Higher order corrections to $H^{\pm}$ production

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- $H^{\pm}$ **production channels**
- **Higher-order corrections**
- **Charged Higgs production at the LHC**

Charged Higgs: sure sign of new physics (MSSM or other 2HDM)

LHC has good potential for discovery

Production processes

$bg \to tH^-$ Zhu ('01) [NLO QCD]; Belyaev, Garcia, Guasch, Sola ('01,'02) [1-loop SUSY];

$(gg \to \bar{b}tH^-)$ Plehn ('02) [NLO QCD+SUSY]; Berger, Han, Jiang, Plehn ('03) [NLO QCD+SUSY];

Jin, Li, Oakes, Zhu ('99) [Yukawa], ('00) [SUSY electroweak];

Alwall, Rathsman ('04) [matching];

Kidonakis ('04) [soft-gluons, approx NNLO], ('05) [approx NNNLO]

$gg \to H^+W^-$ Barrientos *et al* ('98,'00); Brein, Hollik, Kanemura ('00) [quark, squark loops];

$b\bar{b} \to H^+W^-$ Hollik, Zhu ('01); Gao, Li, Li ('07) [NLO QCD]

Eriksson, Hesselbach, Rathsman ('06) [decays of H^+, W^-]

$gg \to H^+H^-$ Jiang *et al* ('97); Krause, Plehn, Spira, Zerwas ('97); Brein, Hollik ('99) [LO loops]

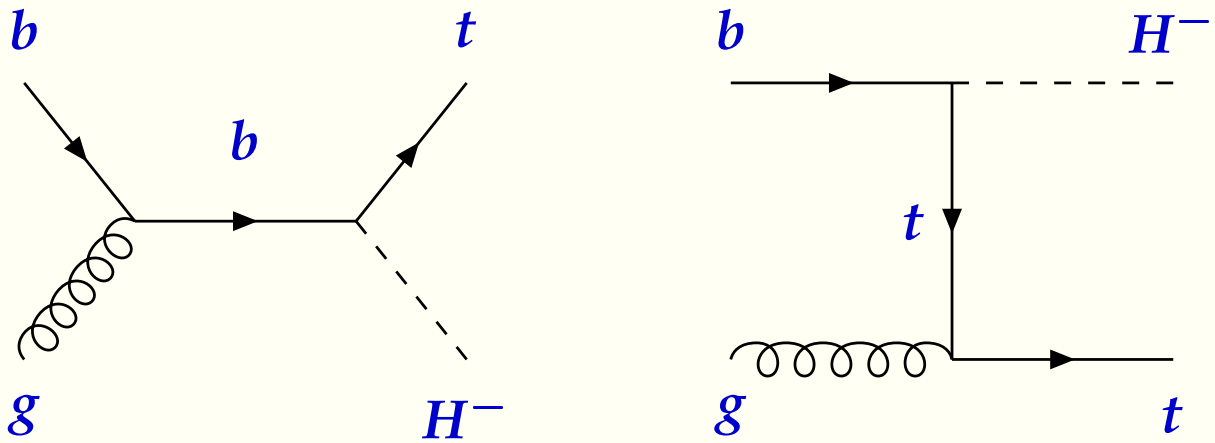
$b\bar{b} \to H^+H^-$ Hou *et al* ('05) [NLO]; Alves, Plehn ('05) [NLO]

$gg \to b\bar{b}H^+H^-$ Moretti, Rathsman ('03) [LO]

$qq \to qqV^*V^* \to qqH^+H^-$ Moretti ('01) [LO]

Associated H^- and top quark production

LO: $bg \to tH^-$



Born cross section $\propto \alpha\alpha_s(m_b^2 \tan^2\beta + m_t^2 \cot^2\beta)$

