Charged Higgs production in the flavored MSSM

Michael Spannowsky

In collaboration with
Stefan Dittmaier
Gudrun Hiller
Tilman Plehn

Content

- Notation and conventions
- Bounds on flavor structure of the MSSM
- Single Charged-Higgs production
- Charged-Higgs + Jet production

MSSM

- Minimal particle content
- Minimal gauge group

Superfields	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	Particle content
$\hat{Q}$	3	2	$\frac{1}{3}$	$(u_L, d_L), (\tilde{u}_L, \tilde{d}_L)$
$\hat{U}^c$	$\bar{3}$	1	$-\frac{4}{3}$	$\bar{u}_R, \tilde{u}^*_R$
$\hat{D}^c$	$\bar{3}$	1	$\frac{2}{3}$	$\bar{d}_R, \tilde{d}^*_R$
$\hat{L}$	1	2	-1	$(\nu_L, e_L), (\tilde{\nu}_L, \tilde{e}_L)$
$\hat{E}^c$	1	1	2	$\bar{e}_R, \tilde{e}^*_R$
$\hat{H}_d$	1	2	-1	$H_d, \tilde{H}_d$
$\hat{H}_u$	1	2	1	$H_u, \tilde{H}_u$

Superfields	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	Particle content
$\hat{G}_a$	8	1	0	$G^\mu_a, \tilde{G}_a$
$\hat{W}_a$	1	3	0	$W^\mu_a, \tilde{W}_a$
$\hat{B}$	1	1	0	$B^\mu, \tilde{B}$

Cancellation of chiral anomaly among fermions

↓

Two oppositely charged Higgsinos

$$\tan\beta = \frac{v_u}{v_d} \qquad \langle H_d^0 \rangle = \frac{v_d}{\sqrt{2}} \qquad \langle H_u^0 \rangle = \frac{v_u}{\sqrt{2}}$$

Charginos and Neutralinos after mixing of Winos, Bino and Higgsinos

Superpotential: $W = \hat{Q}_i Y^u_{ij} \hat{U}_j \hat{H}_u - \hat{Q}_i Y^d_{ij} \hat{D}_j \hat{H}_d + \mu \hat{H}_u \hat{H}_d$

SUSY has to be broken

No need to assume specific breaking scenario → Explicit breaking by soft terms → Large number of free parameters induced

Relevant soft-breaking Lagrangian:

$$\begin{aligned}\mathcal{L}_{\text{soft}} &= -\tilde{u}^*_{Ri} m^2_{\tilde{U}_R ij} \tilde{u}_{Rj} - \tilde{d}^*_{Ri} m^2_{\tilde{D}_R ij} \tilde{d}_{Rj} - \tilde{u}^*_{Li} m^2_{\tilde{U}_L ij} \tilde{u}_{Lj} - \tilde{d}^*_{Li} m^2_{\tilde{D}_L ij} \tilde{d}_{Lj} \\ &- \left[\tilde{u}_{Li} A^u_{ij} \tilde{u}^*_{Rj} H^0_u - \tilde{d}_{Li} V_{ki} A^u_{kj} \tilde{u}^*_{Rj} H^+_u - \tilde{u}_{Li} V^*_{ik} A^d_{kj} \tilde{d}^*_{Rj} H^-_d + \tilde{d}_{Li} A^d_{ij} \tilde{d}^*_{Rj} H^0_d \;+\; \text{h.c.} \right]\end{aligned}$$

In super-CKM basis squarks undergo same rotation as quarks:

$$u_L \equiv V^u \Psi_{U_L}, \quad d_L \equiv V^d \Psi_{D_L}, \quad u_R \equiv U^u \Psi_U, \quad d_R \equiv U^d \Psi_D,$$

$$\tilde{u}_L = V^u \tilde{U}_L, \quad \tilde{d}_L = V^d \tilde{D}_L, \quad \tilde{u}_R = U^u \tilde{U}, \quad \tilde{d}_R = U^d \tilde{D}$$

→ CKM matrix $V \equiv V^u V^{d\dagger}$

$$m^2_{\tilde{D}_L} = V^d m^2_{\tilde{Q}} V^{d\dagger}$$

$$m^2_{\tilde{U}_L} = V^u m^2_{\tilde{Q}} V^{u\dagger}$$

→ $m^2_{\tilde{U}_L} = V \cdot m^2_{\tilde{D}_L} \cdot V^\dagger$ SU(2) relation

Minimal flavor violation

[D'Ambrosio *et al*, 2002]

Basic principle of MFV:

The Yukawa couplings are the only sources of flavor and CP violation

Motivation of MFV:

- Success of SM predictions in FCNC processes
- Reduction of free parameters
- Phenomenologically more predictive

Resulting Squark mass matrices in MFV and NMFV (to good approximation)

$$\mathcal{M}^u_{mfv} = \begin{pmatrix} \left(M_u^2\right)^u_{LL} & 0 & 0 & \Delta^u_{LR,11} & 0 & 0 \\ & \left(M_u^2\right)^c_{LL} & 0 & 0 & \Delta^u_{LR,22} & 0 \\ & & \left(M_u^2\right)^t_{LL} & 0 & 0 & \Delta^u_{LR,33} \\ & & & \left(M_u^2\right)^u_{RR} & 0 & 0 \\ & \text{h.c.} & & & \left(M_u^2\right)^c_{RR} & 0 \\ & & & & & \left(M_u^2\right)^t_{RR} \end{pmatrix}$$

$$\mathcal{M}^u_{nmfv} = \begin{pmatrix} \left(M_u^2\right)^u_{LL} & \Delta^u_{LL,12} & \Delta^u_{LL,13} & \Delta^u_{LR,11} & \Delta^u_{LR,12} & \Delta^u_{LR,13} \\ & \left(M_u^2\right)^c_{LL} & \Delta^u_{LL,23} & \Delta^u_{LR,21} & \Delta^u_{LR,22} & \Delta^u_{LR,23} \\ & & \left(M_u^2\right)^t_{LL} & \Delta^u_{LR,31} & \Delta^u_{LR,32} & \Delta^u_{LR,33} \\ & & & \left(M_u^2\right)^u_{RR} & \Delta^u_{RR,12} & \Delta^u_{RR,13} \\ & \text{h.c.} & & & \left(M_u^2\right)^c_{RR} & \Delta^u_{RR,23} \\ & & & & & \left(M_u^2\right)^t_{RR} \end{pmatrix}$$

$$\left(M_u^2\right)^q_{LL} = M^2_{\tilde{Q},q} + m_q^2 + \left(T_3^q - Q_q \sin^2\theta_w\right) m_Z^2 \cos 2\beta$$

$$\left(M_u^2\right)^q_{RR} = M^2_{\tilde{u},q} + m_q^2 + Q_q \sin^2\theta_w m_Z^2 \cos 2\beta$$

$$\Delta^u_{LR,ii} = \left\langle H_2^0 \right\rangle A^u_{ii} - m_{q_i} \mu \cot\beta$$

$$\Delta^u_{LR,ij} = \left\langle H_2^0 \right\rangle A^u_{ij}$$

$$\Delta^u_{LL,ij} = M^2_{\tilde{Q},ij} \quad i \neq j$$

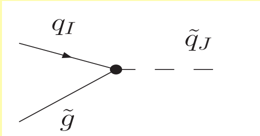
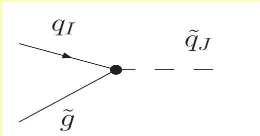
$$\Delta^u_{RR,ij} = M^2_{\tilde{u},ij} \quad i \neq j$$

