Constraints and experimental prospects for the charged Higgs boson in the MSSM

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Based on work with D. Eriksson and F. Mahmoudi
JHEP 0811 (2008) 035, [arXiv:0808.3551] [hep-ph]

EWSB in the MSSM

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Fermion masses generated from two complex doublets

$$H_u = \begin{pmatrix} H_u^+ \\ v_u + H_u^0 \end{pmatrix} \quad H_d = \begin{pmatrix} v_d + H_d^0 \\ H_d^- \end{pmatrix}$$

$$-\mathcal{L}_{\mathrm{Yukawa}} = \overline{Q}_L \cdot H_d Y^D D_R + \overline{Q}_L \cdot H_u Y^U U_R + \overline{L}_L \cdot H_d Y^L E_R + \mathrm{h.c.},$$

$$\mathcal{V}_{\mathrm{MSSM}}\left(H_d, H_u\right) = m_d^2|H_d|^2 + m_u^2|H_u|^2 - m_{12}^2\epsilon_{ab}\left(H_d^a H_u^b + \mathrm{h.c.}\right)$$

$$m_i^2 = m_{H_i}^2 + |\mu|^2 \qquad + \frac{g^2 + g'^2}{8}\left(|H_d|^2 - |H_u|^2\right)^2 + \frac{1}{2}g^2|H_d^\dagger H_u|^2$$

Supersymmetry $\to$ quartic terms fixed by gauge couplings

Physical Higgs states: h, H, A, $H^\pm$ Goldstone bosons: G^0, $G^\pm$

Two parameters at tree-level: $\tan\beta = \frac{v_u}{v_d}$ $m_{H^+}^2 = m_W^2 + m_A^2$

MSSM charged Higgs couplings

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2HDM Type II at tree-level:

$$g_{\bar{t}bH^+} = \frac{\mathrm{i}}{\sqrt{2}\,v} V_{tb} \left[m_b \tan\beta \,(1+\gamma^5) + m_t \cot\beta \,(1-\gamma^5) \right]$$

Running $\overline{\text{MS}}$ b-mass in coupling resums leading-log QCD corrections

Broken SUSY: non-holomorphic loop corrections at high $\tan\beta$

$$m_b \tan\beta \to \frac{m_b \tan\beta}{1+\epsilon_b \tan\beta} \qquad \Delta_b \equiv \epsilon_b \tan\beta$$

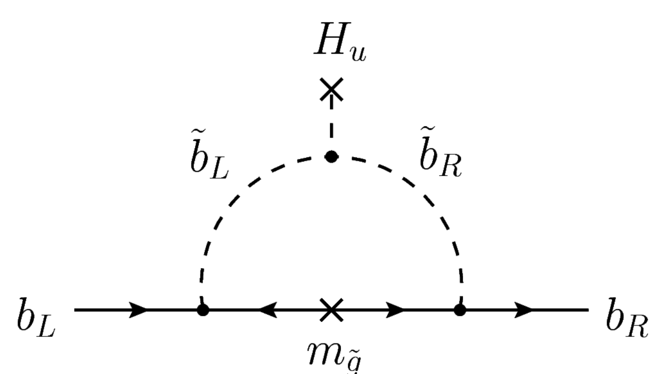
$$\epsilon_b = \frac{2\alpha_s}{3\pi} m_{\tilde{g}} \mu \times F(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}}) + \frac{y_t^2}{16\pi^2} A_t \mu \times F(m_{\tilde{t}_1}, m_{\tilde{t}_2}, \mu)$$

Hall, Rattazzi, Sarid, PRD50 (1994)

Non-decoupling effect

$\epsilon_b \to$ const.

for $m_{\tilde{g}}$, μ, $M_{\text{SUSY}} \to \infty$



The CMSSM and NUHM models

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- The full MSSM has 124 parameters → stick to limited models
  Minimal flavor violation (MFV)
  Parameter universality assumptions (unification)

- Constrained MSSM (CMSSM)
  Non-Universal Higgs Mass models (NUHM)

- CMSSM boundary conditions on soft-breaking parameters at GUT scale:

$$\begin{aligned} \text{Universal scalar (incl. Higgs) mass: } & m_0 \\ \text{Universal gaugino mass: } & m_{1/2} \\ \text{Universal trilinear coupling: } & A_0 \\ \text{Sign of Higgsino mass parameter: } & \text{sign}(\mu) \\ & + \tan\beta \end{aligned}$$

- In the NUHM model the universality of scalar masses are relaxed for the Higgs doublets. → Two new mass parameters m_{H_u}, m_{H_d}

- RGE determines spectrum at EW scale
  GUT-scale Higgs mass parameters traded for m_A and μ at low scale

Parameter range

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- To identify the allowed regions for the charged Higgs we scan over the parameter spaces in CMSSM and NUHM

- Theoretical constraints, radiative breaking of the EW symmetry, restricts the useful ranges for the input parameters

- Physical mass spectrum at the EW scale calculated with SOFTSUSY

B. Allanach, CPC 143 (2002) 305 [hep-ph/0104145]

Parameter	min	max	note
m_0	50	2000	
$m_{1/2}$	50	2000	
A_0	-2000	2000	
μ	-2000	2000	CMSSM: only sign $\pm$
m_A	5	600	NUHM only
$\tan\beta$	1	60	

Constraints

- With R-parity conservation, all SUSY-effects on low-energy observables occur through loops (→ Important role of H^+)

- For the charged Higgs boson, several types of observables constraining $(m_{H^+}, \tan\beta)$ can be identified:

  Direct search limits

  Flavor constraints (B-physics)

  Anomalous magnetic moment of muon
  → *Favors $\mu > 0$*

  Cosmological constraints on dark matter abundance
  → *No specific exclusion power for H^+ in NUHM*

- All flavor data constraints calculated using SuperIso 2.3

F. Mahmoudi, [arXiv:0808.3144]

SuperIso

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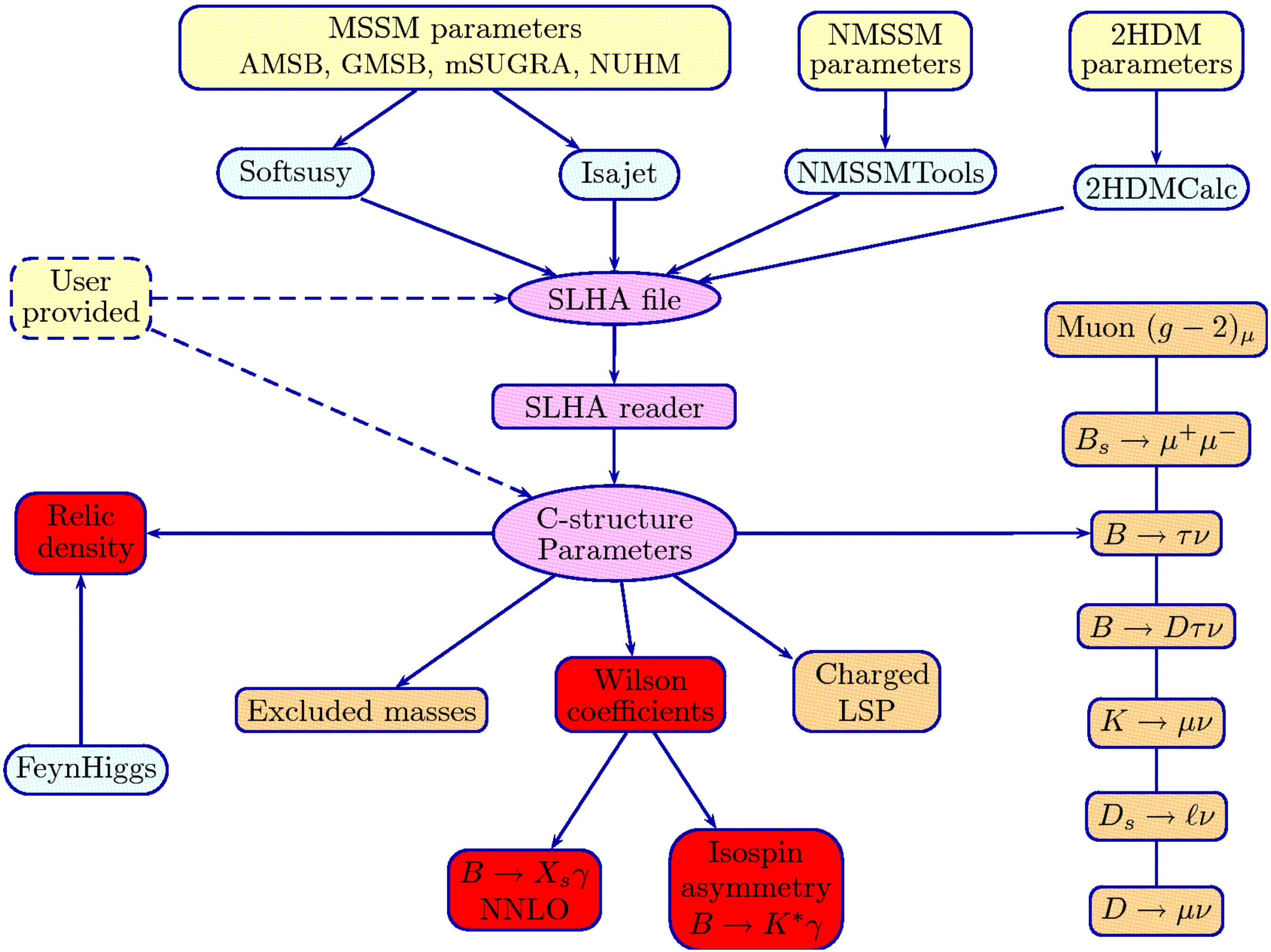


