Charged Higgs boson production at the LHC: NLO supersymmetric QCD corrections

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in collaboration with S. Dittmaier, M. Spira, M. Walser
Introduction: charged Higgs bosons in the MSSM

**MSSM:** 2HDM with 5 physical Higgs particles $h, H, A, H^\pm$

SUSY → MSSM Higgs sector determined by $M_A$ and $\tan \beta$ (at tree level)

mass constraint: $M_{H^-}^2 = M_W^2 + M_A^2$

Yukawa couplings: $g_{t\bar{b}H^-} = \frac{\sqrt{2}}{v} (m_t P_R \cot \beta + m_b P_L \tan \beta)$
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charged Higgs searches at LEP

\[ e^+e^- \rightarrow H^+H^- \Rightarrow M_{H^\pm} \gtrsim 80 \text{ GeV (95\% CL)} \] [LEP Higgs WG]

MSSM: \( M_{H^\pm} = \sqrt{M_W^2 + M_A^2} \gtrsim 122 \text{ GeV from } M_A \gtrsim 92 \text{ GeV} \) [LEP Higgs WG]
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- charged Higgs searches at the Tevatron

  \[ p\bar{p} \rightarrow t(\rightarrow bH^+)\bar{t}(\rightarrow \bar{b}H^-) \]
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![Graph showing branching ratios for different decay modes of charged Higgs bosons](image)
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charged Higgs searches at the Tevatron
Introduction: charged Higgs boson production at the LHC

- $pp \rightarrow t\bar{t}$ with $t \rightarrow bH^\pm$ for $M_{H^\pm} \lesssim m_{top}$

- $pp \rightarrow tbH^\pm$ for $M_{H^\pm} \gtrsim m_{top}$

alternative production mechanisms like $qq' \rightarrow H^\pm$, $pp \rightarrow H^\pm + \text{jet}$, $pp \rightarrow H^\pm W^\mp$, or Higgs pair production are suppressed...
Introduction: charged Higgs boson production at the LHC

\[ \sigma(pp \to \Phi+X) \ [\text{pb}] \]
\[
\begin{align*}
\sqrt{s} &= 14 \text{ TeV} \\
\tan \beta &= 3
\end{align*}
\]

\[
\tau \Phi
\]

\[ gg \to \Phi \]

\[ b\bar{b}\Phi \]

\[ qq\Phi \]

\[ W\Phi \]

\[ Z\Phi \]

\[ t\bar{t}\Phi \]
Associated $t b H^\pm$ production: two calculational schemes

4-flavour scheme

- exact $g \rightarrow b\bar{b}$ splitting & mass effects
- no summation of $\ln(M_H/M_b)$ terms

5-flavour scheme

- summation of $\ln(M_H/M_b)$ terms
- LL approximation to $g \rightarrow b\bar{b}$ splitting
Associated \(tbH^{\pm}\) production: two calculational schemes

4-flavour scheme

- exact \(g \rightarrow b\bar{b}\) splitting & mass effects
- no summation of \(\ln(M_H/M_b)\) terms

5-flavour scheme

- summation of \(\ln(M_H/M_b)\) terms
- LL approximation to \(g \rightarrow b\bar{b}\) splitting

The 4- and 5-flavour schemes

- are both theoretically consistent & well-defined
- represent different ways of ordering perturbation theory
- should agree at sufficiently high order
- do not match exactly at finite order
Associated $tbH^{\pm}$ production: two calculational schemes

Comparison at LO

4-flavour scheme

\[ \sigma(gg/\tilde{q}\tilde{q} \rightarrow H^-tb) \, [\text{pb}] \]
\[ \sqrt{s} = 14 \, \text{TeV} \]
\[ \tan \beta = 10 \]

5-flavour scheme

\[ \sigma(gb \rightarrow H^-t) \, [\text{pb}] \]
\[ \sqrt{s} = 14 \, \text{TeV} \]
\[ \tan \beta = 10 \]
Associated $tbH^\pm$ production: two calculational schemes

**Comparison at LO**

4-flavour scheme

\[ \sigma(gg/q\bar{q} \rightarrow H^-tb) \] [pb]

\[ \sqrt{s} = 14\text{ TeV} \]

\[ \tan \beta = 10 \]

