-)}{\text{BR}(B_u \rightarrow \tau \nu)} \right) / \left( \frac{\text{BR}(D_s \rightarrow \tau \nu)}{\text{BR}(D \rightarrow \mu \nu)} \right)$$

From the form factor and CKM matrix point of view:

$$R \propto \frac{|V_{ts} V_{tb}|^2}{|V_{ub}|^2} \frac{(f_{B_s}/f_B)^2}{(f_{D_s}/f_D)^2} \quad \text{with:} \quad \frac{(f_{B_s}/f_B)}{(f_{D_s}/f_D)} \approx 1$$

$R$  has no dependence on the form factors, contrary to each decay taken individually!

- No dependence on lattice quantities
- Interesting for  $V_{ub}$  determination
- Interesting for probing new physics
- Promising experimental situation

B. Grinstein, Phys. Rev. Lett. 71 (1993)

A.G. Akeroyd, FM, JHEP 1010 (2010)

### III) Neutrino modes

#### Double ratios of leptonic decays

For example:

$$R = \left( \frac{\text{BR}(B_s \rightarrow \mu^+ \mu^-)}{\text{BR}(B_u \rightarrow \tau \nu)} \right) / \left( \frac{\text{BR}(D_s \rightarrow \tau \nu)}{\text{BR}(D \rightarrow \mu \nu)} \right)$$

From the form factor and CKM matrix point of view:

$$R \propto \frac{|V_{ts} V_{tb}|^2}{|V_{ub}|^2} \frac{(f_{B_s}/f_B)^2}{(f_{D_s}/f_D)^2} \quad \text{with:} \quad \frac{(f_{B_s}/f_B)}{(f_{D_s}/f_D)} \approx 1$$

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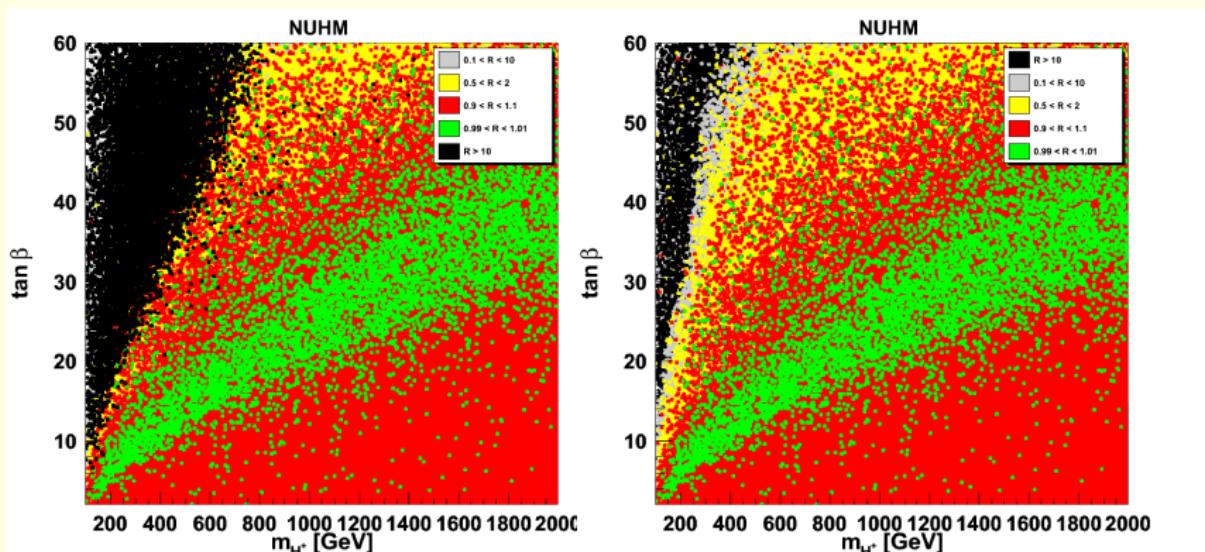
B. Grinstein, Phys. Rev. Lett. 71 (1993)

A.G. Akeroyd, FM, JHEP 1010 (2010)



## Double ratio

$R_{\text{exp}}/R_{\text{SM}} < 10.0$  at 95% C.L.



$$|V_{ub}| = (3.92 \pm 0.46) \times 10^{-4}$$

A.G. Akeroyd, FM, JHEP 1010 (2010)