http://superiso.in2p3.fr

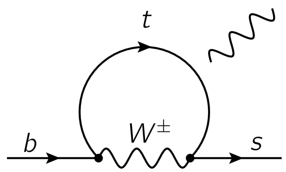
F. Nazila Mahmoudi, current version is SuperIso 2.7

Flavor constraints: $B \to X_s\gamma$

OPE $\to$ Effective Hamiltonian: $\mathcal{H}_{\rm eff}^{\Delta F=1} = \frac{4G_F}{\sqrt{2}} \sum_k C_k(\mu_W, M_{\rm SUSY}, \ldots)\mathcal{O}_k(\mu_W)$

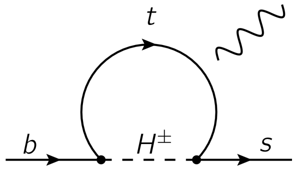
Dominant contributions to $C_7(\mu_W)$

SM



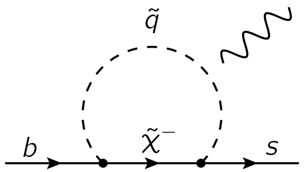
+

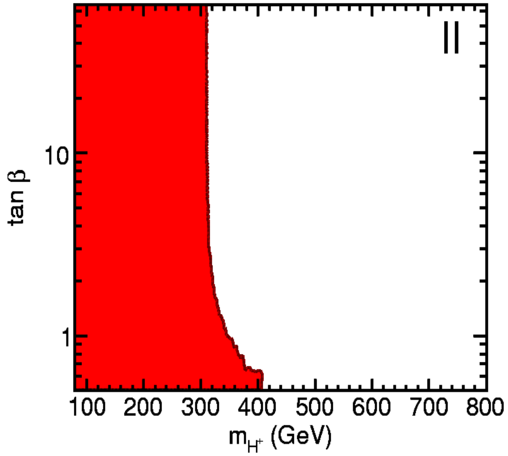
2HDM



+/-

MSSM





2HDM II (w/o SUSY)

$m_{H^+} \gtrsim 300$ GeV

Inclusive branching ratio

$\mathrm{BR}(B \to X_s\gamma)_{\rm exp} = (3.52 \pm 0.23 \pm 0.09) \times 10^{-4}$

HFAG, [arXiv:0808.1089]

$\mathrm{BR}(B \to X_s\gamma)_{\rm SM}^{\rm NNLO} = (3.15 \pm 0.22) \times 10^{-4}$

$E_\gamma > 1.6$ GeV Misiak, Steinhauser, PRL98, 022003 (2007)

Isospin asymmetry

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

$$\Delta_{0-} = (3.1 \pm 2.3) \times 10^{-2}$$

Belle, PRD69 (2004), BaBar, PRD70 (2004)

$$\Delta_{0-}^{\rm SM} = (8.0^{+2.1}_{-3.2}) \times 10^{-2}$$

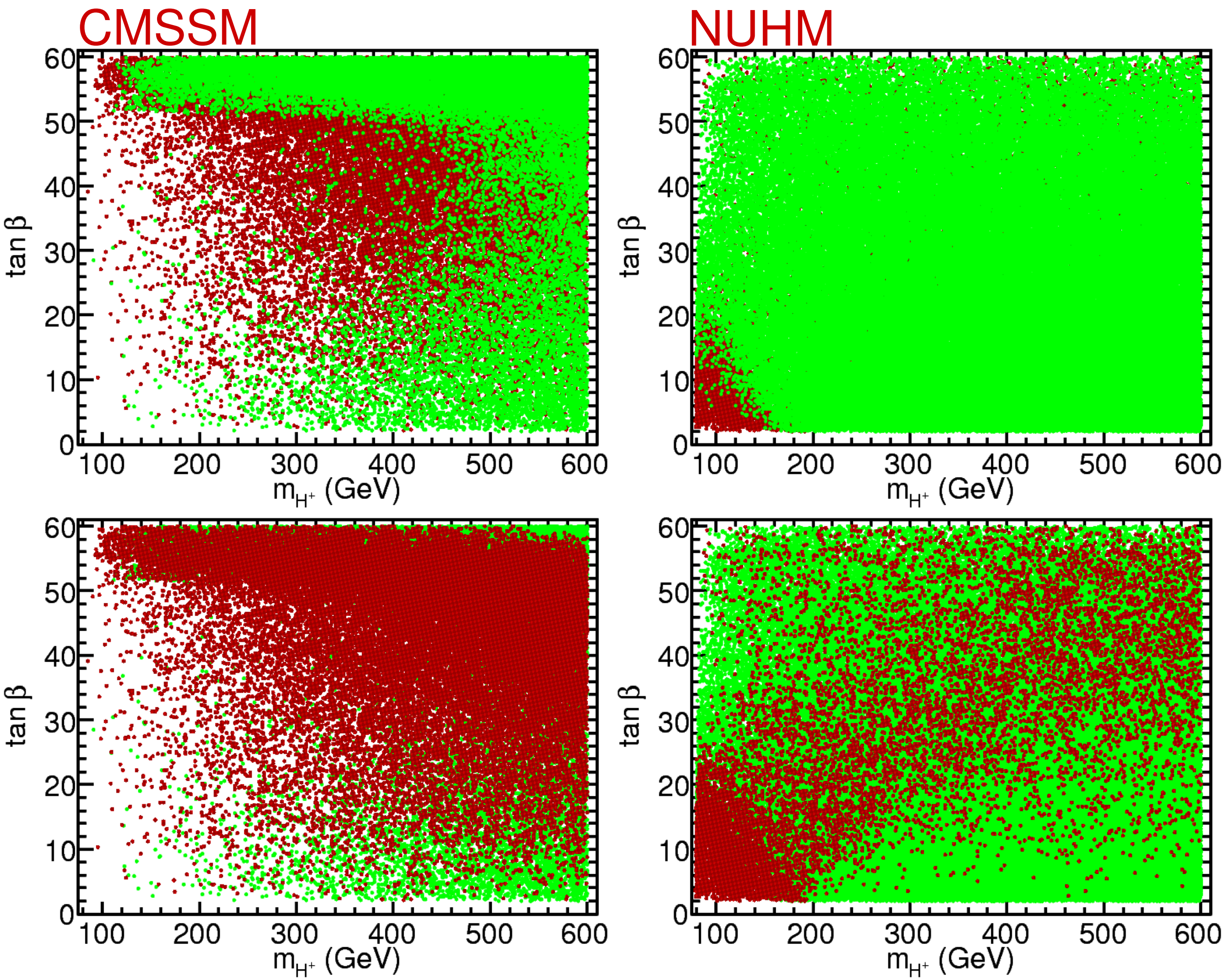
Kagan, Neubert, PLB539 (2002)
Bosch, Buchalla, NPB621 (2002)