Mass Insertion Approximation

In general the squark mass matrix has to be diagonalized

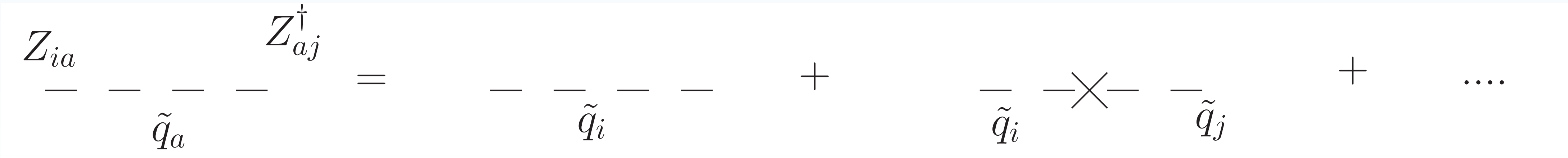
$$Z^u \mathcal{M}^u Z^{u\dagger} = \mathrm{diag}(\mathrm{m}^2_{\tilde{\mathrm{u}}_1}, \mathrm{m}^2_{\tilde{\mathrm{u}}_2})$$

Two 'approximately equivalent' pictures:

	Mass Matrix	Interaction		
mass eigenstate	$\mathcal{M}_I \delta_{IJ}$		$\sim Z_{IJ}$	exact calc.
flavor eigenstate	$\mathcal{M}_{IJ}$		$\sim \delta_{IJ}$	perturb. diag.

For MIA $\delta_{AB,ij} = \Delta_{AB,ij}/\tilde{m}^2$ has to be small and $M^2_{ii} \approx \tilde{m}^2$

$$\mathcal{M} = \begin{pmatrix} M^2_{11} & \Delta_{LL,12} & \cdots \\ \Delta_{LL,21} & M^2_{22} & \cdots \\ \vdots & \vdots & \ddots \end{pmatrix} \simeq \tilde{m}^2 \mathbf{1} + \begin{pmatrix} 0 & \delta_{LL,12} & \cdots \\ \delta_{LL,21} & 0 & \cdots \\ \vdots & \vdots & \ddots \end{pmatrix}$$



Constraints on parameter space

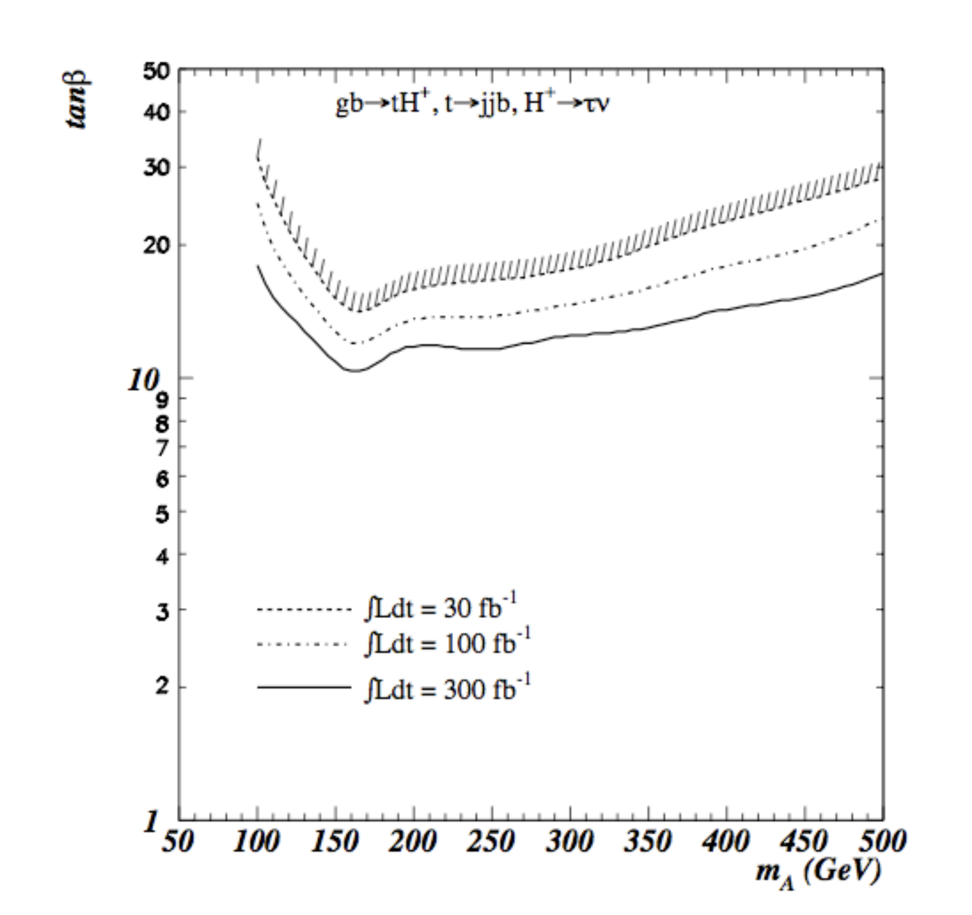
- Flavor bounds
  - Kaon decays
  - $B-\bar{B}$ mixing
  - $B \to X_s\gamma$ and $B \to \rho\gamma$
  - $B \to X_s ll$ and $B \to \pi ll$

- Quark mass: If A-Terms not prop to Yukawas, chiral limit is broken
- Vacuum stability constraints [Casas, Dimopoulos 1996]
- Electroweak precision data: $\rho-\text{parameter},\ \delta M_W,\ \delta \sin^2\theta_{eff}$
- SU(2) relation
- Experimental constraints (Tevatron squark searches)