SuperIso

SuperIso

- public C program
  - dedicated to the flavour physics observable calculations
  - various models implemented
  - interfaced to several spectrum calculators
  - modular program with a well-defined structure
  - SuperIso Relic (with Alex Arbey): extension to the relic density calculation, featuring alternative cosmological scenarios
  - complete reference manuals available

FM, Comput. Phys. Commun. 178 (2008) 745

FM, Comput. Phys. Commun. 180 (2009) 1579

FM, Comput. Phys. Commun. 180 (2009) 1718

A. Arbe, F.M. Comput. Phys. Commun. 181 (2010) 1277



# Models

## Standard Model

### General Two Higgs Doublet Model

automatic interface with 2HDMC for

- General 2HDM and Types I, II, III, IV

### MSSM (with Minimal Flavour Violation)

automatic interfaces with Softsusy, Isajet, Spheno and Suspect available for

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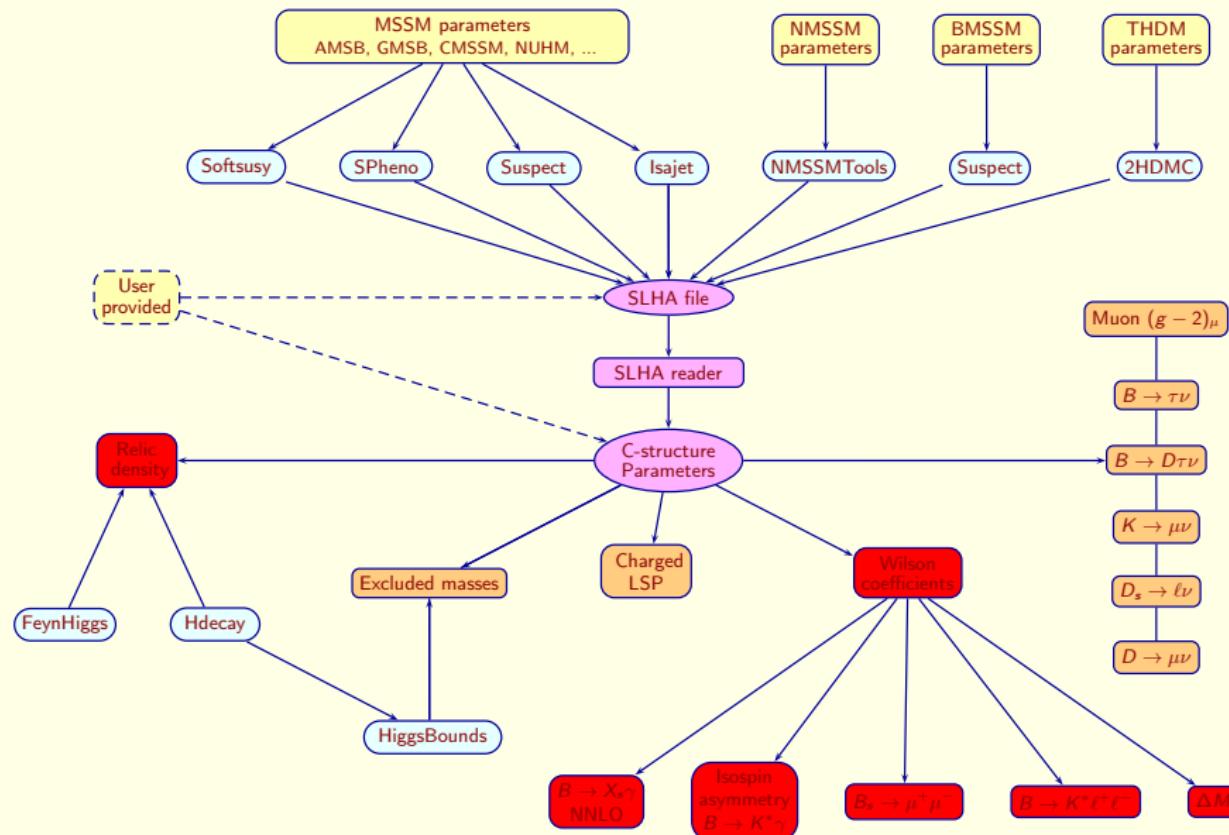
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SuperIso