5-flavour scheme

\[ \sigma(gb \rightarrow H^-t) \] [pb]

\[ \sqrt{s} = 14\text{ TeV} \]

\[ \tan \beta = 10 \]

⇒ need systematic comparison of 4FNS and 5FNS beyond LO
**Associated $tbH^{\pm}$ production: two calculational schemes**

**Comparison of 4- and 5FNS for neutral Higgs plus b-jet production at NLO**

[Campbell, Ellis, Maltoni, Willenbrock; Dittmaier, MK, Spira; Dawson, Jackson, Reina, Wackeroth]

$\sqrt{s} = 14$ TeV

$\mu = (2m_b + M_h)/4$

$p_T^{b/b_\pm} > 20$ GeV

$|\eta_{b/b_\pm}| < 2.5$

- $gb/b \rightarrow b/b+h$
- $gg \rightarrow bb+h$

$\sigma(pp \rightarrow b/b+h + X)$ [fb]
Comparison of 4- and 5FNS for neutral Higgs plus b-jet production at NLO

\[ \sigma(pp \to b\bar{b} + h + X) \text{ [fb]} \]
\[ \sqrt{s} = 14 \text{ TeV} \]
\[ \mu = (2m_b + M_h)/4 \]
\[ p_T^{b\bar{b}} > 20 \text{ GeV} \]
\[ |m_{b\bar{b}}| < 2.5 \]

- 4-flavour calculation includes Higgs radiation off top loops \( \approx -10\% \)
- calculations employ different PDF fits

\[ \rightarrow \text{ consistent comparison should reveal even better agreement} \]
Associated $tbH^\pm$ production: 5FNS calculation at NLO

see Zhu; Gao, Lu, Xiong, Yang; Plehn; Berger, Han, Jiang, Plehn; Kidonakis

\[ \sigma_{\text{tot}} (pp \rightarrow tH^- + X) \text{ [pb]} \]
\[ (m_b \text{ running mass}) \]

\[ \text{m}_b \text{ pole mass} \]

\[ K (pp \rightarrow tH^- + X) \]
\[ \tan \beta = 30, 5, 10, 30 \]
\[ \mu = 4m_{\text{av}}, m_{\text{av}}, m_{\text{av}}/4 \]

\[ \rightarrow \text{scale uncertainty at NLO} \approx 20\% \]
Associated $tbH^\pm$ production: 4FNS calculation

- better description of $b$-quark dynamics in 4FNS
  → needed for searches with additional $b$-tag
  → needed for event reconstruction

- contamination of top reconstruction by additional $b$-jets

$$1/\sigma \frac{d\sigma}{dp_T} (pp \rightarrow t\rightarrow Wb\bar{b}H^- + X) \ [fb/GeV]$$

$\sqrt{s} = 14$ TeV

$0 \leq p_T \leq 200$ GeV

$b$ in $tbH$ production
$b$ from top decay
Associated $tbH^\pm$ production: 4FNS calculation at NLO

see Peng et al.; Dittmaier, MK, Spira, Walser

- generic Feynman graphs

+ graphs with virtual SUSY particles...

→ calculation using standard techniques

FeynArts, LoopTools, dipole subtraction; Denner/Dittmaier tensor reduction, MadGraph...
Associated $tbH^{\pm}$ production: 4FNS calculation at NLO

**scale dependence** (here and in the following we use SPS1b)

\[ \mu_0 = \frac{m_b + m_t + m_{H^-}}{3} \]

\[ m_{H^-} = 214 \text{ GeV} \]

\[ \sigma (pp \rightarrow t\bar{b}H^- + X) \text{ [fb]} \]

\[ \sqrt{s} = 14 \text{ TeV} \]
Associated $t\bar{b}H^\pm$ production: 4FNS calculation at NLO

**scale dependence exclusive cross section** ($p_{T,b} > 20$ GeV)

\[ \sigma (pp \rightarrow t\bar{b}H^- + X) \, [fb] \]