Charged Higgs production in the flavored MSSM

Charged Higgs is a clear signal for 'New Physics'
but difficult to find: no $H^{\pm}W^{\mp}Z$ interaction at tree-level

- Production in association with heavy quarks or Yukawa-coupling suppressed
- Search strategy: Couple it to a bottom quark in the large $\tan\beta$ regime
- Left with hole for $\tan\beta < 10$

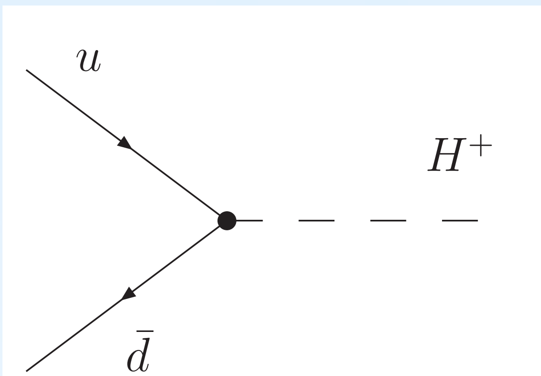


[Assamagan, Coadou 2002]

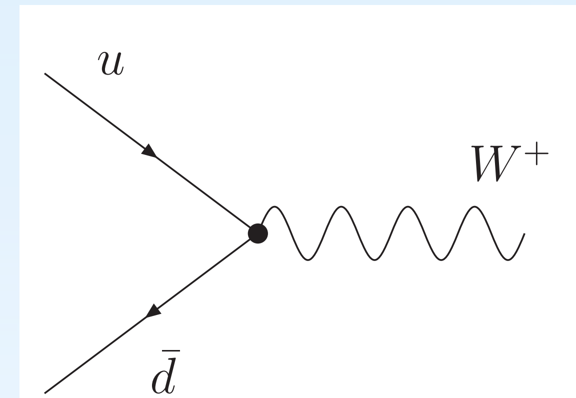
Can charged Higgs production for small $\tan\beta$ be enhanced in NMFV?

Single charged Higgs production in NMFV

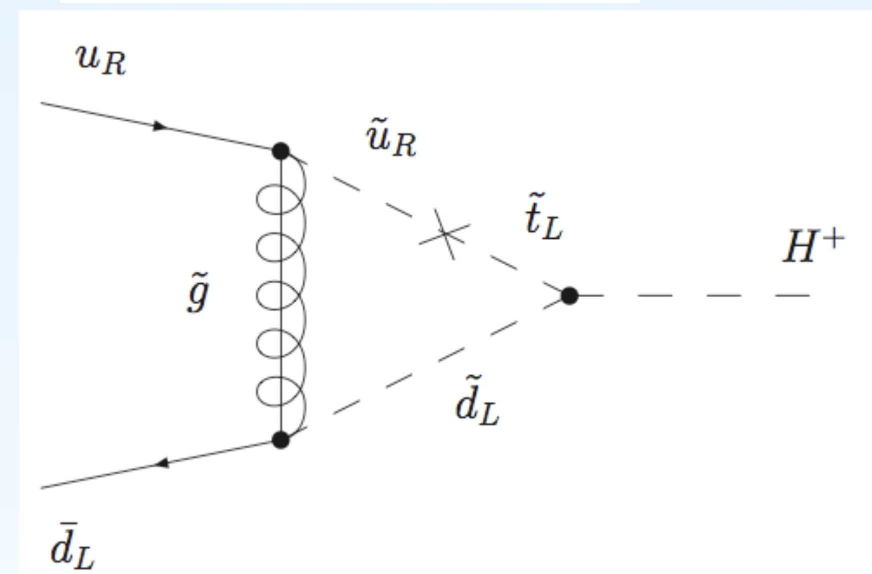
- Direct production without phase-space suppression
- But what about the background?



$$\frac{C_{H^+}}{C_{W^+}} = \frac{m_d tan\beta}{m_W} \approx 10^{-4}$$



$$\mathcal{L}_{H^\pm \tilde{q}\tilde{q}'} \ni g\left[-\frac{m_W}{\sqrt{2}}\sin 2\beta + \frac{m_d^2 \tan\beta + m_u^2 \cot\beta}{\sqrt{2}m_W}\right]\tilde{d}_L^\dagger \tilde{u}_L H^- + \left[\frac{g}{\sqrt{2}m_W}(\langle H_1^0\rangle A^d \tan\beta - m_d\mu)\right]\tilde{d}_R^\dagger \tilde{u}_L H^- + \left[\frac{g}{\sqrt{2}m_W}(\langle H_2^0\rangle A^u \cot\beta - m_u\mu)\right]\tilde{d}_L^\dagger \tilde{u}_R H^-$$



- In MFV all contributions suppressed by small Yukawa-couplings

→ In $m_q \to 0$ amplitude strictly zero

- NMFV circumvents Yukawa-coupling suppression - especially for small $\tan\beta$

Results from last two parts:

$$\mathcal{M}^u_{nmfv} = \begin{pmatrix} (M^2_u)^u_{LL} & \Delta^u_{LL,12} & \Delta^u_{LL,13} & \Delta^u_{LR,11} & \Delta^u_{LR,12} & \Delta^u_{LR,13} \\ & (M^2_u)^c_{LL} & \Delta^u_{LL,23} & \Delta^u_{LR,21} & \Delta^u_{LR,22} & \Delta^u_{LR,23} \\ & & (M^2_u)^t_{LL} & \Delta^u_{LR,31} & \Delta^u_{LR,32} & \Delta^u_{LR,33} \\ & & & (M^2_u)^u_{RR} & \Delta^u_{RR,12} & \Delta^u_{RR,13} \\ & \text{h.c.} & & & (M^2_u)^c_{RR} & \Delta^u_{RR,23} \\ & & & & & (M^2_u)^t_{RR} \end{pmatrix}$$

Red entries severely constrained by:

- Kaon physics
- $B_d - B_{\bar{d}}$ and $B_s - B_{\bar{s}}$ mixing
- $B \to X_s\gamma$ and $B \to \rho\gamma$
- $B \to X_s ll$ and $B \to \pi ll$
- Corrections to quark masses
- $m_{\tilde{q}_i} > 200$ GeV - exp. constraint

Green entries give main contributions to Charged Higgs production

No severe bounds for the production of a charged Higgs!