<http://superiso.in2p3.fr>

# SuperIso

By Farrah Nazila Mahmoodi

Superior

- ## » Description

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Superior Relic

- ## ⇒ Description

Download

- Superiso
  - Superiso Relic
  - Superiso Relic phased

Calculation of flavor physics observables

SuperIso is a program for calculation of flavor physics observables in the Standard Model (SM), general two-Higgs-doublet model (2HDM), minimal supersymmetric Standard Model (MSSM) and next to minimal supersymmetric Standard Model (NMSSM). SuperIso, in addition to the isospin asymmetry of  $B \rightarrow K^* \gamma$ , gamma, which was the main purpose of the first version, incorporates other flavor observables such as the branching ratio of  $B \rightarrow X_s$  gamma at NNLO, the branching ratio of  $B_s \rightarrow \mu^+ \mu^-$ , the branching ratio of  $B \rightarrow \tau^- \bar{\nu}_\tau$ , tau nu, the branching ratio of  $B \rightarrow D \bar{\tau} \nu_\tau$ , the branching ratio of  $K \rightarrow \mu \bar{\nu}_\mu$  as well as the branching ratios of  $D_s \rightarrow \tau \bar{\nu}_\tau$  and  $D_s \rightarrow \mu \bar{\nu}_\mu$ . It also computes the muon anomalous magnetic moment ( $\alpha_s^{(2)}$ ).

For the isospin asymmetry, the program calculates the NLO supersymmetric contributions using the effective Hamiltonian approach and within the QCD factorization method. Isospin asymmetry is a particularly useful observable to constrain supersymmetric parameter spaces.

SuperIso uses a SUSY Les Houches Accord file (SLHA1 or SLHA2) as input, which can be either generated automatically by the program via a call to SOFTSUSY, ISAJET, NMSSMTools or provided by the user. SuperIso can also use the LHA inspired format for the 2D histogram by 2HDMC.

SuperIso is able to perform the calculations automatically in the SM, in the 2HDM (general 2HDM or types I-IV) and in different supersymmetry breaking scenarios, such as mSUGRA, NUHM, AMSB and GMSB (for MSSM) and CMNSSM, NMSSM and NNJLHM (for NMSSM).

For any comment, question or bug report please contact Nazila Mahmoudi

Manual



 The latest version of the manual can be found [here](#) (10 September 2009).

**For more information:**

- F. Mahmoudi, arXiv:0710.3791 [hep-ph], JHEP12 (2007), 026
  - M.R. Ahmady and F. Mahmoudi, hep-ph/0608212, Phys. Rev. D75 (2007), 015007
  - D. Eriksson, F. Mahmoudi and O. Stål, arXiv:0808.3551 [hep-ph], JHEP11 (2008), 035



## Conclusion

- Indirect constraints and in particular flavour physics are essential to restrict new physics parameters
- That will become even more interesting when combined with LHC data
- This kind of analysis can be generalized to more new physics scenarios

- We have learned a lot from flavour physics so far
- But what is still to be discovered is more!



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## Backup

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General THDM

Charged Higgs boson couplings to fermions

$$H^+ D \bar{U} : \quad \frac{ig}{2\sqrt{2}m_W} V_{UD} \left[ \lambda^U m_U (1 - \gamma^5) - \lambda^D m_D (1 + \gamma^5) \right]$$

$$H^+ \ell^- \bar{\nu}_\ell : \quad - \frac{ig}{2\sqrt{2}m_W} \lambda^\ell m_\ell (1 + \gamma^5)$$

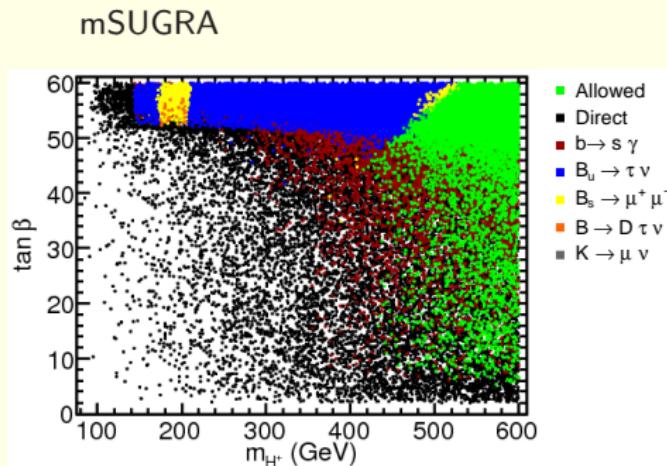
THDM types I–IV

- **Type I:** one Higgs doublet provides masses to all quarks (up and down type quarks) ( $\sim$  SM)
  - **Type II:** one Higgs doublet provides masses for up type quarks and the other for down-type quarks ( $\sim$  MSSM)
  - **Type III,IV:** different doublets provide masses for down type quarks and charged leptons