$B \to X_s\gamma$

Allowed ranges imposed at 95% C.L. (1 dof)

$$2.15 \times 10^{-4} \leq \mathrm{BR}(B \to X_s\gamma) \leq 4.89 \times 10^{-4}$$

$$-1.7 \times 10^{-2} < \Delta_0 < 8.9 \times 10^{-2}$$



Allowed points (green) plotted on top

→ Easy to cancel charged Higgs and sparticle contributions in NUHM

Excluded points (red) plotted on top

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

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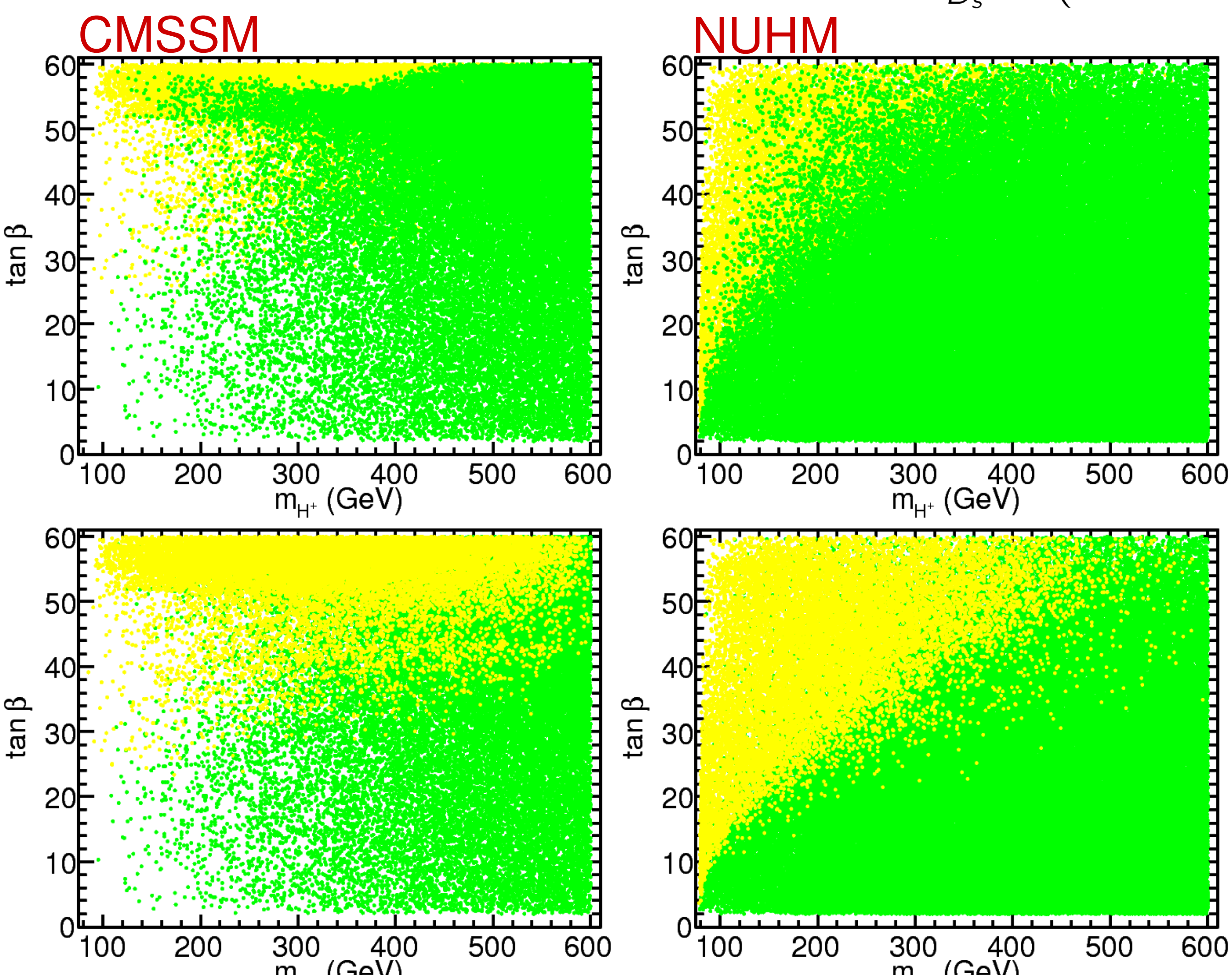
- Rare FCNC, decay not observed, only upper limit:

$$\mathrm{BR}(B_s \to \mu^+\mu^-) < 5.8 \times 10^{-8}$$

CDF, PRL 100 (2008) 02180

$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = (3.2 \pm 0.5) \times 10^{-9}$$

$$f_{B_s} = (245 \pm 25)\ \mathrm{MeV}$$



- Higgs sector contribution proportional to:

$$\frac{m_\mu^2 m_B^2}{m_A^4} \tan^6\beta$$

- Charged Higgs constraint from mass relation

$$m_{H^+}^2 = m_A^2 + m_W^2$$

(tree-level)

$B_u \to \tau\, \nu_\tau$

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- Tree-level decay, helicity suppressed in SM. H^+ at tree-level reduces rate.

- SUSY effects enter through tan β-enhanced SUSY-QCD corrections ϵ_b.

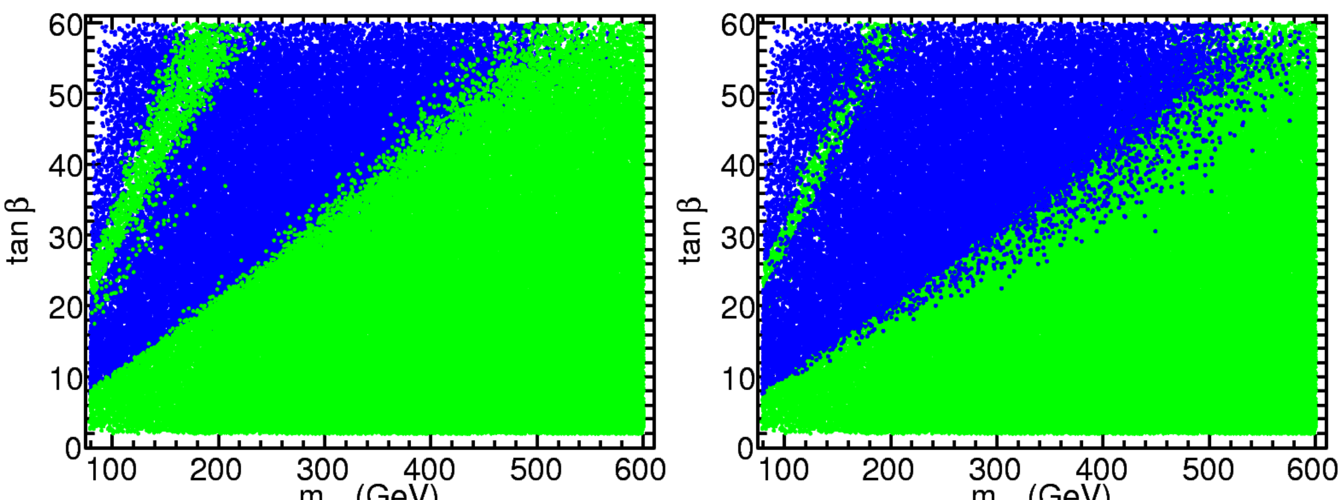
$$\mathrm{BR}_{\mathrm{MSSM}} = \frac{G_F^2 f_B^2 |V_{ub}|^2}{8\pi \Gamma_B} m_B m_\tau^2 \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 \left[1 - \left(\frac{m_B^2}{m_{H^+}^2}\right) \frac{\tan^2\beta}{1+\epsilon_b \tan\beta}\right]^2$$

Hou, PRD48 (1993) 2342

- Large theoretical uncertainties from f_B, V_{ub}

$$R_{\tau\nu_\tau}^{\mathrm{exp}} \equiv \frac{\mathrm{BR}(B_u \to \tau\nu_\tau)_{\mathrm{exp}}}{\mathrm{BR}(B_u \to \tau\nu_\tau)_{\mathrm{SM}}} = 1.28 \pm 0.38 \qquad 0.53 < R_{\tau\nu_\tau}^{\mathrm{MSSM}} < 2.03$$

- H+ contribution universal over leptons, interesting for $B \to \mu\nu_\mu$



NUHM

- Strong exclusion, but can be shifted by change in V_{ub}

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

[PDG2008]

$$f_B = 200 \pm 20\,\mathrm{MeV}$$

$B \to D \tau \nu_\tau$

- Also a tree-level process. Proportional to V_{cb} instead of V_{ub}.

