Charged Higgs at the LHC in minimal flavor violation and beyond

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Outline

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- Charged Higgs at the 'Ring of Fire'

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- Charged Higgs + Jet

Minimal Supersymmetric Standard Model

Model:	R-parity conserving MSSM
MSSM:	Minimal gauge group and particle content

SUSY explicitly broken

Relevant soft-breaking Lagrangian:

$$\mathcal{L}_{soft} = - M^2_{\tilde{Q}_i} \tilde{Q}^\dagger_i \tilde{Q}_i - M^2_{\tilde{u}_i} |\tilde{u}_{R_i}|^2 - M^2_{\tilde{d}_i} |\tilde{d}_{R_i}|^2$$
$$- \left[A^u_{ij} \tilde{u}^*_{R_i} H_2 \cdot \tilde{Q}_j + A^d_{ij} \tilde{d}^*_{R_i} H_1 \cdot \tilde{Q}_j \right]$$

Often imposed Minimal Flavor Violation (MFV) assumption [D'Ambrosio,Giudice,Isidori,Strumina 2002]

Up-type squark matrix in MFV and NMFV:

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

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

$$\begin{aligned} \left(M_u^2\right)^q_{LL} &= M^2_{\tilde{Q},q} + m_q^2 + \left(T_3^q - Q_q \sin^2\theta_w\right) m_Z^2 \cos 2\beta \\ \left(M_u^2\right)^q_{RR} &= M^2_{\tilde{u},q} + m_q^2 + Q_q \sin^2\theta_w m_Z^2 \cos 2\beta \\ \Delta^u_{LR,ii} &= \left\langle H_2^0 \right\rangle A^u_{ii} - m_{q_i}\mu^* \cot\beta \end{aligned}$$

$$\begin{aligned} \Delta^u_{LR,ij} &= \left\langle H_2^0 \right\rangle A^u_{ij} \\ \Delta^u_{LL,ij} &= M^2_{\tilde{Q},ij} \quad i \neq j \\ \Delta^u_{RR,ij} &= M^2_{\tilde{u},ij} \quad i \neq j \end{aligned}$$

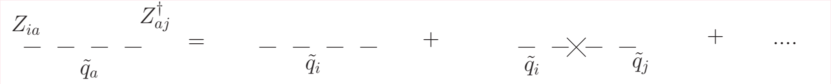
In general the squark mass matrix has to be diagonalized

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

Mass Insertion Approximation can be used if off-diagonal entries are small compared to $\tilde{m}_q$ (average squark mass)

$$\delta^q_{AB,ij} = \frac{\Delta^q_{AB,ij}}{\tilde{m}^2_q}$$

$$\begin{aligned} < \tilde{q}^i_A \tilde{q}^{j*}_B > &= \mathrm{i}(\mathrm{k}^2 \mathbf{1} - \tilde{\mathrm{m}}^2_\mathrm{q} \mathbf{1} - \Delta^\mathrm{q}_\mathrm{AB})^{-1}_\mathrm{ij} \\ &\backsimeq \frac{\mathrm{i}\delta_\mathrm{ij}}{k^2 - \tilde{m}^2_q} + \frac{\mathrm{i}(\Delta^\mathrm{q}_\mathrm{AB})_\mathrm{ij}}{(k^2 - \tilde{m}^2_q)} + \mathcal{O}(\Delta^2) \end{aligned}$$



Charged Higgs at the LHC

- Charged Higgs is a signature for 'New Physics'
- Studying a light neutral Higgs alone is not sufficient to identify an extended Higgs sector
- Tedious Task: No $H^{\pm}W^{\mp}Z$ interaction at tree-level. In the two Higgs doublet model not the $H^{\pm}$ but the Goldstone boson $G^{\pm}$ couples to $W^{\pm}Z$.