Working assumptions:

- All soft-breaking parameters are real
- Just flavor violation in up-squark sector

Parameter point:

$$\tan\beta = 7 \qquad m_A = 170\text{ GeV} \quad \mu = -300\text{ GeV}$$

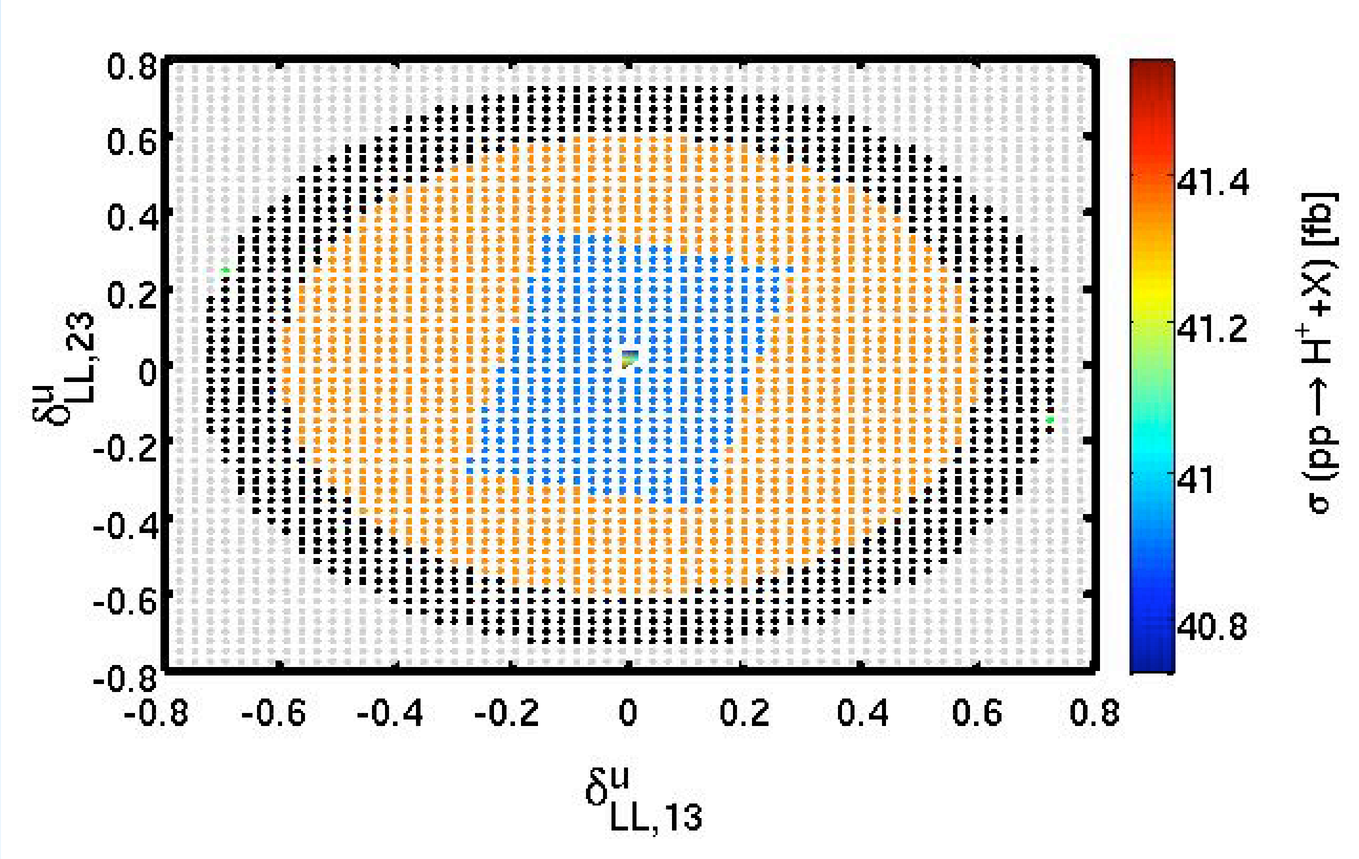
$$m_{\text{diag}} = 600\text{ GeV} \quad m_{\tilde{g}} = 500\text{ GeV}$$

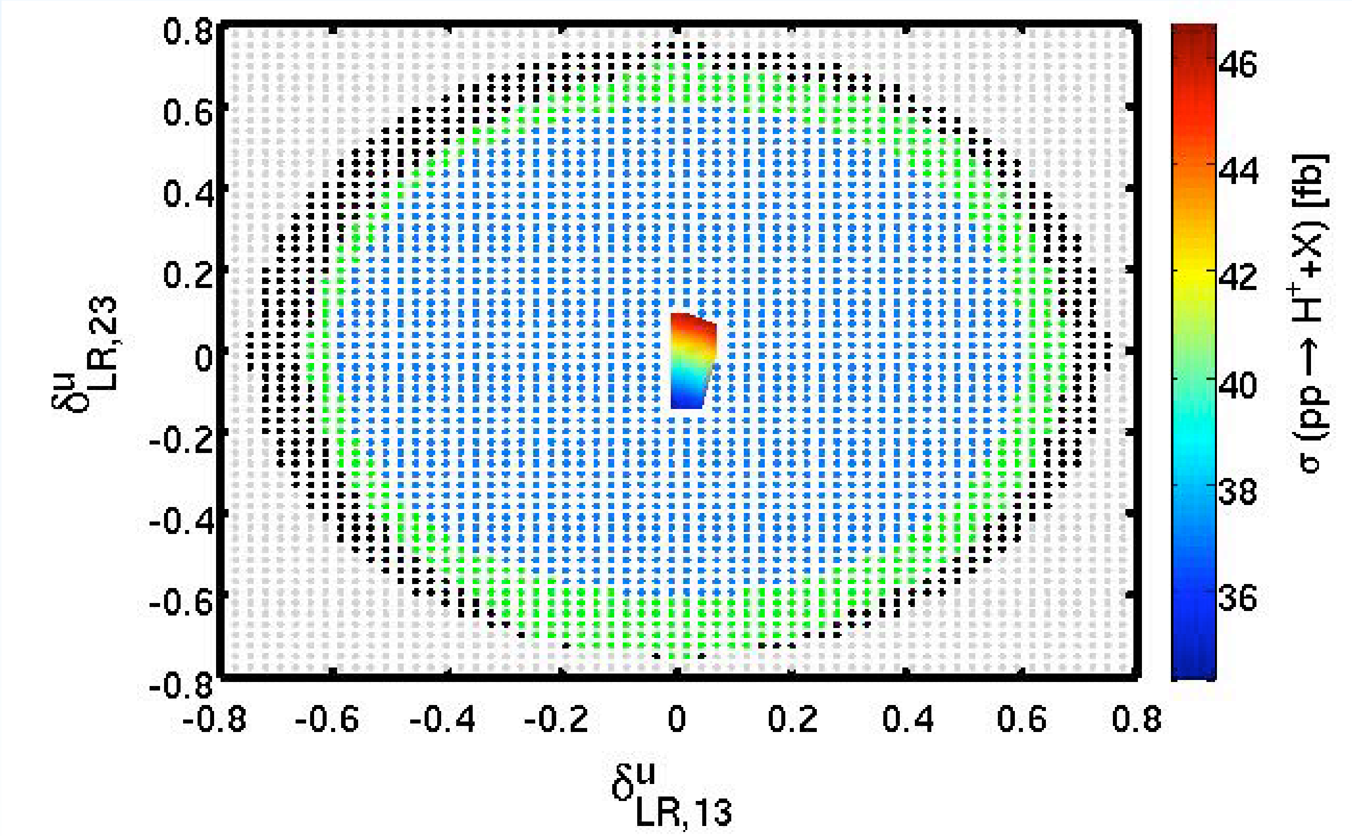
$$A^{u,c} = 0 \qquad A^{d,s,b} = 0 \qquad A^t = 1400\text{ GeV}$$