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

$w = v_B \cdot v_D$

Grzadowski, Hou, PLB 272 (1991) 383
Nierste, Trine, Westhoff, PRD78 (2008)
Kamenik, Mescia, PRD78 (2008) 014003

- Uncertainties from form-factors ρ_V and ρ_S (lattice).

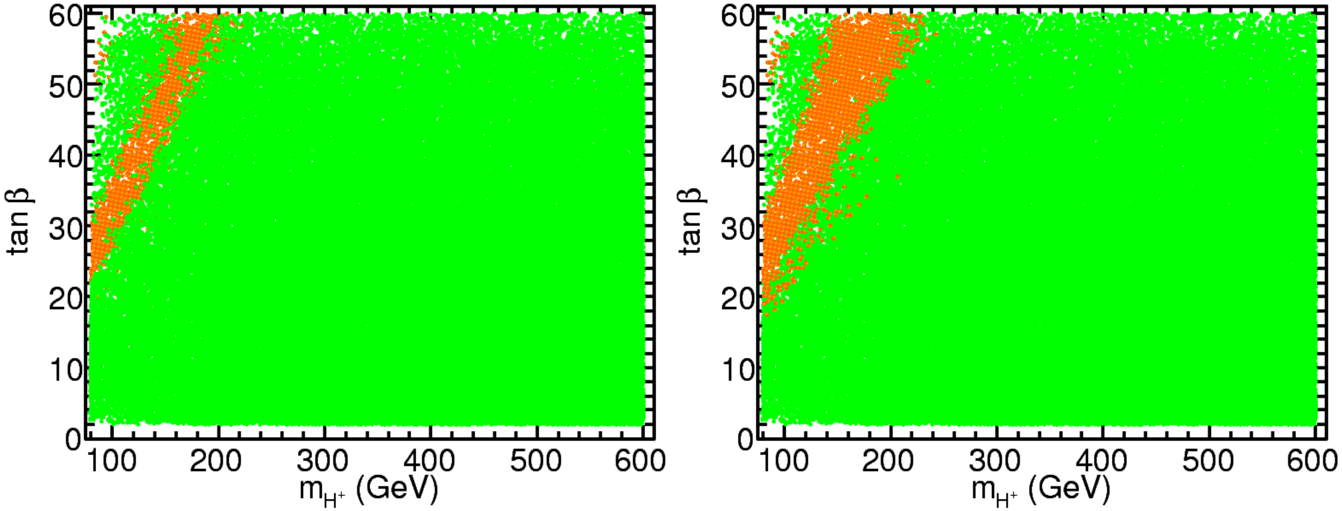
→ See talk by S. Westhoff at this workshop

$$\xi_{D\ell\nu} \equiv \frac{\mathrm{BR}(B \to D\tau\nu_\tau)}{\mathrm{BR}(B \to De\nu_e)} = (29 \pm 3) \times 10^{-2} \quad \text{(SM)}$$

$$\xi_{D\ell\nu}^{\mathrm{exp}} = (41.6 \pm 11.7 \pm 5.2) \times 10^{-2}$$

BABAR, PRL100 (2008) 014003

$$15.1 \times 10^{-2} < \xi_{D\ell\nu} < 68.1 \times 10^{-2}$$



NUHM

- Complementary to $B \to \tau \nu_\tau$
- Closes 'wedge' region

Constraints from direct searches: LEP

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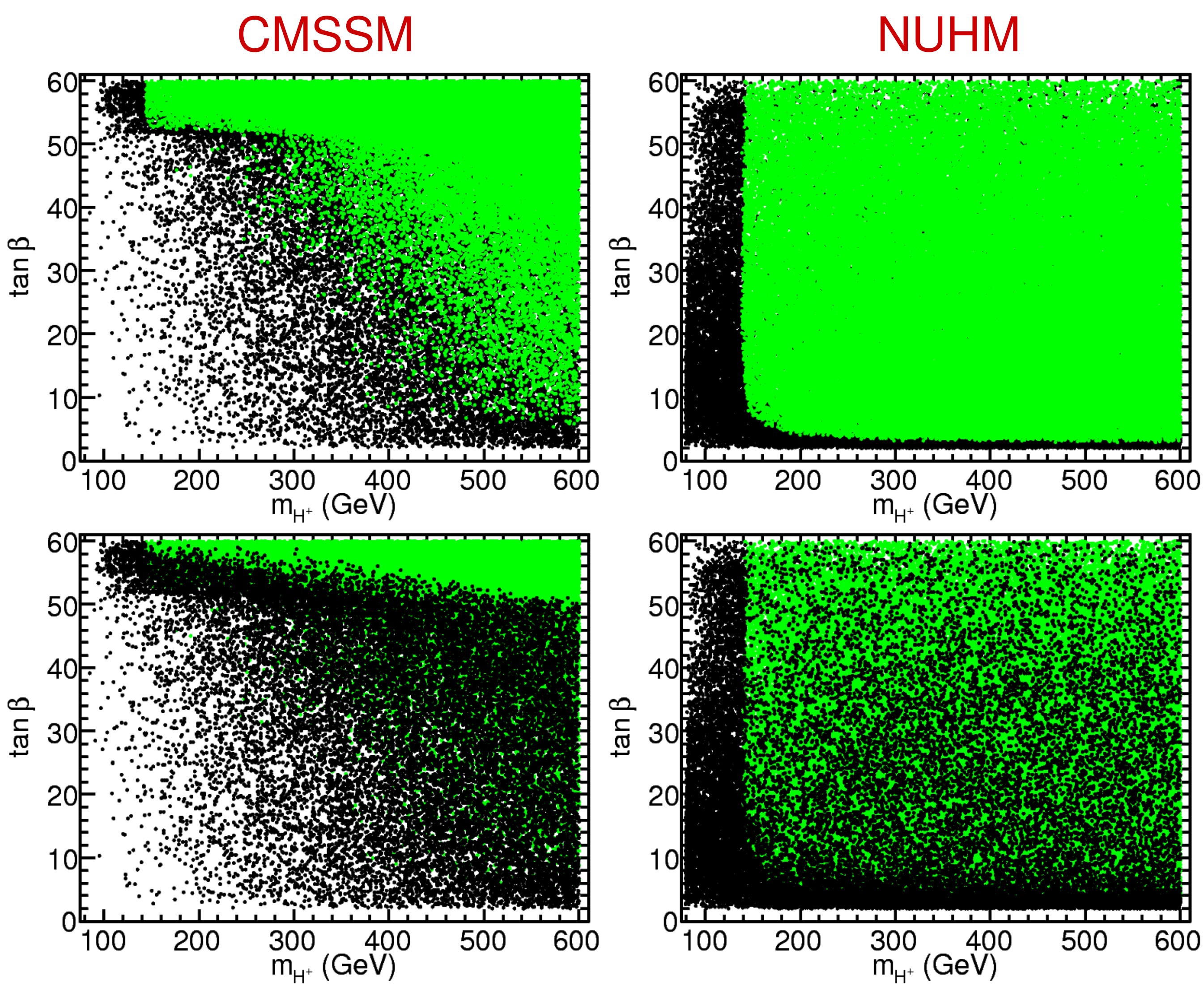
Mass constraints at 95% CL (auxiliary conditions applied)

Particle	H^+	A	h	χ_1^0	χ_1^+	$\tilde{e}_R$	$\tilde{\mu}_R$	$\tilde{\tau}_1$	$\tilde{\nu}$	$\tilde{b}_1$	$\tilde{t}_1$	$\tilde{g}$
Mass limit (GeV)	79.3	93.4	111	46	94	73	94	81.9	94	89	95.7	308

[PDG]



