Charged Higgs boson production at the LHC: NLO SUSY-QCD corrections

Michael Krämer (CERN-TH & RWTH Aachen)

with Stefan Dittmaier, Michael Spira and Manuel Walser (arXiv:0906.2648)
Introduction: charged Higgs 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 $q\bar{q}' \rightarrow H^\pm$, $pp \rightarrow H^\pm + \text{jet}$, $pp \rightarrow H^\pm W^\mp$, or Higgs pair production are suppressed...
Status of (MSSM) calculations

- **5FS NLO SUSY-QCD** [Plehn; Berger et al.]
- **5FS in MC@NLO** [Weydert et al.] → talk by T. Plehn
- **5FS NNLL/NNLO** [Kidonakis]
- **5FS SUSY-EWK** [Jin et al., Belyaev et al., Beccaria et al.] → talk by C. Verzegnassi
- **4FS NLO SUSY-QCD** [Peng et al.; Dittmaier et al.]
- **LO 4FS and 5FS matched** [Borzumati et al.; Alwall, Rathsman]
Status of (MSSM) calculations

- **5FS NLO SUSY-QCD** [Plehn; Berger et al.]
- **5FS in MC@NLO** [Weydert et al.] → talk by T. Plehn
- **5FS NNLL/NNLO_{approx.}** [Kidonakis]
- **5FS SUSY-EWK** [Jin et al., Belyaev et al., Beccaria et al.]
  → talk by C. Verzegnassi
- **4FS NLO SUSY-QCD** [Peng et al.; Dittmaier et al.]
- **LO 4FS and 5FS matched** [Borzumati et al.; Alwall, Rathsman]
Associate $tbH^\pm$ production: two calculational schemes

4-flavour scheme

- exact $g \to b\bar{b}$ 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 $g \to b\bar{b}$ splitting
Associate $tbH^\pm$ 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
Associate $tbH^\pm$ production: 4FS calculation

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

contamination of top reconstruction by additional $b$-jets

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

$\sqrt{s} = 14 \text{ TeV}$
Associate $tbH^\pm$ production: 4FS calculation at NLO

see Dittmaier, MK, Spira, Walser (arXiv:0906.2648)

- **some generic Feynman graphs**

- **calculation using standard techniques**

  **FeynArts, LoopTools, dipole subtraction, Denner/Dittmaier tensor reduction, MadGraph...**
Associate $tbH^\pm$ production: 4FS calculation at NLO

- Scale dependence at 7 TeV (here and in the following we use SPS1b)

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

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

\[ \sqrt{s} = 7 \text{ TeV} \]

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

\[ \mu \leq \mu_0 \leq 3\mu_0 \]

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

\[ \mu/\mu_0 \]

\[ 0.1 \quad 1 \quad 10 \]

\[ 0 \quad 100 \quad 600 \]

→ choose $\mu_0 = (m_b + m_t + m_{H^-})/3$ with scale variation $\mu/3 \leq \mu \leq 3\mu_0$
Associate $tbH^\pm$ production: 4FS calculation at NLO

- **scale dependence at 7 TeV** (here and in the following we use SPS1b)

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

$$m_{H^-} = 214 \text{ GeV}$$

$$\sqrt{s} = 7 \text{ TeV}$$

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

$\Delta\sigma = \pm 100\%$ (LO) and $\pm 25\%$ (NLO)
Associate $tbH^\pm$ production: 4FS calculation at NLO

- total cross section at 7 TeV

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

$$\sqrt{s} = 7 \text{ TeV}$$

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

[Dittmaier, MK, Spira, Walser]
Associate $tbH^\pm$ production: 4FS calculation at NLO

**total cross section at 14 TeV**

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

[Dittmaier, MK, Spira, Walser]
Associate $tbH^\pm$ production: 4FS pdf uncertainty

- total cross section with MSTW08 4FS pdf

\[ \frac{\sigma_{\text{central}}}{\sigma_{\text{pdf} \uparrow \downarrow}} \]

\[ \text{pp} \rightarrow t\bar{b}H^- + X \]
\[ \sqrt{s} = 14 \text{ TeV} \]

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

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

$\Delta \text{pdf} \lesssim 5\%$
Associate $tbH^\pm$ production: 4FS calculation at NLO

- **total cross section (14 TeV):** individual NLO contributions

$$\sigma_{\text{NLO}} = \sigma_0 \times (1 + \delta_{\text{SUSY-QCD}}^{\tan \beta - \text{resum.}}) \times (1 + \delta_{\text{QCD}} + \delta_{\text{SUSY-QCD}}^{\text{remainder}})$$