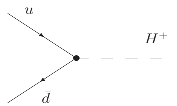
⇒ Most promising strategy of finding a charged Higgs at LHC: Couple it to a bottom quark in the large $\tan\beta$ regime:

- Light $H^{\pm}$: $M_{H^{\pm}} \leq m_t - m_b \approx 170 GeV$
  $pp \to t\bar{t} \to H^{\pm}tb$
- Heavy $H^{\pm}$: $M_{H^{\pm}} \geq 170 GeV$
  $pp \to H^{-}tb$
  $pp \to H^{-}t$

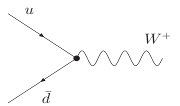
⇒ Leaving a hole for $\tan\beta \leq 20$ [CMS TDR, 2007]

Single Higgs in non-minimal flavor violation

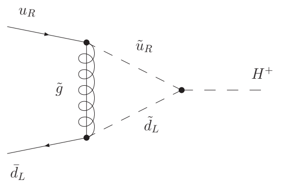
- Direct production without phase-space suppression
- But what about the Background?



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



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



- 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 $\tan\beta$

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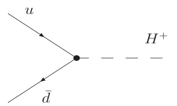

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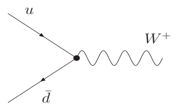
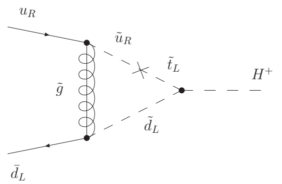


$$\begin{aligned}\mathcal{L}_{H^\pm\tilde q\tilde q'} \ni & \left[-\frac{g m_W}{\sqrt{2}}\sin 2\beta + \frac{g m_d^2 \tan\beta}{\sqrt{2} m_W} + \frac{g m_u^2 \cot\beta}{\sqrt{2} m_W}\right] \tilde d_L^\dagger \tilde u_L H^- \\ & + \left[\frac{g \tan\beta}{\sqrt{2} m_W}\langle H_1^0\rangle A^d + \frac{g}{\sqrt{2} m_W} m_d \mu^*\right] \tilde d_R^\dagger \tilde u_L H^- \\ & + \left[\frac{g \cot\beta}{\sqrt{2} m_W}\langle H_2^0\rangle A^{u*} + \frac{g}{\sqrt{2} m_W} m_u \mu)\right] \tilde d_L^\dagger \tilde u_R H^-\end{aligned}$$



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  $\Rightarrow$ in $m_q \rightarrow 0$ amplitude strictly zero
- NMFV circumvents Yukawa-Coupling suppression.
  Especially for small $\tan\beta$

Relevant Bounds

No severe bounds for the production of a charged Higgs!

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

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

Green entries give main contributions to Charged Higgs production.

Working Assumptions:

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

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$$\begin{array}{llll} \text{Parameters :} & \tan\beta = 7 & m_A = 170\ \text{GeV} & \mu = -300\ \text{GeV} \\ & m_{\text{diag}} = 600\ \text{GeV} & m_{\tilde{g}} = 500\ \text{GeV} & M_2 = 700\ \text{GeV} \\ & A^{u,c} = 0 & A^{d,s,b} = 0 & A^t = 1400\ \text{GeV} \end{array}$$

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

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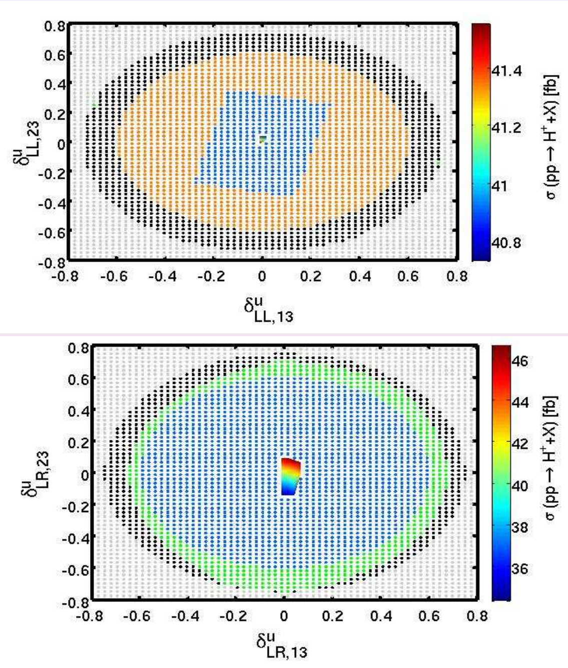
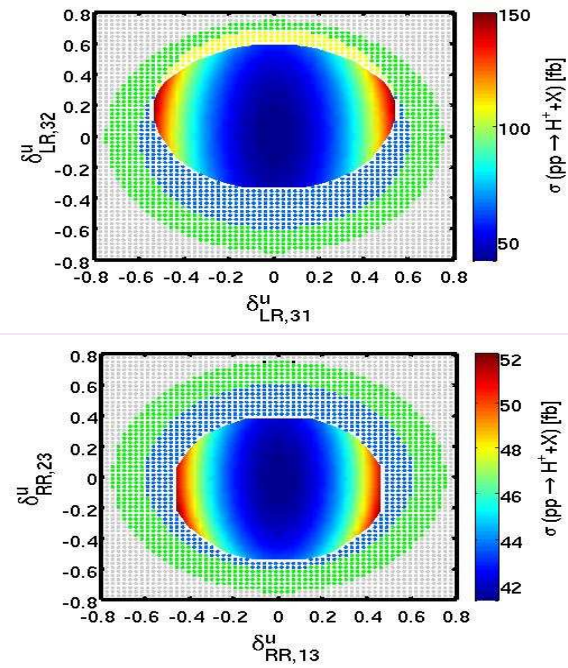
Flavor bounds at 90% C.L.