$$\Rightarrow m_{h^0} = 119\text{ GeV} \quad (\text{at 2 Loop}) \quad \mathrm{m_{H^+}} = 188\text{ GeV} \quad (\text{at Tree} - \text{Level})$$

Flavor bounds at 90 % C.L.

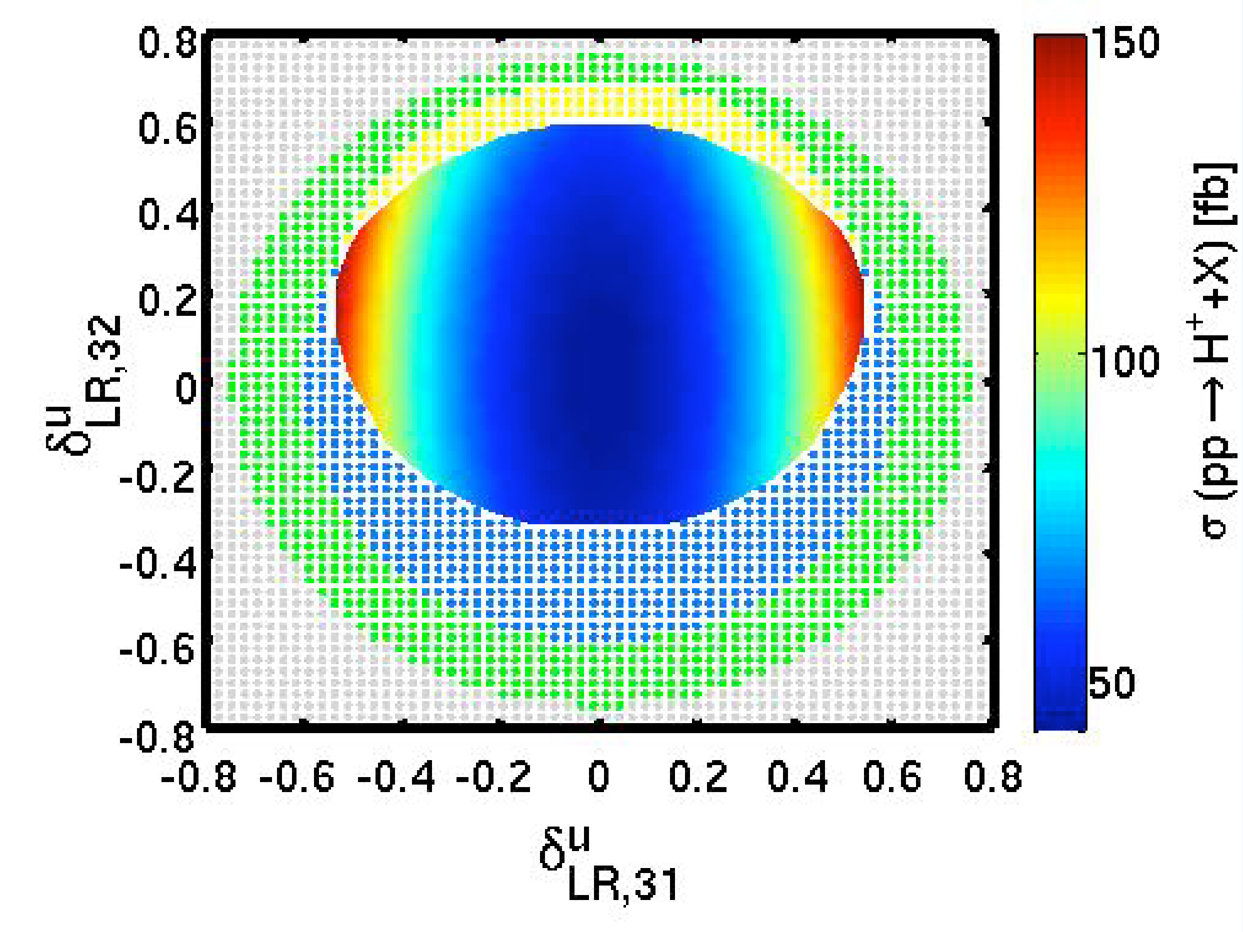
- $0.63 \cdot 10^{-6} < \mathrm{BR}(B \to \rho\gamma) < 1.24 \cdot 10^{-6}$
- $2.94 \cdot 10^{-4} < \mathrm{BR}(B \to X_s\gamma) < 4.14 \cdot 10^{-4}$
- $\mathrm{B_s - B_{\bar{s}}}: \;\; 0.56 < \frac{\Delta m_s}{\Delta m_s^{SM}} < 1.44$
- $\mathrm{B_d - B_{\bar{d}}}: \;\; 0.46 < \frac{\Delta m_d}{\Delta m_d^{SM}} < 1.54$
- $2.8 \cdot 10^{-6} < \mathrm{BR}(B \to X_s ll) < 6.2 \cdot 10^{-6}$
- $\mathrm{BR}(B \to \pi ll) < 9.1 \cdot 10^{-8}$