- Light charged Higgs in CMSSM only at high tan β (RGE running)
- Limit on lightest Higgs mass gives sharp limit:

$$m_{H^+} \gtrsim 135 \text{ GeV}$$
$$(m_h > 111 \text{ GeV})$$

$$m_{H^+} \gtrsim 120 \text{ GeV}$$
$$(m_h > 90 \text{ GeV})$$

$$\tan\beta \gtrsim 3$$

Superimposed constraints

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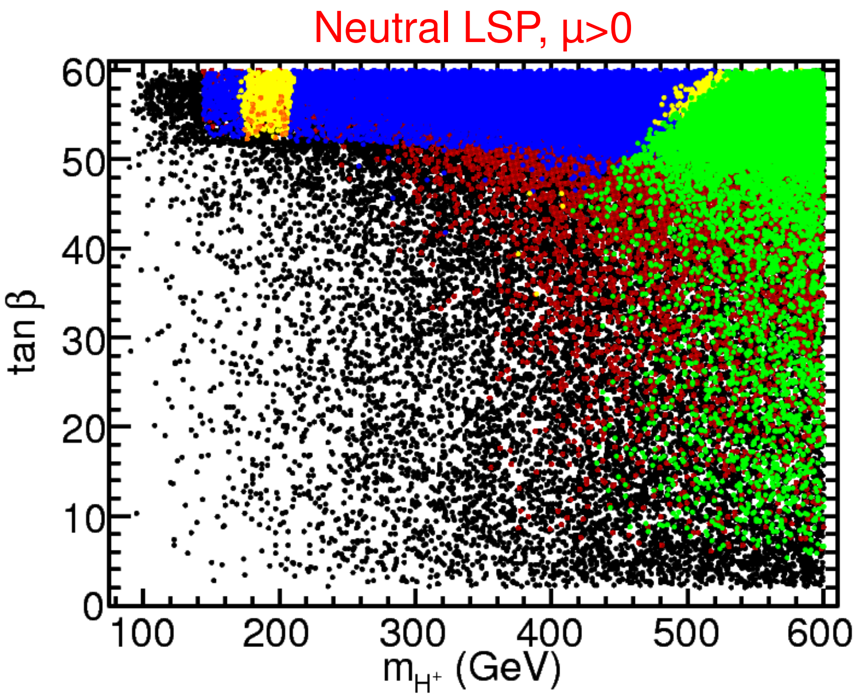


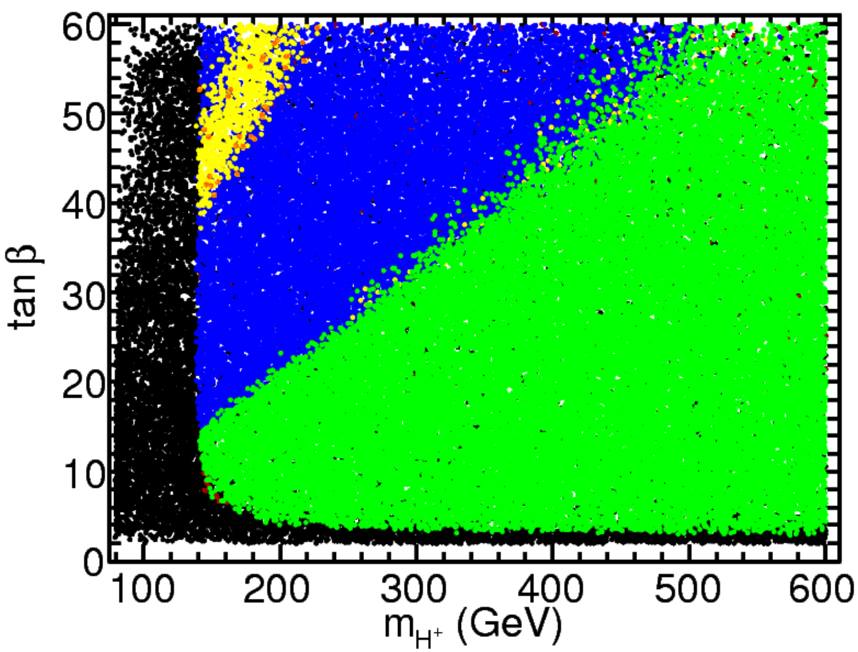
CMSSM

$m_0, m_{1/2}, A_0, \mathrm{sign}(\mu), \tan\beta$

- Allowed
- Direct
- b→ s γ
- $B_u \to \tau\nu$
- $B_s \to \mu^+\mu^-$
- $B \to D\tau\nu$
- $K \to \mu\nu$

- High tan β “tail” excluded by comb. flavor constraints

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



NUHM

$m_0, m_{1/2}, A_0, \mu, m_A, \tan\beta$

- Allowed
- Direct
- b→ s γ
- $B_u \to \tau\nu$
- $B_s \to \mu^+\mu^-$
- $B \to D\tau\nu$
- $K \to \mu\nu$

- Large exclusion from flavor.
- Low mass H+ only for intermediate tan β.

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

Charged Higgs bosons at the LHC

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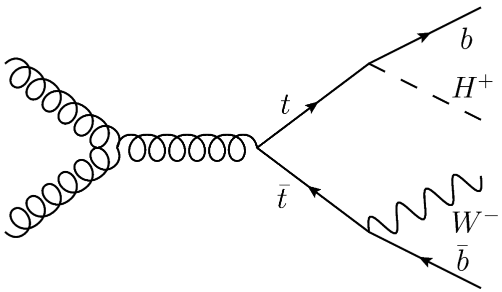
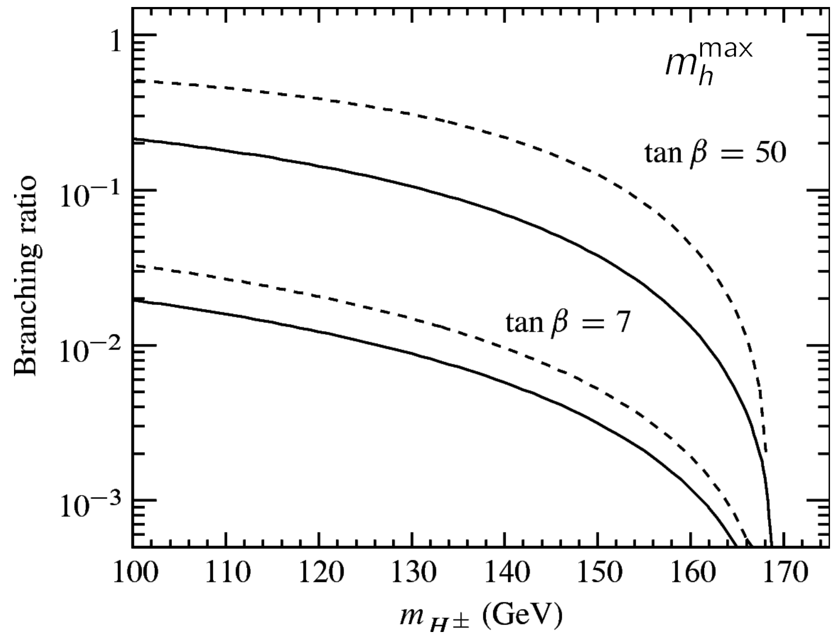
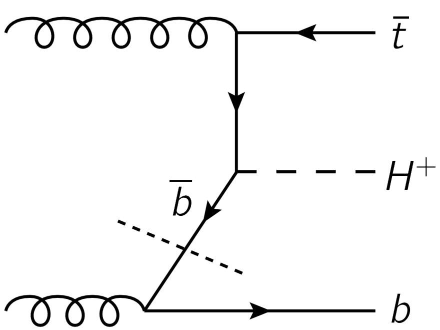
Light H^+ $(m_{H^+} < m_t - m_b)$