<table>
<thead>
<tr>
<th>$M_{H^\pm}$ [GeV]</th>
<th>$\sigma_0$ [fb]</th>
<th>$\delta_{\text{QCD}}$</th>
<th>$\delta_{\text{SUSY-QCD}}^{\tan \beta - \text{resum.}}$</th>
<th>$\delta_{\text{SUSY-QCD}}^{\text{remainder}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>214</td>
<td>545</td>
<td>0.57</td>
<td>-0.30</td>
<td>-0.002</td>
</tr>
<tr>
<td>310</td>
<td>234</td>
<td>0.61</td>
<td>-0.30</td>
<td>-0.002</td>
</tr>
<tr>
<td>407</td>
<td>109</td>
<td>0.63</td>
<td>-0.30</td>
<td>-0.002</td>
</tr>
</tbody>
</table>
Associate $tbH^\pm$ production: 4FS calculation at NLO

- total cross section (14 TeV): individual NLO contributions

\[ \sigma_{\text{NLO}} = \sigma_0 \times (1 + \delta_{\text{SUSY-QCD, tan } \beta - \text{resum.}}) \times (1 + \delta_{\text{QCD}} + \delta_{\text{remainder SUSY-QCD}}) \]

<table>
<thead>
<tr>
<th>$M_{H^\pm}$ [GeV]</th>
<th>$\sigma_0$ [fb]</th>
<th>$\delta_{\text{QCD}}$</th>
<th>$\delta_{\text{SUSY-QCD, tan } \beta - \text{resum.}}$</th>
<th>$\delta_{\text{remainder SUSY-QCD}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>214</td>
<td>545</td>
<td>0.57</td>
<td>-0.30</td>
<td>-0.002</td>
</tr>
<tr>
<td>310</td>
<td>234</td>
<td>0.61</td>
<td>-0.30</td>
<td>-0.002</td>
</tr>
<tr>
<td>407</td>
<td>109</td>
<td>0.63</td>
<td>-0.30</td>
<td>-0.002</td>
</tr>
</tbody>
</table>

- partial cancellation between QCD and SUSY-QCD corrections
Associate $tbH^\pm$ production: 4FS calculation at NLO

- **total cross section (14 TeV):** individual NLO contributions

$$\sigma_{\text{NLO}} = \sigma_0 \times (1 + \delta_{\text{SUSY-QCD}}^{\tan \beta - \text{resum.}}) \times (1 + \delta_{\text{QCD}} + \delta_{\text{SUSY-QCD}}^{\text{remainder}})$$

<table>
<thead>
<tr>
<th>$M_{H^\pm} , [\text{GeV}]$</th>
<th>$\sigma_0 , [\text{fb}]$</th>
<th>$\delta_{\text{QCD}}$</th>
<th>$\delta_{\text{SUSY-QCD}}^{\tan \beta - \text{resum.}}$</th>
<th>$\delta_{\text{SUSY-QCD}}^{\text{remainder}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>214</td>
<td>545</td>
<td>0.57</td>
<td>-0.30</td>
<td>-0.002</td>
</tr>
<tr>
<td>310</td>
<td>234</td>
<td>0.61</td>
<td>-0.30</td>
<td>-0.002</td>
</tr>
<tr>
<td>407</td>
<td>109</td>
<td>0.63</td>
<td>-0.30</td>
<td>-0.002</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:**

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

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

[Hall, Rattazzi, Sarid, . . . ; Carena, Garcia, Nierste, Wagner; . . . Noth, Spira]
Associate $tbH^{\pm}$ production: 4FS calculation at NLO

- transverse momentum distribution

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

$\sqrt{s} = 14$ TeV, $m_{H^{-}} = 214$ GeV

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

[Dittmaier, MK, Spira, Walser]
Associate $tbH^\pm$ production: 4FS calculation at NLO

- bottom transverse momentum distribution at LO/NLO

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

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

$\sqrt{s} = 14 \text{ TeV}, \ m_{H^-} = 214 \text{ GeV}$

$K = \text{NLO/LO}$
Comparison of 4 and 5FS calculations at NLO
Comparison of 4 and 5FS calculations at NLO

- Look first at $b\bar{b}H$ associated production at NLO/NNLO

[Harlander, Kilgore; Dittmaier, MK, Spira]
Comparison of 4 and 5FS calculations at NLO

**NLO scale dependence**

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

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

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

\[
m_{H^-} = 214 \text{ GeV}
\]
Comparison of 4 and 5FS calculations at NLO

- total cross section

\[ \sigma (pp \rightarrow tH^- + X) \text{ [fb]} \]
\[ \sqrt{s} = 14 \text{ TeV} \]
\[ \mu = (m_b + m_t + m_{H^-})/3 \]
NLO QCD
We should