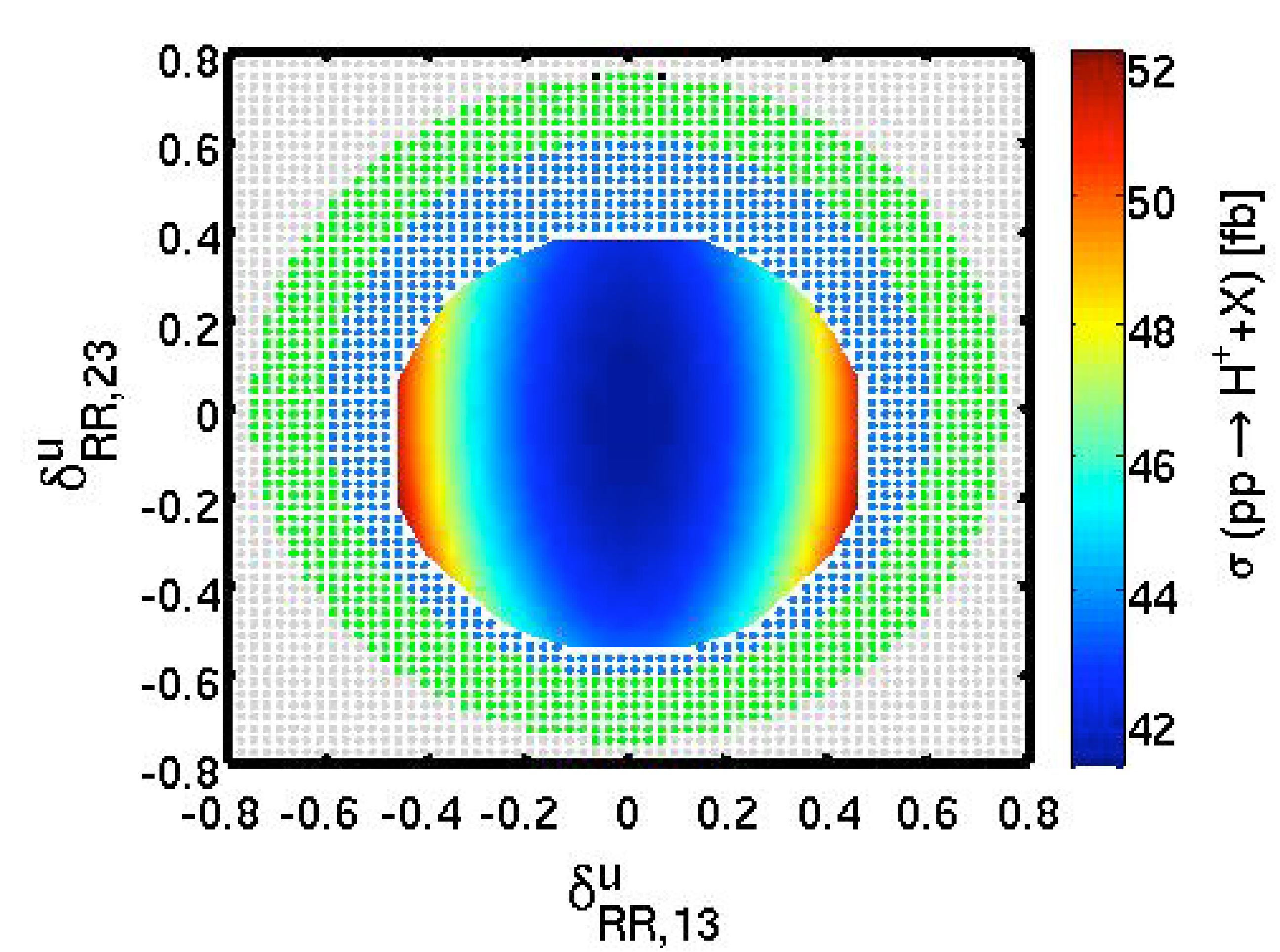




Points outside rainbow-coded area forbidden:

- Blue: Violates radiative and semileptonic decays
- Green: Violates rad. and semilep. decays and exp. squark mass bounds
- Grey: Negative squark mass square
- Orange: Violates BB-Mixing bounds and rad. and semilep. decays
- Black: Violates BB-Mixing bounds, rad. and semilep. decays and exp. squark mass bounds





Points outside rainbow-coded area forbidden:

- Blue: Violates radiative and semileptonic decays
- Green: Violates rad. and semilep. decays and exp. squark mass bounds
- Grey: Negative squark mass square
- Yellow: Violates exp. squark mass bounds

- Flavor-mixing can strongly enhance charged Higgs production cross-section

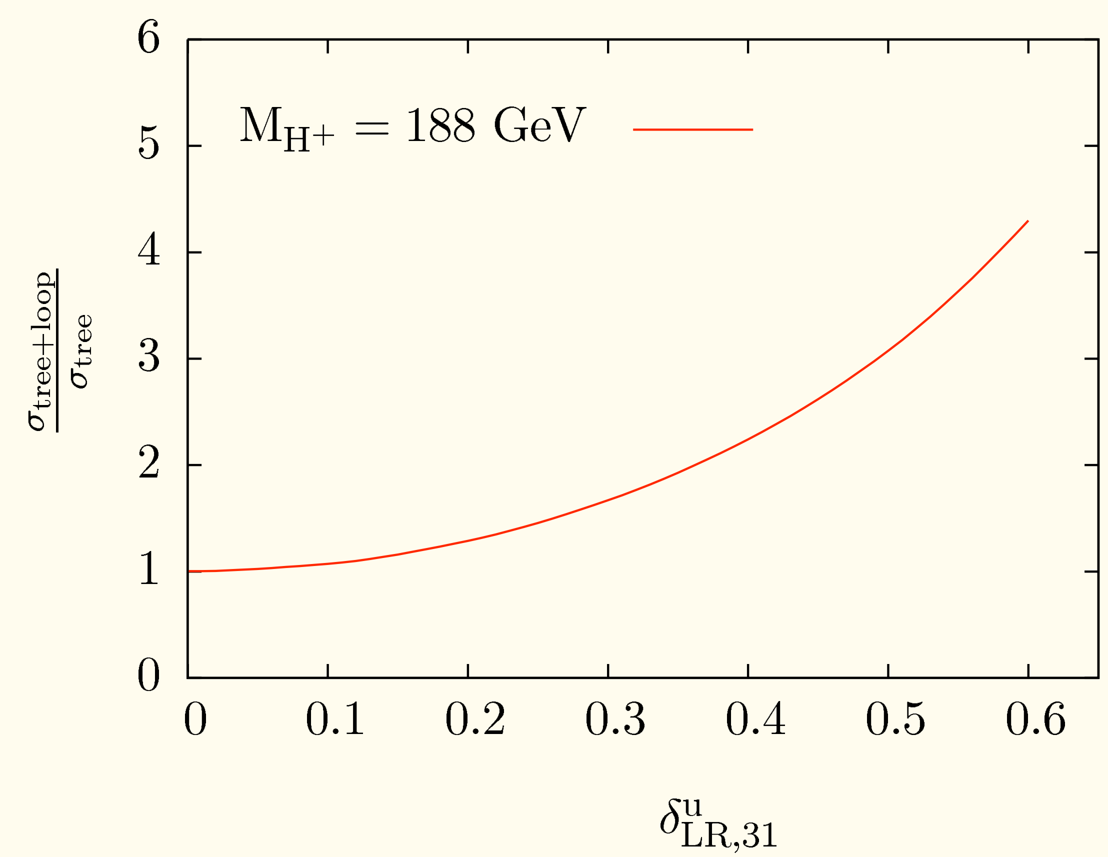
- Largest contribution from $\delta^u_{LR,31}$