$t \to bH^+$

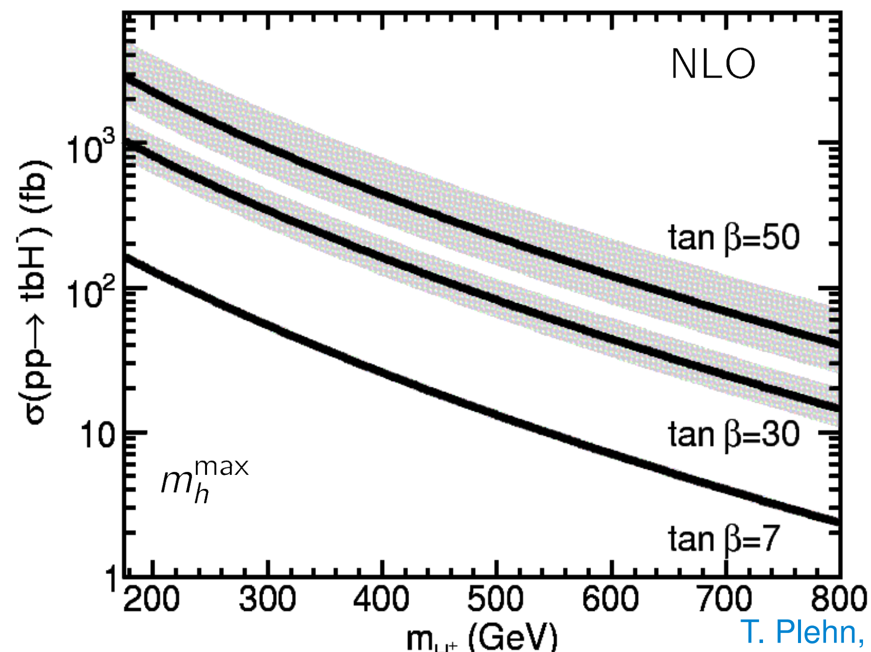


Heavy H^+ $(m_{H^+} > m_t - m_b)$



$gg \to \bar{t}bH^+$

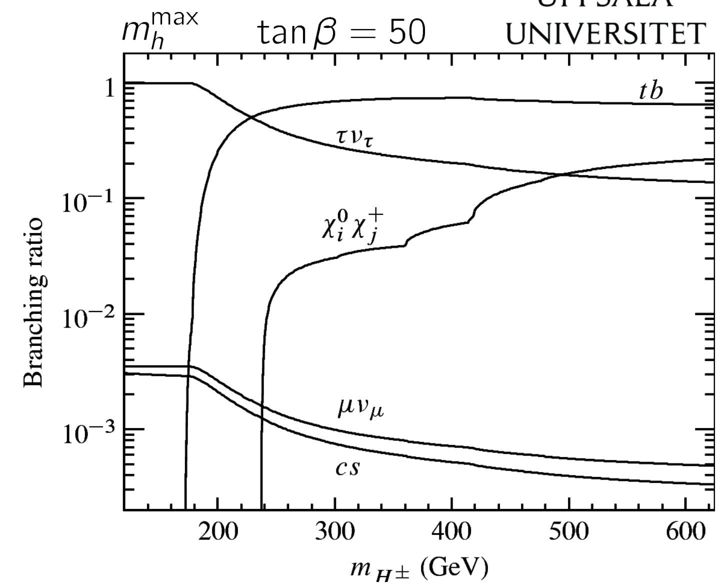
$g\bar{b} \to \bar{t}H^+$

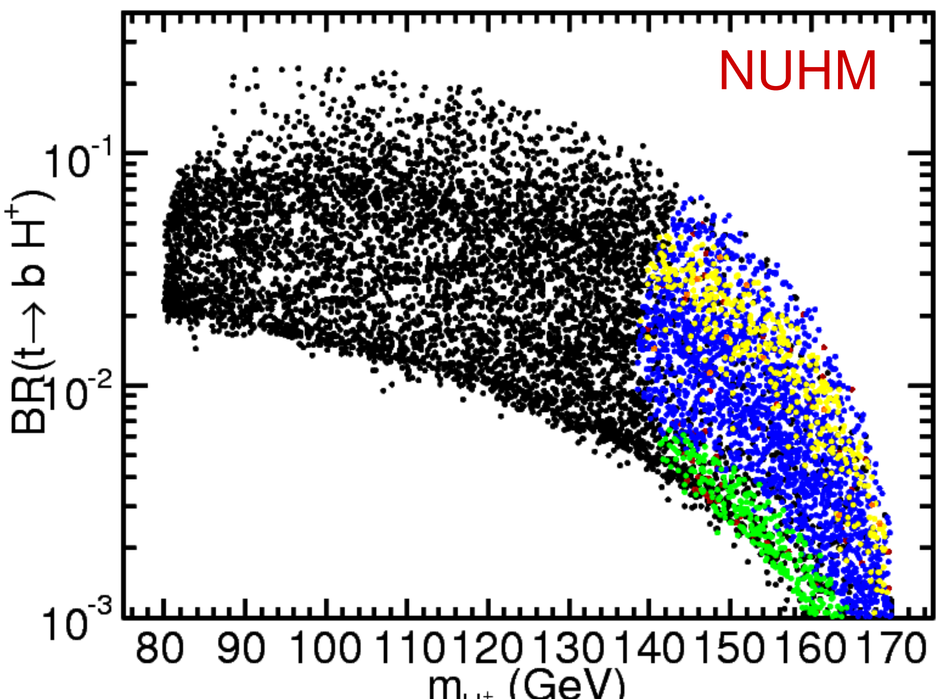


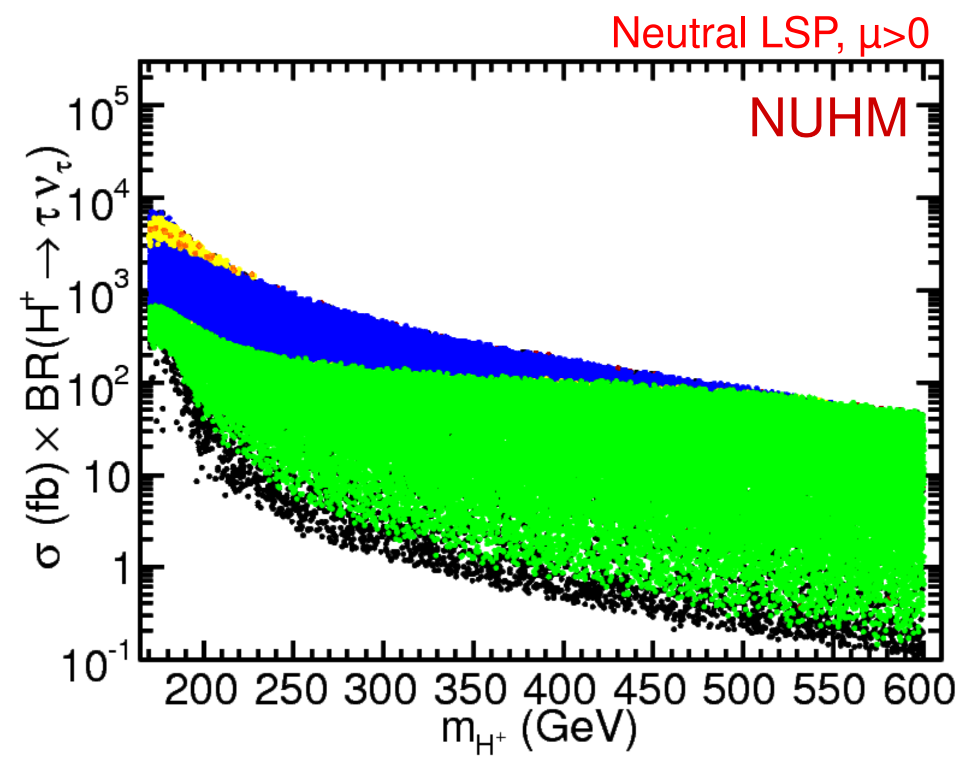
T. Plehn, PRD67 (2003) 014018
Berger et al, PRD71 (2005) 115012

LHC discovery prospects for H^+

- Main discovery channel is $H^+ \to \tau^+ \nu_\tau$, both for light and heavy H^+ for allowed tan β
- Cross section (BR) for each point in NUHM scan
  NLO cross section + HDECAY (FeynHiggs)
  tan β-enhanced corr. to m_b included consistently
- Points with highest cross-section (BR) are also where constraints are most restrictive







Comparing flavour physics to LHC reach

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- Tevatron results with 1 fb^{-1} starting to probe interesting NUHM region