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



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



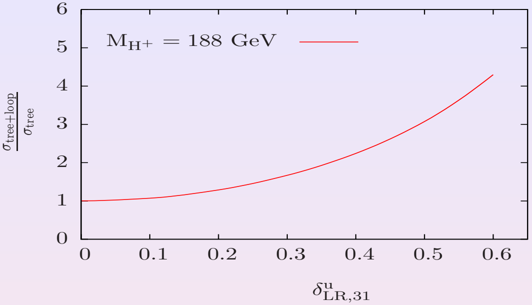
Points outside rainbow-coded area forbidden:

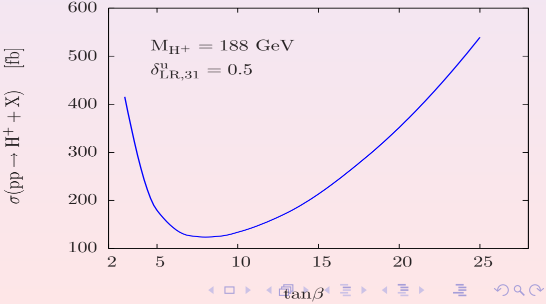
- Yellow: Violates exp. squark mass bounds
- Blue: Violates radiative and semileptonic decays
- Green: Violates rad. and semilep. decays and exp. squark mass bounds
- Grey: Negative squark mass square

Results of single Higgs production

- Flavor-mixing can strongly enhance charged Higgs production cross-section
- Largest contribution from $\delta^u_{LR,31}$

- Tree-Level value for hadr. cross-section with $M_{H^+} = 188\ \mathrm{GeV}$: $\sigma_{tree}(pp \to H^+ + X) = 41\mathrm{fb}$
- Unfortunately, $\sigma(pp \to W^+ + X) \approx 90\mathrm{nb}$ $\Rightarrow$ bad signal to background ratio H^+

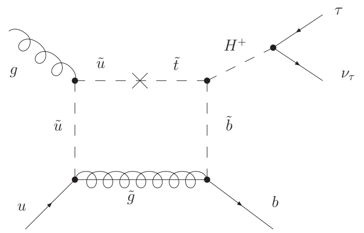




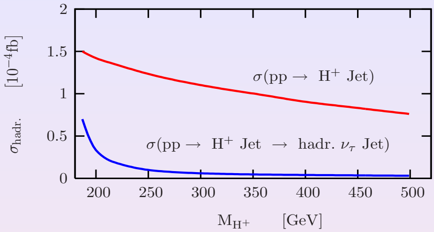
Charged Higgs + Jet production

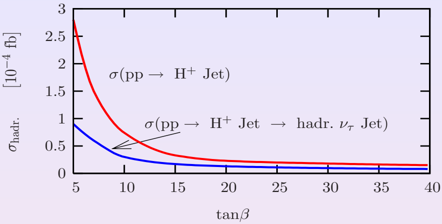
Considered process: $\sigma(pp \to H^+ + \mathrm{Jet})$

