Charged Higgs production with a $W$ boson or a top quark

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- Charged Higgs production
- Higher-order corrections
- $tH^-$ production
- $H^-W^+$ production
Charged Higgs production

A charged Higgs would be sure sign of new physics

2-Higgs doublet models

LHC has good potential for discovery

I will discuss two production processes

\( bg \rightarrow tH^- \) and \( b\bar{b} \rightarrow H^-W^+ \)

Higher-order corrections are significant

very massive final states

Soft-gluon corrections are important
Top is the heaviest known elementary particle
Decays before hadronization

Born cross section for $bg \to tH^- \propto \alpha_s \left( m_b^2 \tan^2 \beta + m_t^2 \cot^2 \beta \right)$

$\tan \beta = v_2/v_1$ ratio of vevs of two Higgs doublets
Higher-order corrections

\[ b(p_b) + g(p_g) \rightarrow t(p_t) + H^-(p_H) \]

Define \( s = (p_b + p_g)^2 \), \( t = (p_b - p_t)^2 \), \( u = (p_g - p_t)^2 \)
and \( s_4 = s + t + u - m_t^2 - m_H^2 \)

At partonic threshold \( s_4 \rightarrow 0 \)

Soft corrections \( \left[ \frac{\ln^k (s_4/m_H^2)}{s_4} \right]_+ \)

For the order \( \alpha_s^n \) corrections \( k \leq 2n - 1 \)

Resum these soft corrections for the double-differential cross section

At NNLL accuracy we need two-loop soft anomalous dimensions

Derive approximate cross sections at NNLO
Soft-gluon Resummation

moments of the partonic cross section with moment variable $N$:
\[ \hat{\sigma}(N) = \int (ds_4/s) \, e^{-N s_4/s} \hat{\sigma}(s_4) \]

factorized expression for the cross section:
\[ \hat{\sigma}^{bg \rightarrow tH^-}(N, \epsilon) = \left( \prod_{i=b,g} J_i(N, \mu, \epsilon) \right) H^{bg \rightarrow tH^-}(\alpha_s(\mu)) \, S^{bg \rightarrow tH^-}(\frac{m_H}{N \mu}, \alpha_s(\mu)) \]

Soft function $S$ satisfies the renormalization group equation
\[ \left( \mu \frac{\partial}{\partial \mu} + \beta(g_s, \epsilon) \frac{\partial}{\partial g_s} \right) S^{bg \rightarrow tH^-} = -2 S^{bg \rightarrow tH^-} \Gamma_S^{bg \rightarrow tH^-} \]

Soft anomalous dimension $\Gamma_S^{bg \rightarrow tH^-}$ calculated at two loops
- controls evolution of $S^{bg \rightarrow tH^-}$ resulting in exponentiation of logarithms of $N$

The aNNLO soft-gluon corrections are:
\[ \frac{d^2 \hat{\sigma}^{(2) bg \rightarrow tH^-}_{aNNLO}}{dt \, du} = F_{LO}^{bg \rightarrow tH^-} \frac{\alpha_s^2}{\pi^2} \sum_{k=0}^{3} C_k^{(2)} \left[ \frac{\ln^k(s_4/m_H^2)}{s_4} \right] + \]
$tH^-$ production Total cross sections

\begin{align*}
\text{bg} \to tH^\nu \text{ at LHC} & \quad \text{aNNLO} \quad \text{tan}\beta=10 \quad \mu=m_{H^\nu} \\
\text{14 TeV} & \quad \text{13 TeV} \quad \text{8 TeV} \quad \text{7 TeV}
\end{align*}

\begin{align*}
\text{bg} \to tH^\nu \text{ at LHC} & \quad \text{aNNLO} \quad \text{tan}\beta=30 \quad \mu=m_{H^\nu} \\
\text{14 TeV} & \quad \text{13 TeV} \quad \text{8 TeV} \quad \text{7 TeV}
\end{align*}