- complete the pdf and $\alpha_s$ uncertainty analysis;
- study the factorization of SUSY corrections for a wider range of scenarios;
- pursue the comparison of 4FS and 5FS calculations for distributions;
- combine the NLO SUSY-QCD and EWK corrections;
- match the 4FS calculation with parton showers;
- include the decay of the Higgs and the top.
- consider the transition region where $m_H \approx m_{\text{top}}$. 
backup
Associate $tbH^{\pm}$ production: 4FS calculation at NLO

- scale dependence at 14 TeV

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

$\sqrt{s} = 14 \text{ TeV}$

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

$m_{H^-} = 214 \text{ GeV}$

- NLO
- LO

$\mu_0 = \mu / \mu_0$
Associate $tbH^\pm$ production: 4FS calculation at NLO

- scale dependence with $p_{T,b}$-cut

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

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

\[
p_{T,b} > 20 \text{ GeV}
\]

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

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

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

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

$\sqrt{s} = 14 \text{ TeV}$

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

$m_{H^-} = 214 \text{ GeV}$

$p_{T,b} > 20 \text{ GeV}$

- NLO
- LO
Associate $tbH^\pm$ production: 4FS calculation at NLO

- cross section with $p_{T,b}$-cut

$\sigma (pp \to t\bar{b}H^- + X) \ [fb]$
$\sqrt{s} = 14 \text{ TeV}$
$\mu = (m_b + m_t + m_{H^-})/3$
$p_{T,b} > 20 \text{ GeV}$

$K = \frac{\text{NLO}}{\text{LO}}$
Associate $tbH^{±}$ production: 4FS calculation at NLO

- Higgs transverse momentum distribution at LO/NLO

\[ d\sigma/dp_{T,H} \text{ (pp} \rightarrow \text{t}\bar{b}H^{-} + X) \text{ [fb/GeV]} \]
\[ \sqrt{s} = 14 \text{ TeV, } m_{H^{-}} = 214 \text{ GeV} \]
\[ \mu = (m_{b} + m_{t} + m_{H^{-}})/3 \]

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

- top transverse momentum distribution at LO/NLO

$\sqrt{s} = 14$ TeV, $m_{H^-} = 214$ GeV

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

$\frac{d\sigma}{dp_{T,t}} (pp \rightarrow t\bar{b}H^- + X)$ [fb/GeV]
Associate $t b H^\pm$ production: 4FS calculation at NLO

- rapidity distribution

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

\[ \sqrt{s} = 14 \text{ TeV}, \quad m_{H^-} = 214 \text{ GeV} \]

NLO, \( \mu = \left( m_b + m_t + m_{H^-} \right)/3 \)
Associate $tbH^\pm$ production: 4FS calculation at NLO

- bottom rapidity distribution at LO/NLO

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

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

$\sqrt{s} = 14 \text{ TeV}, \ m_{H^-} = 214 \text{ GeV}$

[Dittmaier, MK, Spira, Walser]
Associate $tbH^\pm$ production: 4FS calculation at NLO

- Higgs rapidity distribution at LO/NLO

\[ d\sigma/dy_H (pp \to t\bar{b}H^\pm + X) \ [fb] \]
\[ \sqrt{s} = 14 \text{ TeV}, \ m_{H^\pm} = 214 \text{ GeV} \]
\[ \mu = (m_b + m_t + m_{H^\pm})/3 \]

[Dittmaier, MK, Spira, Walser]
Associate $tbH^\pm$ production: 4FS calculation at NLO

- top rapidity distribution at LO/NLO

$\sqrt{s} = 14$ TeV, $m_{H^-} = 214$ GeV

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

$d\sigma/dy_t (pp \rightarrow t\bar{b}H^- + X)$ [fb]
Associate $tbH^\pm$ production: two calculational schemes

NLO comparison of 4FS and 5FS for $pp \rightarrow b/\bar{b} + h$

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

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

Note: consistent treatment of pdf and Higgs radiation off top should lead to even better agreement
Search for charged MSSM Higgs bosons at the LHC

cf. Hashemi, Heinemeyer, Kinnunen, Nikitenko, Weiglein

Consider $pp \rightarrow tH^\pm(\rightarrow \tau\nu_\tau) + X$ and calculate number of events as

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

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

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

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

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

LO cross section

with scale uncertainty
Search for charged MSSM Higgs bosons at the LHC

cf. Hashemi, Heinemeyer, Kinnunen, Nikitenko, Weiglein

Consider $pp \rightarrow tH^\pm (\rightarrow \tau \nu_{\tau}) + X$ and calculate number of events as

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

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

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

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

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

LO/NLO cross section with scale uncertainty