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

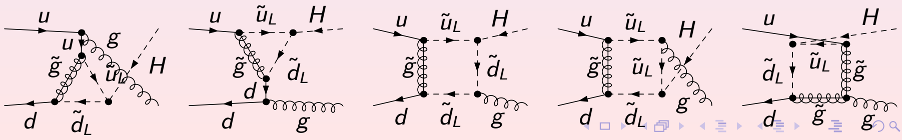


Results for $m_q \rightarrow 0$ in MFV

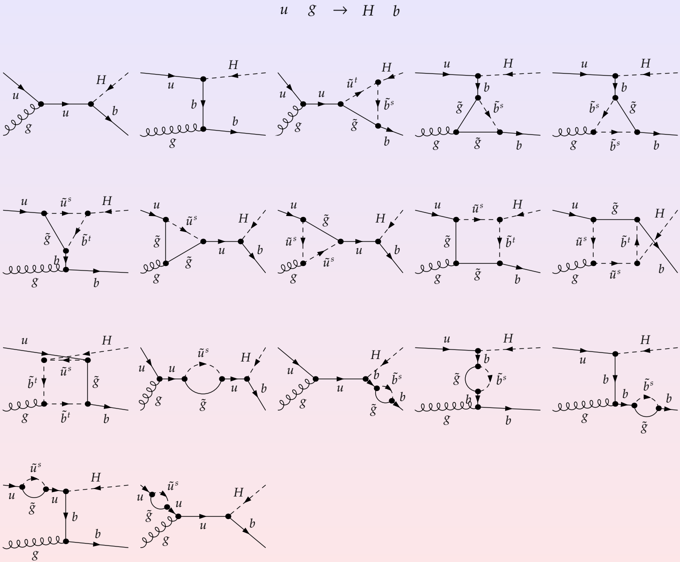




- For $m_q \rightarrow 0$ just D-Term couplings present
- Cross-sections are very small because the D-Terms decouple with $1/M^4_{SUSY}$ on the amplitude level (Large mass expansion)
- D-Term contributions to the Amplitude are proportional to $\sin(2\beta)$



Diagrams for 1 of 18 partonic processes - $ug \to H^+ b$:



Results: H^+ + Jet

m_{H^+}	$\tan\beta$	$\sigma_{\rm 2HDM}$	$\sigma^{(m_s=0)}_{\rm 2HDM}$	$\sigma_{\rm MFV}$	$\sigma^{(m_s=0)}_{\rm MFV}$	$\sigma^{(m_q=0)}_{\rm MFV}$
188 GeV	3	$2.5 \cdot 10^{-1}$	$1.9 \cdot 10^{-1}$	$2.6 \cdot 10^{-1}$	$2.0 \cdot 10^{-1}$	$6.7 \cdot 10^{-4}$
188 GeV	7	$9.9 \cdot 10^{-1}$	$6.0 \cdot 10^{-1}$	$1.1 \cdot 10^{0}$	$6.5 \cdot 10^{-1}$	$1.5 \cdot 10^{-4}$
400 GeV	3	$4.0 \cdot 10^{-2}$	$3.0 \cdot 10^{-2}$	$4.2 \cdot 10^{-2}$	$3.2 \cdot 10^{-2}$	$4.2 \cdot 10^{-4}$
400 GeV	7	$1.6 \cdot 10^{-1}$	$1.0 \cdot 10^{-1}$	$1.7 \cdot 10^{-1}$	$1.1 \cdot 10^{-1}$	$9.1 \cdot 10^{-5}$

m_{H^+}	$\tan\beta$	$\sigma_{\rm SUSY}$	$\sigma^{(m_s=0)}_{\rm SUSY}$	$\sigma^{(m_q=0)}_{\rm SUSY}$
188 GeV	3	14.3	14.2	13.9
188 GeV	7	4.6	4.4	3.0
400 GeV	3	2.4	2.4	2.3
400 GeV	7	0.79	0.73	0.54

- 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 $\tan\beta$

Conclusions

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

Can we detect a charged Higgs in this channel although Signal to Background Ratio quite small?