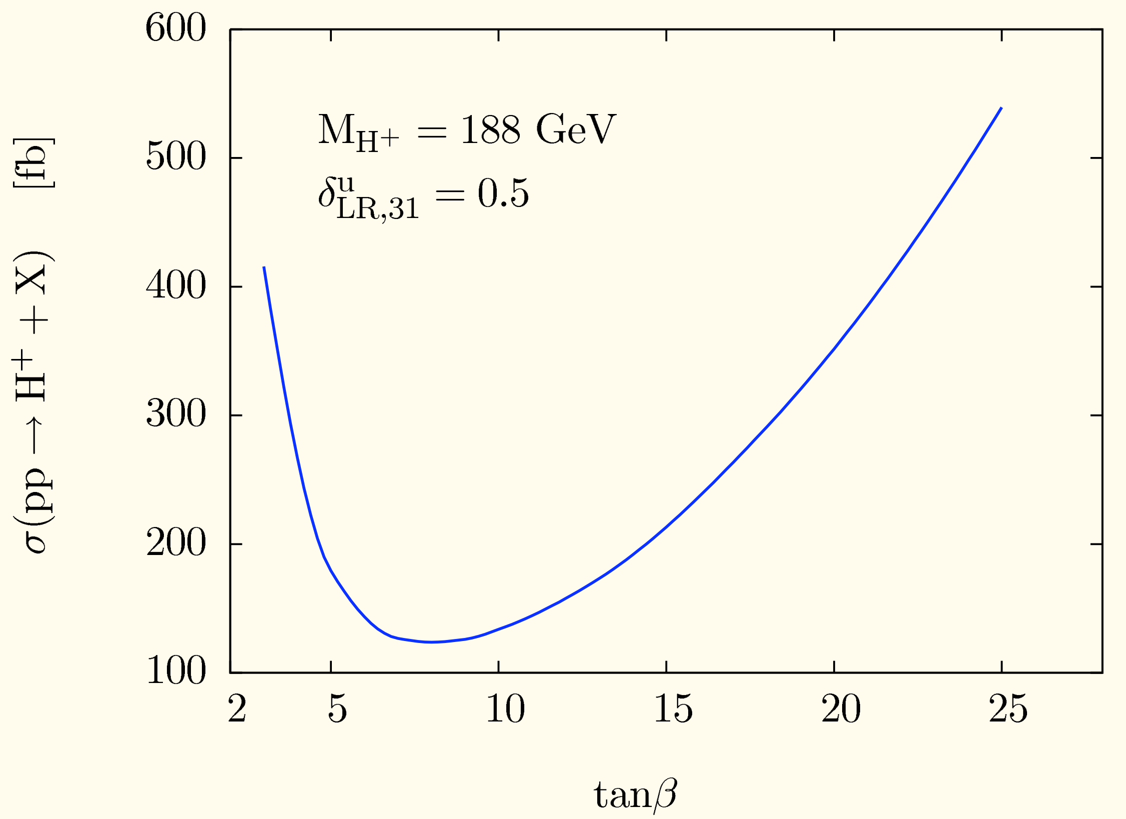
- Tree-Level value for hadronic cross-section with $M_{H^+} = 188\text{GeV}$:

  $\sigma_{tree}(pp \to H^+ + X) = 41\text{fb}$

- Unfortunately, $\sigma(pp \to W^+ + X) \approx 90\text{nb}$

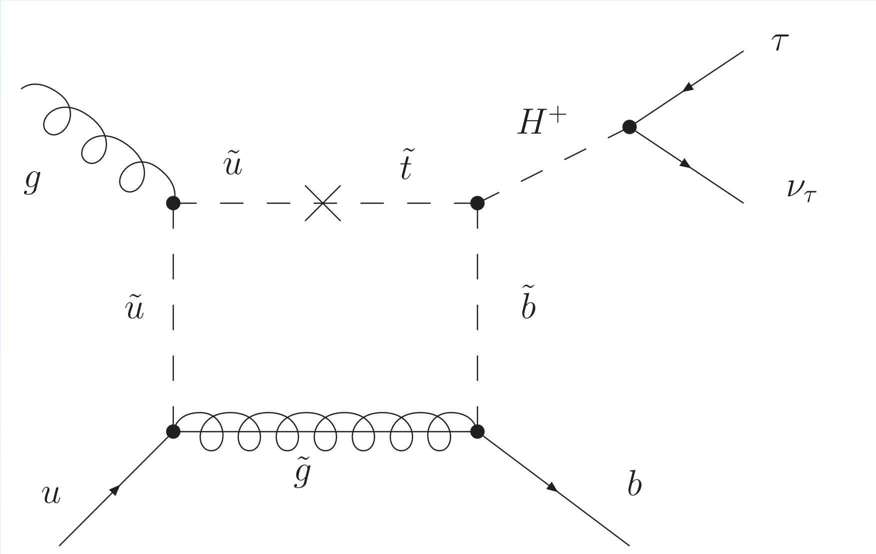
  ➡ bad signal to background ratio



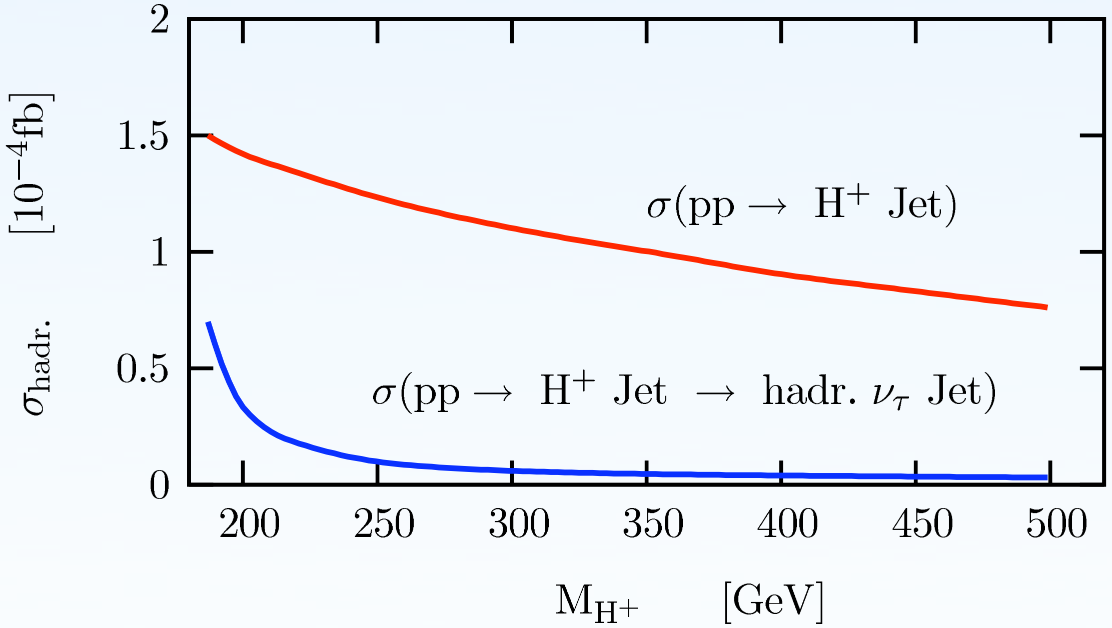


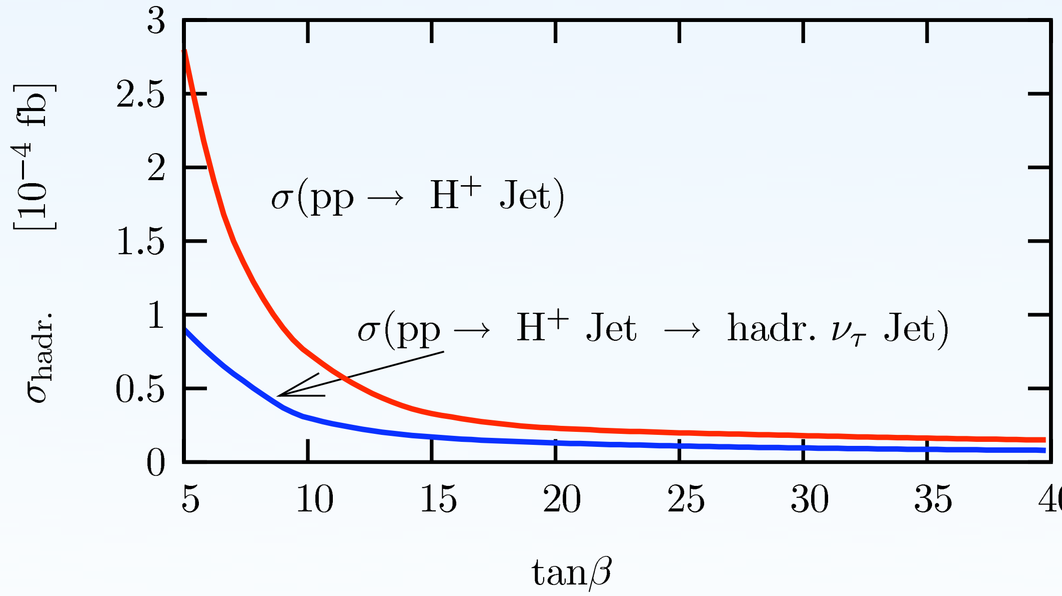
Considered process: $\sigma(pp \to H^+ + \mathrm{Jet})$

- Even with $m_q \to 0$ (just D-Terms) and MFV cross-section is finite
- Just SUSY-QCD corrections - expected to cause largest enhancement
- We require a hard jet to handle collinear divergencies $p_{T,j} \geq 100$ GeV
- Background is large: $\sigma(pp \to W^+ + \mathrm{Jet}) \approx 1.1$ nb



Result for MFV with $m_q \to 0$





Just D-Term contribution neglectable due to decoupling with $\mathcal{A} \sim 1/M^4_{\mathrm{SUSY}}$

Results

m_{H^+}	$\tan\beta$	σ_{2HDM}	$\sigma_{\text{2HDM}}^{(m_s=0)}$	σ_{MFV}	$\sigma_{\text{MFV}}^{(m_s=0)}$	$\sigma_{\text{MFV}}^{(m_q=0)}$
187 GeV	3	$2.1 \cdot 10^{-1}$	$7.5 \cdot 10^{-2}$	$1.4 \cdot 10^{-1}$	$1.9 \cdot 10^{-1}$	$6.7 \cdot 10^{-4}$
187 GeV	7	$7.8 \cdot 10^{-1}$	$4.8 \cdot 10^{-1}$	$5.3 \cdot 10^{-1}$	$5.7 \cdot 10^{-1}$	$1.5 \cdot 10^{-4}$
400 GeV	3	$3.3 \cdot 10^{-2}$	$1.3 \cdot 10^{-2}$	$2.6 \cdot 10^{-2}$	$3.0 \cdot 10^{-2}$	$4.2 \cdot 10^{-4}$
400 GeV	7	$1.3 \cdot 10^{-1}$	$7.3 \cdot 10^{-2}$	$8.8 \cdot 10^{-2}$	$1.1 \cdot 10^{-1}$	$9.1 \cdot 10^{-5}$

m_{H^+}	$\tan\beta$	σ_{SUSY}	$\sigma_{\text{SUSY}}^{(m_s=0)}$	$\sigma_{\text{SUSY}}^{(m_q=0)}$
188 GeV	3	9.9	9.7	8.4
188 GeV	7	3.1	3.1	1.8
400 GeV	3	1.5	1.5	1.4
400 GeV	7	0.47	0.46	0.032

- σ_{SUSY} corresponds to $\delta^u_{LR,31} = 0.5$
- Light-flavor and bottom Yukawa have roughly the same impact $m_b V_{cb} \sim m_s V_{cs}$
- The D-Term couplings are numerically irrelevant
- NMFV can enhance cross-section by one order of magnitude for small

Conclusion

Two loop induced H^+ production processes were studied in MFV and NMFV:

Can we detect a charged Higgs in these channels although Signal to Background is quite small?

If answer is 'yes'

- Viable process to detect a charged Higgs for small $\tan\beta$
- It is possible to rule out the MFV assumption
- It is possible to constrain the free parameters $A^u_{LR,3(1,2)}$ and $M^u_{RR,3(1,2)}$ which is not possible by flavor physics

Intersectional field of flavor and collider physics might give interesting results for LHC