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tH$^-$ production Top $p_T$ distributions

bg→ tH$^-$ at LHC top $p_T$ aNNLO tanβ=30 $m_H=300$ GeV

bg→ tH$^-$ at LHC top $p_T$ aNNLO tanβ=30 $m_H=800$ GeV

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$tH^-$ production

$K$-factors for top $p_T$ distributions

Significant corrections at all LHC energies

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$tH^-$ production Top rapidity distributions

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$tH^-$ production

*K-factors for top rapidity distributions*

Significant corrections especially at large rapidities
$H^- W^+ \text{ production}$

\[
\begin{align*}
    b(p_1) + \bar{b}(p_2) &\rightarrow H^-(p_3) + W^+(p_4) \\

\text{Define } s &= (p_1 + p_2)^2, \quad t = (p_1 - p_3)^2, \quad u = (p_2 - p_3)^2 \\
\text{and } s_4 &= s + t + u - m_H^2 - m_W^2 \\

\text{At partonic threshold } s_4 &\rightarrow 0
\end{align*}
\]

The NNLO collinear and soft-gluon corrections are

\[
\begin{align*}
    \frac{d^2\hat{\sigma}^{(2)}_{ab\rightarrow H^- W^+}}{dt \, du} &= F_{LO}^{b\bar{b} \rightarrow H^- W^+} \frac{\alpha_s^2}{\pi^2} \left\{ -C_3^{(2)} \frac{1}{m_H^2} \ln^3 \left( \frac{s_4}{m_H^2} \right) + \sum_{k=0}^3 C_k^{(2)} \left[ \frac{\ln^k(s_4/m_H^2)}{s_4} \right] \right\}
\end{align*}
\]
$H^- W^+$ production

Total cross sections

\[ b \bar{b} \rightarrow H^- W^+ \text{ at LHC aNLO} \quad \tan \beta = 1 \quad \mu = m_H \]

\[ b \bar{b} \rightarrow H^- W^+ \text{ at LHC aNNLO} \quad \tan \beta = 1 \quad \mu = m_H \]
$H^- W^+$ production

Charged Higgs $p_T$ distributions

$b \bar{b} \to H^- W^+$ at LHC  
aNNLO  \tan\beta=1  \ m_H=200$ GeV

$b \bar{b} \to H^- W^+$ at LHC  
aNNLO  \tan\beta=1  \ m_H=500$ GeV

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$H^- W^+$ production

Normalized charged Higgs $p_T$ distributions

\[ \frac{1}{\sigma} \frac{d\sigma}{dp_T} (\text{GeV}^{-1}) \]

\[ b \bar{b} \rightarrow H^- W^+ \text{ aNNLO} \]

$m_H = 200 \text{ GeV}$

$m_H = 500 \text{ GeV}$

14 TeV
13 TeV
8 TeV
7 TeV

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**$H^- W^+$ production**

**Charged Higgs rapidity distributions**

\[ b \bar{b} \rightarrow H^- W^+ \text{ at LHC } aNNLO \ \tan \beta = 1 \ \ m_H = 200 \text{ GeV} \]

\[ b \bar{b} \rightarrow H^- W^+ \text{ at LHC } aNNLO \ \tan \beta = 1 \ \ m_H = 500 \text{ GeV} \]
$H^- W^+$ production

Normalized charged Higgs rapidity distributions

\[ \frac{1}{\sigma} \frac{d\sigma}{d|Y|} \]

\[ b \bar{b} \rightarrow H^- W^+ \text{ aNNLO} \]

\[ m_H = 200 \text{ GeV} \]

\[ m_H = 500 \text{ GeV} \]
Summary

- many new results in charged Higgs production
- total cross sections for $tH^-$ production
- top-quark $p_T$ and rapidity distributions in $tH^-$ production
- total cross sections for $H^-W^+$ production
- charged-Higgs $p_T$ and rapidity distributions in $H^-W^+$ production
- higher-order corrections are very significant