$\sqrt{s} = 14$ TeV

$\mu_0 = (m_b + m_t + m_{H^-})/3$

$m_{H^-} = 214$ GeV

$p_{T,b} > 20$ GeV
Associated $tbH^{\pm}$ production: 4FNS calculation at NLO

total cross section

$\sigma \ (pp \rightarrow t\bar{b}H^{-} + X) \ [fb]$  
$\sqrt{s} = 14 \text{ TeV}$  
$\mu = (m_b + m_t + m_{H^-})/3$

[Dittmaier, MK, Spira, Walser, prelim.]
Associated $tbH^\pm$ production: 4FNS calculation at NLO

<table>
<thead>
<tr>
<th>$M_{H^\pm}$ [GeV]</th>
<th>$\sigma_{NLO} = \sigma_0 \times (1 + \delta_{\text{SUSY-QCD}}^{\text{tan}\beta-\text{resum.}}) \times (1 + \delta_{\text{QCD}} + \delta_{\text{remainder}}^{\text{SUSY-QCD}})$</th>
<th>$\sigma_{\text{fixed-order}}^{\text{NLO}}$ [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>214.28</td>
<td>$\sigma_0$ [fb] = 502, $\delta_{\text{QCD}} = 0.54$, $\delta_{\text{SUSY-QCD}}^{\text{tan}\beta-\text{resum.}} = -0.27$, $\delta_{\text{SUSY-QCD}}^{\text{remainder}} = -0.001$</td>
<td>538</td>
</tr>
<tr>
<td>309.70</td>
<td>$\sigma_0$ [fb] = 219, $\delta_{\text{QCD}} = 0.58$, $\delta_{\text{SUSY-QCD}}^{\text{tan}\beta-\text{resum.}} = -0.28$, $\delta_{\text{SUSY-QCD}}^{\text{remainder}} = -0.001$</td>
<td>243</td>
</tr>
<tr>
<td>407.33</td>
<td>$\sigma_0$ [fb] = 103, $\delta_{\text{QCD}} = 0.56$, $\delta_{\text{SUSY-QCD}}^{\text{tan}\beta-\text{resum.}} = -0.28$, $\delta_{\text{SUSY-QCD}}^{\text{remainder}} = -0.0003$</td>
<td>116</td>
</tr>
</tbody>
</table>

→ partial cancellation between QCD and SUSY-QCD corrections

→ dominant SUSY-QCD (non-decoupling) contributions from corrections to bottom-Higgs Yukawa coupling:

$$\frac{M_b \tan \beta}{v} \rightarrow \frac{M_b \tan \beta}{v} \frac{1}{1 + \Delta M_b}$$

[Hall, Rattazzi, Sarid, …; Carena, Garcia, Nierste, Wagner; …]

where

$$\Delta M_b = \frac{C_F}{2} \frac{\alpha_s}{\pi} m_{\tilde{g}} \mu \tan \beta \times I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}})$$

→ remaining SUSY corrections negligible
Associated $tbH^\pm$ production: 4FNS calculation at NLO

transverse momentum distribution

\[ \frac{d\sigma}{dp_T} (pp \rightarrow t\bar{b}H^- + X) \ [fb/GeV] \]

\[ \sqrt{s} = 14 \text{ TeV} \]

NLO, \( \mu = (m_b + m_t + m_{H^-})/3 \)
**Associated $t\bar{b}H^\pm$ production: 4FNS calculation at NLO**

- **bottom transverse momentum distribution at LO/NLO**

\[ d\sigma/dp_{T,b} (pp \rightarrow t\bar{b}H^- + X) \ [fb/GeV] \]
\[ \sqrt{s} = 14 \text{ TeV} \]
\[ \mu = (m_b + m_t + m_{H^-})/3 \]

[Dittmaier, MK, Spira, Walser, prelim.]
Associated $t\bar{b}H^\pm$ production: 4FNS calculation at NLO

rapidity distribution

$$d\sigma/dy (pp \rightarrow t\bar{b}H^{-} + X) \ [fb]$$
$$\sqrt{s} = 14 \text{ TeV}$$
$$NLO, \mu = (m_b + m_t + m_{H^-})/2$$
Associated $t\bar{b}H^\pm$ production: 4FNS calculation at NLO