D0 note 5715-CONF

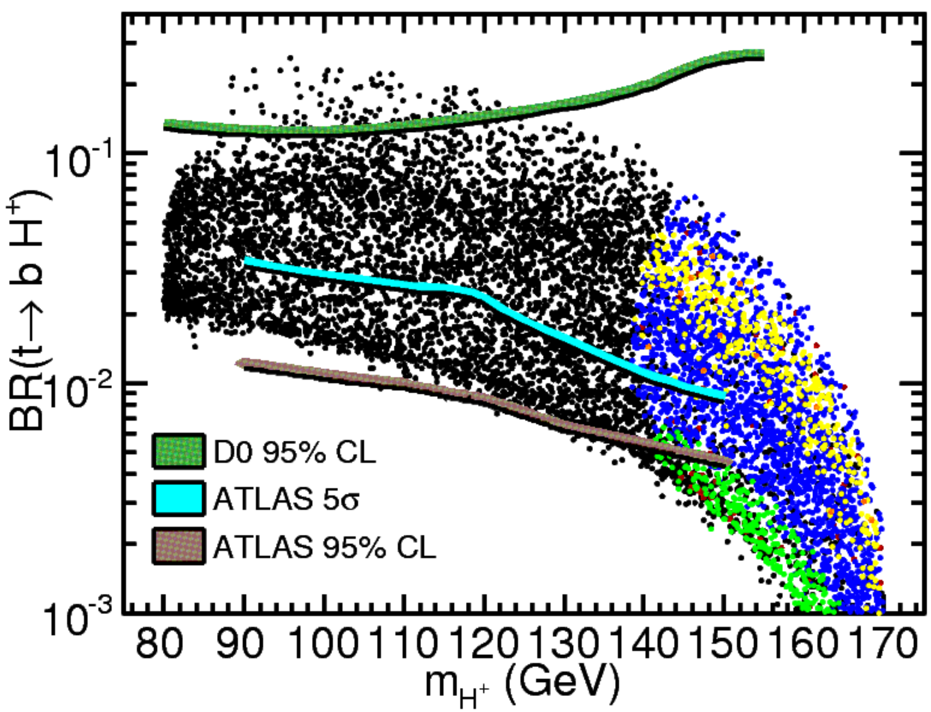
- Reach for CMS and ATLAS with 30 fb^{-1} (3 years of “low” luminosity @ 14 TeV)

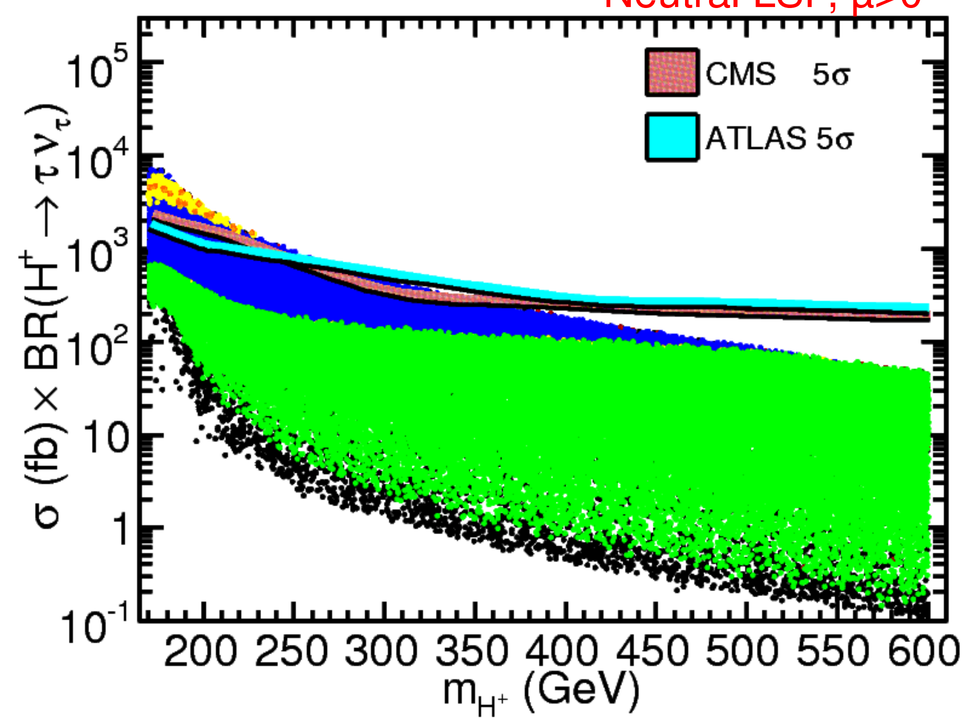
CMS-NOTE-2006-100, 2006-056
ATLAS, arXiv:0901.0512
pp. 1451-1479

- LHC experiments will probe most of the NUHM parameter space for low m_{H+}.
- High m_{H+} region will require more luminosity.

- Allowed
- Direct
- $b \to s \gamma$
- $B_u \to \tau \nu$
- $B_s \to \mu^+ \mu^-$
- $B \to D \tau \nu$
- $K \to \mu \nu$

Neutral LSP, $\mu>0$

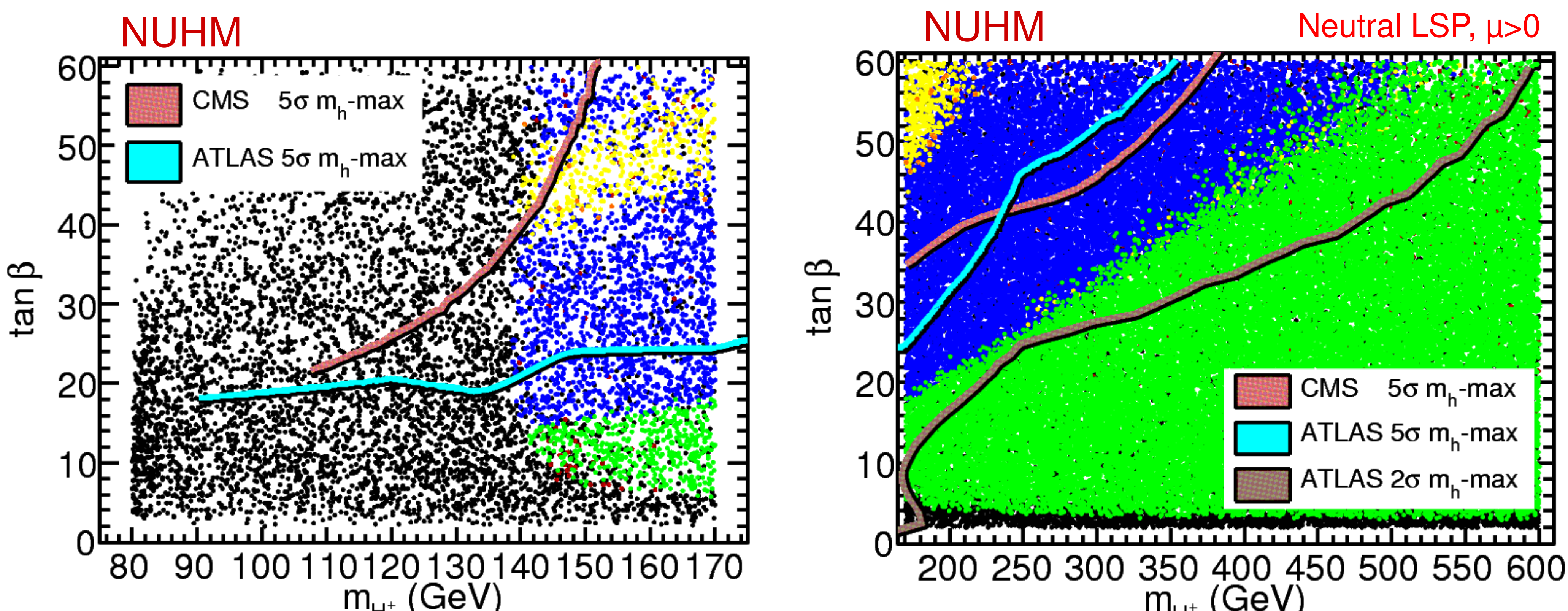




Model-dependent comparison

- Experimental results interpreted in m_h-max scenario
- Discovery contours shift slightly with scenario, in particular for low mass H^+
- NUHM model points with constraints superimposed

Allowed
Direct
$b \to s\gamma$
$B_u \to \tau\nu$
$B_s \to \mu^+\mu^-$
$B \to D\tau\nu$
$K \to \mu\nu$



Conclusions and outlook

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- Restrictive constraints exist on the charged Higgs boson in the MSSM, although not as strict as in the 2HDM type II without supersymmetry.

- In particular B-physics yields powerful constraints.
  Limited by uncertainties, both from theory and experiment.
  → Opportunities for SuperB to improve

- Indirect searches obtains best exclusion where cross sections are largest for H^+ production at the LHC (true both for low and high masses).