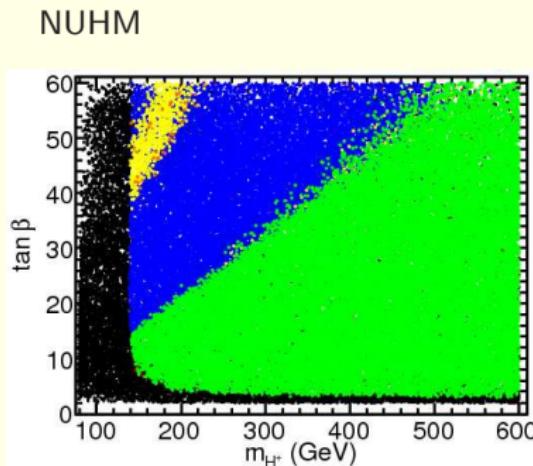
Type	$\lambda_U$	$\lambda_D$	$\lambda_L$
I	$\cot \beta$	$\cot \beta$	$\cot \beta$
II	$\cot \beta$	$-\tan \beta$	$-\tan \beta$
III	$\cot \beta$	$-\tan \beta$	$\cot \beta$
IV	$\cot \beta$	$\cot \beta$	$-\tan \beta$



## Combined results



$$m_{H^+} \gtrsim 400 \text{ GeV}$$



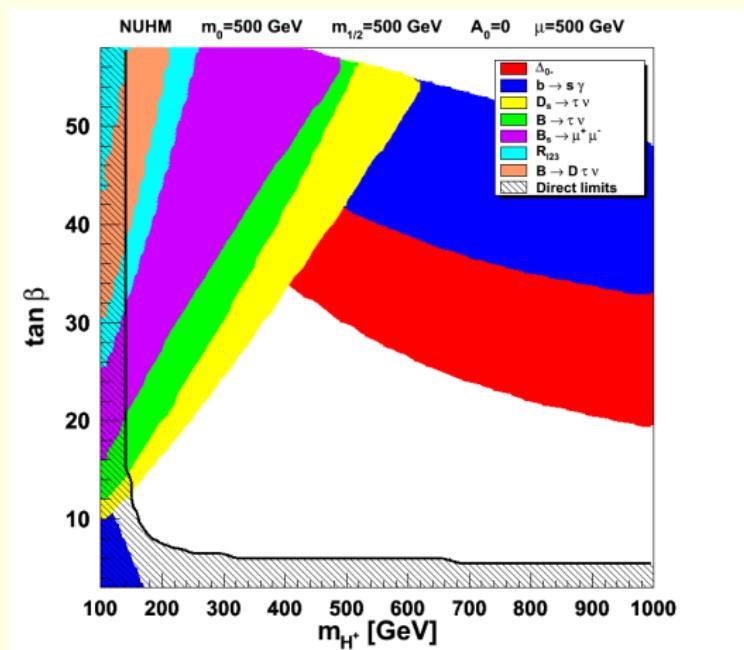
$$m_{H^+} \gtrsim 135 \text{ GeV}$$

D. Eriksson, FM, O. Stål, JHEP 0811 (2008)



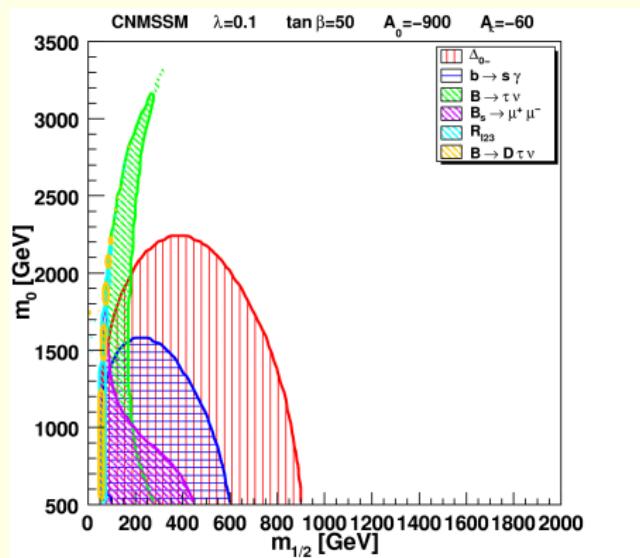
## Combined results

## NUHM scenario



## Combined results

CNMSSM



## FM, preliminary results