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- Viable process to detect a charged Higgs for small $\tan\beta$, yielding a clear signal for physics beyond the standard model
- 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

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

Appendix

B-B-Mixing Chargino Contributions

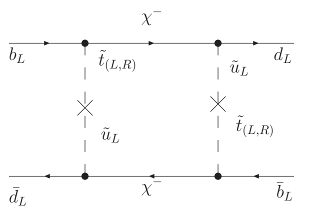
The dominant Operators are:

$$H_{eff}^{\Delta B=2} = \sum_{i=1}^{5} C_i(\mu) O_i(\mu) + \sum_{i=1}^{3} \tilde{C}_i(\mu) \tilde{O}_i(\mu)$$

$$O_1 = \bar{d}_L^\alpha \gamma_\mu b_L^\alpha \;\; \bar{d}_L^\beta \gamma_\mu b_L^\beta, \;\; O_2 = \bar{d}_R^\alpha b_L^\alpha \;\; \bar{d}_R^\beta b_L^\beta,$$

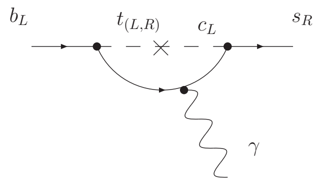
$$O_3 = \bar{d}_R^\alpha b_L^\beta \;\; \bar{d}_R^\beta b_L^\alpha, \quad O_4 = \bar{d}_R^\alpha b_L^\alpha \;\; \bar{d}_L^\beta b_R^\beta, \quad O_5 = \bar{d}_R^\alpha b_L^\beta \;\; \bar{d}_L^\beta b_R^\alpha$$

The operators $\tilde{O}_{1,2,3}$ are obtained from $O_{1,2,3}$ by exchanging $L \leftrightarrow R$



- Light quark masses are neglected $\Rightarrow$ just O_1 and $\tilde{O}_3$ at high scale
- Main contributions from $\delta^u_{LL,13}$ and $\delta^u_{LR,13}$

$B \longrightarrow X_s\gamma$ and $B \longrightarrow \rho\gamma$



Operators:

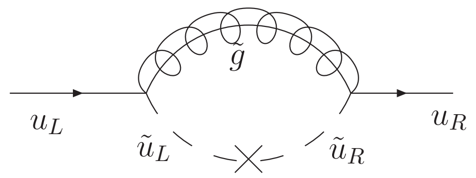
$$O_2 = \bar{s}_L \gamma_\mu c_L \gamma^\mu b_L$$
$$O_7 = \frac{e}{16\pi^2} m_b \bar{s}_L \sigma_{\mu\nu} F^{\mu\nu} b_R$$
$$O_8 = \frac{gs}{16\pi^2} m_b \bar{s}_L \sigma_{\mu\nu} G_a^{\mu\nu} t_a b_R$$

The Operators $\tilde{O}_7$ and $\tilde{O}_8$ are obtained by interchanging L and R.

Exp. Values for $BR(b \to s\gamma)$: $355 \pm 24^{+9}_{-10} \pm 3 \cdot 10^{-6}$

Exp. Values for $BR(B \to \rho\gamma)$: BaBar: $0.79^{0.22}_{-0.20} \pm 0.06 \cdot 10^{-6}$

Belle: $1.25^{0.37+0.07}_{-0.33-0.06} \cdot 10^{-6}$

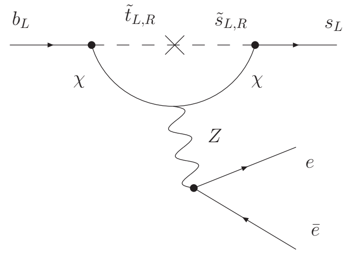


Gluino corrections to quark masses:

$$\delta m_i \propto -\frac{\alpha_s}{4\pi} m_{\tilde{g}} \mathrm{Re}(\delta^{\mathrm{q}}_{\mathrm{ii}})_{\mathrm{LR}} \mathrm{I(x)}$$

Assumption: δm_i smaller than the values of the absolute value of the quark masses

$B \to X_s ll$ and $B \to \pi ll$



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$$O_9 = \frac{e^2}{16\pi^2} \bar{s}_L \gamma^\mu b_L \bar{l} \gamma_\mu l$$
$$O_{10} = \frac{e^2}{16\pi^2} \bar{s}_L \gamma^\mu b_L \bar{l} \gamma_\mu \gamma_5 l$$

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