- Consistent comparison of scenarios necessary, e.g. 2HDM vs MSSM, 95% exclusion vs 5 sigma discovery

- Early charged Higgs discovery at the LHC points to model beyond the MSSM.

- B-physics can also test more charged Higgs couplings: $B^+ \to \mu^+ \nu_\mu$
  → Complementarity of flavor and high-pt physics

BACKUP

Uncertainties in $\mathrm{B} \to \tau\,\nu_\tau$ from $\mathbf{V_{ub}}$

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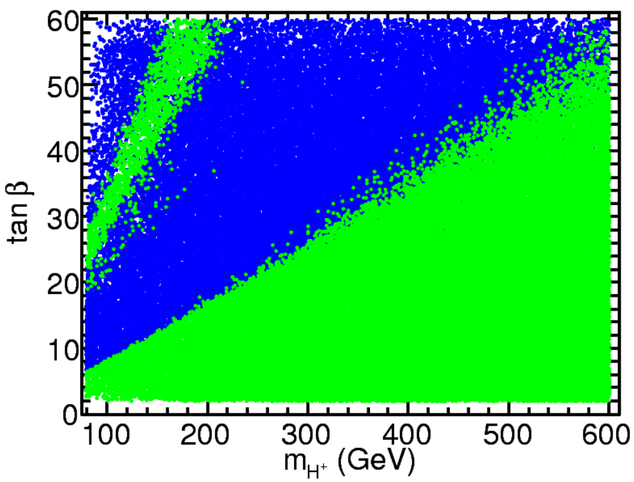
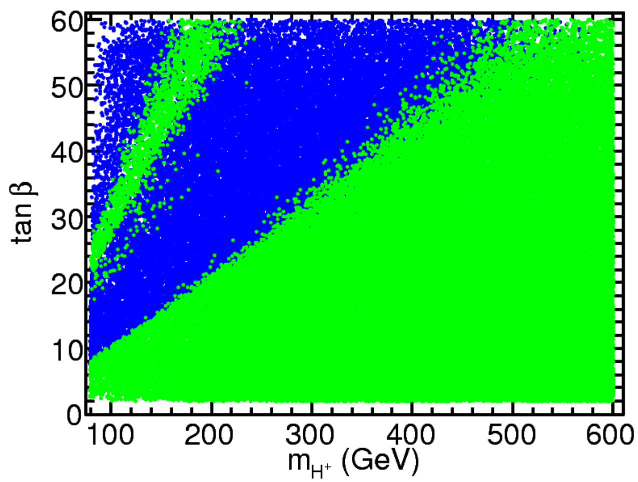
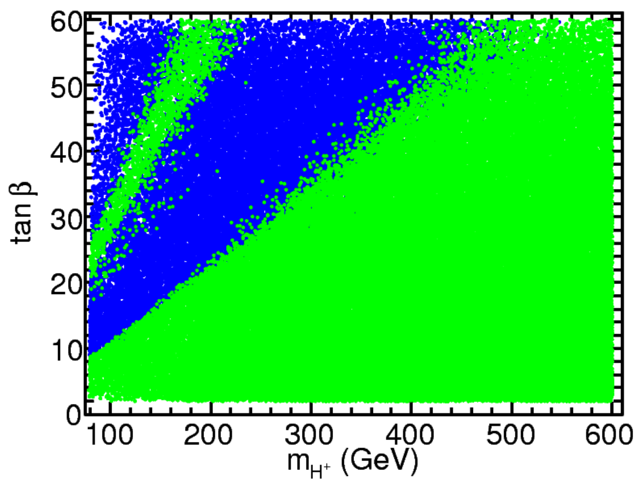
$$|V_{ub}^{\mathrm{excl}}| = (3.5 \pm 0.6) \times 10^{-3}$$



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



$$|V_{ub}^{\mathrm{incl}}| = (4.12 \pm 0.43) \times 10^{-3}$$



$\mathbf{K} \rightarrow \mu \, \nu_\mu$

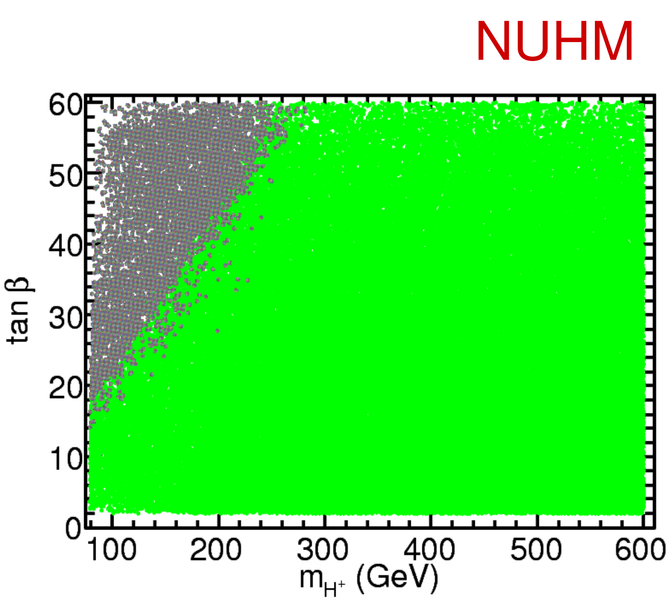
- Similar to $\mathbf{B} \rightarrow \tau \, \nu_\tau$. Also mediated by H⁺ at tree-level.

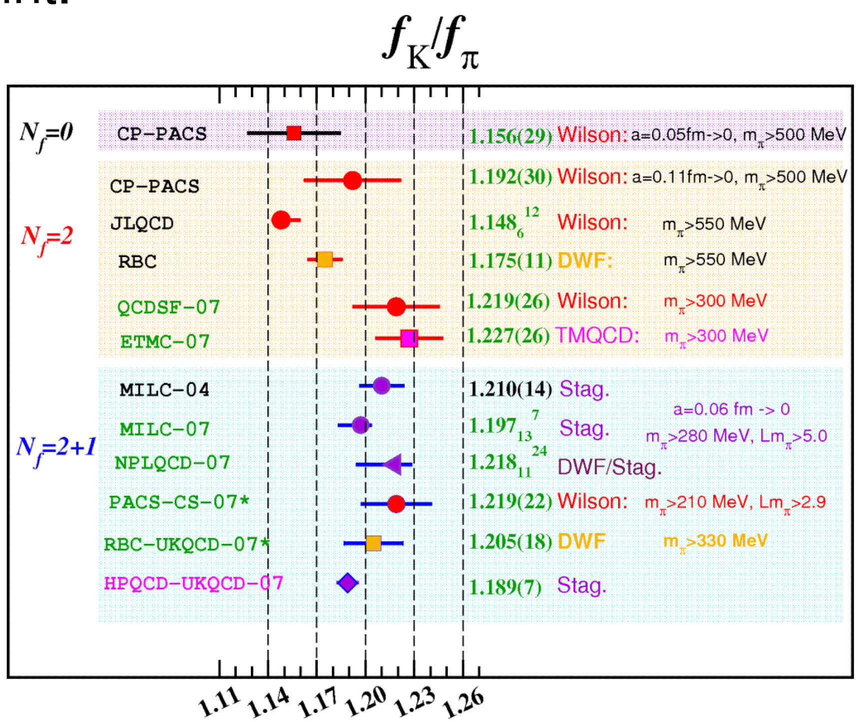
$$R_{\ell 23} \equiv \left| \frac{V_{us}(K_{\ell 2})}{V_{us}(K_{\ell 3})} \times \frac{V_{us}(0^+ \to 0^+)}{V_{ud}(\pi_{\ell 2})} \right| = \left| 1 - \frac{m_{K^+}^2}{M_{H^+}^2} \left(1 - \frac{m_d}{m_s}\right) \frac{\tan^2\beta}{1+\epsilon_0 \tan\beta} \right|$$

FlaviaNet Kaon WG, [arXiv:0801.1817]

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

- Large parametric uncertainty in this quantity from f_K/f_π obtained using lattice QCD Using value with larger error removes constraint.





NUHM model dependence

- Green: NUHM points which are "5σ detectable" by ATLAS
- Red: NUHM points which are **not** 5σ detectable due to ε_b corrections
- Blue: NUHM points which are 5σ detectable thanks to ε_b corrections