Bottom rapidity distribution at LO/NLO

\[
\frac{d\sigma}{dy_b} (pp \rightarrow t\bar{b}H^- + X) \text{ [fb]}
\]

$\sqrt{s} = 14$ TeV

$\mu = (m_b + m_t + m_{H^-})/2$

$K = \text{NLO/LO}$
Search for charged MSSM Higgs bosons at the LHC

see Hashemi, Heinemeyer, Kinnunen, Nikitenko, Weiglein

→ sensitivity to MSSM parameters through $\Delta M_b$

Consider

$$pp \to tH^\pm(\to \tau \nu_\tau) + X$$

and calculate number of events as

$$N_{\text{events}} = \mathcal{L} \times \sigma(pp \to H^\pm + X) \times \text{BR}(H^\pm \to \tau + \nu_\tau) \times \text{BR}(\tau \to \text{hadrons}) \times \text{exp. eff.}$$

(experimental efficiency from CMS 2006/100 (Kinnunen))

→ 5$\sigma$ discovery contours in $(\tan \beta, M_{H^\pm})$ plane (very preliminary)

\[\mathcal{L} = 30 \text{ fb}^{-1}\]

SPS1b with $\tan \beta$ and $M_A$ varied

LO cross section with scale uncertainty
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NLO cross section with scale uncertainty
**Associated $tbH^\pm$ production: Outlook & Summary**

**Outlook**

- include leading electroweak correction through $\Delta M_b$

- systematic NLO comparison of 4FNS and 5FNS calculations (cf. Plehn; Berger et al.)

- matching of 4FNS and 5FNS? (cf. Borzumati, Kneur, Polonsky; Alwall, Rathsman)
Associated $tbH^\pm$ production: Outlook & Summary

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**Summary**

- two schemes for calculating Higgs+b-jet cross sections at the LHC
  \[\rightarrow\] should agree at sufficiently high order
- NLO-QCD corrections significant;
  higher-order SUSY and electroweak effects can be absorbed in $\Delta M_b$
- reliable cross section predictions are crucial for Higgs exclusion or discovery
Backup slides
**Associated $tbH^\pm$ production:** 4FNS calculation at NLO

- **Higgs transverse momentum distribution at LO/NLO**

\[
d\sigma/dp_{T,H} (pp \rightarrow t\bar{b}H^- + X) \ [fb/GeV]
\]

\[
\sqrt{s} = 14 \text{ TeV}
\]

\[
\mu = (m_b + m_t + m_{H^-})/3
\]

![Graph showing Higgs transverse momentum distribution at LO/NLO](attachment:image.png)

\[
K = \text{NLO/LO}
\]
Associated $tbH^\pm$ production: 4FNS calculation at NLO

Top transverse momentum distribution at LO/NLO

\[ d\sigma/dp_{T,t} (pp \rightarrow t\bar{b}H^\pm + X) \text{ [fb/GeV]} \]

\[ \sqrt{s} = 14 \text{ TeV} \]

\[ \mu = (m_b + m_t + m_{H^-})/3 \]

\[ K = \frac{\text{NLO}}{\text{LO}} \]
Associated $tbH^\pm$ production: 4FNS calculation at NLO

Higgs rapidity distribution at LO/NLO

\[ d\sigma/dy_H (pp \rightarrow t\bar{b}H^- + X) \ [fb] \]
\[ \sqrt{s} = 14 \text{ TeV} \]
\[ \mu = (m_b + m_t + m_{H^-})/3 \]

[Graph showing Higgs rapidity distribution at LO and NLO, with K = NLO/LO ratio]
Associated $tbH^\pm$ production: 4FNS calculation at NLO

- top rapidity distribution at LO/NLO

\[ d\sigma/dy_t (pp \rightarrow t\bar{b}H^- + X) \ [fb] \]
\[ \sqrt{s} = 14 \text{ TeV} \]
\[ \mu = (m_b + m_t + m_{H^-})/2 \]

Diagram showing the rapidity distribution with NLO and LO calculations, and the ratio $K = \text{NLO}/\text{LO}$. The y-axis represents the rapidity $y_t$, and the x-axis represents the rapidity distribution.