use $\overline{\rm MS}$ m_b **in the coupling;** $m_b = 0$ **elsewhere**

Associated H^- and top quark production

NLO: $bg \to tH^-$ **(virtual corrections)**

$bg \to tH^- g$

$gg \to tH^- \bar{b}$ $\qquad$ $q\bar{q} \to tH^- \bar{b}$

$bq \to tH^- q$ $\qquad$ $b\bar{q} \to tH^- \bar{q}$

$bb \to tH^- b$ $\qquad$ $b\bar{b} \to tH^- \bar{b}$

QCD corrections large

Reduced scale dependence

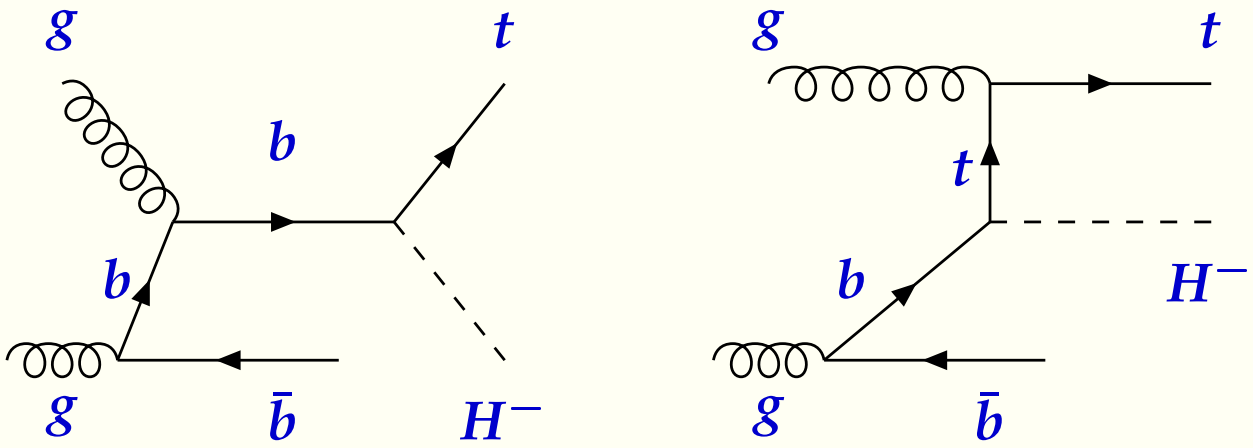
SUSY corrections significant

Issues: bottom parton distribution

gluon splitting to $b\bar{b}$ in collinear approximation

valid for small b-quark p_T

$gg \to \bar{b}tH^-$



Matching [Alwall, Rathsman]

Find reliable description for all b-quark p_T

large p_T: use matrix elements

small p_T: use parton showers

simple adding gives double counting for small p_T

$bg \to tH^-$

resums large logarithms $[\alpha_s \ln(\mu_F/m_b)]^n$ for small p_T

$2 \to 3$ process described by gluon splitting times matrix element of $2 \to 2$ process

$gg \to \bar{b}tH^-$

outgoing b-quark described by $2 \to 3$ matrix element for large p_T

Match $\to$ analytic double-counting subtraction term:

$$\sigma = \sigma_{2\to 2} + \sigma_{2\to 3} - \sigma_{\rm DC}$$

[Alwall, Rathsman]

can be implemented in event generators (PYTHIA, HERWIG)

$\to$ smooth differential distributions

Production near threshold

$b(p_b) + g(p_g) \longrightarrow t(p_t) + H^-(p_H)$

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 threshold $s_4 \to 0$

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

Near threshold soft corrections are dominant and provide excellent approximations to the full cross section

For the order α_s^n **corrections** $l \leq 2n-1$

LL: l=2n-1

NLL: l=2n-2

Calculate NLO and NNLO corrections at NLL accuracy

The hadronic cross section

$$\sigma = \sum_f \int dx_1 dx_2 \, \phi_{f_1/p}(x_1, \mu_F) \, \phi_{f_2/\bar{p}}(x_2, \mu_F) \, \hat{\sigma}(s, t, u, \mu_F, \mu_R, \alpha_s)$$

Resummed cross section

Resummation follows from factorization properties of the cross section - performed in moment space

$$\hat{\sigma}^{res}(N) = \exp\left[\sum_i E^{f_i}(N_i)\right] \exp\left[\sum_i 2\int_{\mu_F}^{\sqrt{s}} \frac{d\mu}{\mu}\, \gamma_{i/i}\left(N_i, \alpha_s(\mu)\right)\right]$$
$$\times \exp\left[\sum_i 2\int_{\mu_R}^{\sqrt{s}} \frac{d\mu}{\mu}\, \beta\left(\alpha_s(\mu)\right)\right] H^{f_i f_j}\left(\alpha_s(\mu_R)\right)$$
$$\times \tilde{S}^{f_i f_j}\left(\alpha_s\left(\frac{\sqrt{s}}{\tilde{N}}\right)\right) \exp\left[\int_{\sqrt{s}}^{\sqrt{s}/\tilde{N}} \frac{d\mu}{\mu}\, 2\mathrm{Re}\Gamma_S^{f_i f_j}\left(\alpha_s(\mu)\right)\right]$$

where

$$\sum_i E^{f_i}(N_i) = -\sum_i C_i \int_0^1 dz \frac{z^{N_i-1}-1}{1-z} \left\{\int_{(1-z)^2}^1 \frac{d\lambda}{\lambda} \frac{\alpha_s(\lambda s)}{\pi} + \frac{\alpha_s((1-z)^2 s)}{\pi}\right\} + \mathcal{O}(\alpha_s^2)$$

$C_i = C_F = (N_c^2-1)/(2N_c)$, $B_q^{(1)} = 3C_F/4$ **for quarks;** $C_i = C_A = N_c$, $B_g^{(1)} = \beta_0/4$ **for gluons**

Γ_S **is the soft anomalous dimension - a matrix in color space**

$$\Gamma_S^{(1)} = C_F \ln\left(\frac{-t+m_t^2}{m_t\sqrt{s}}\right) + \frac{C_A}{2}\ln\left(\frac{-u+m_t^2}{-t+m_t^2}\right) + \frac{C_A}{2}(1-i\pi)$$

NNNLO expansions of resummed cross section

Invert back to momentum space and expand to arbitrary order

NLO soft gluon corrections

$$\hat{\sigma}^{(1)} = F^B \frac{\alpha_s(\mu_R^2)}{\pi} \left\{ c_3 \left[\frac{\ln(s_4/m_H^2)}{s_4} \right]_+ + c_2 \left[\frac{1}{s_4} \right]_+ + c_1^{\mu} \delta(s_4) \right\}$$

with $c_3 = 2(C_F + C_A)$

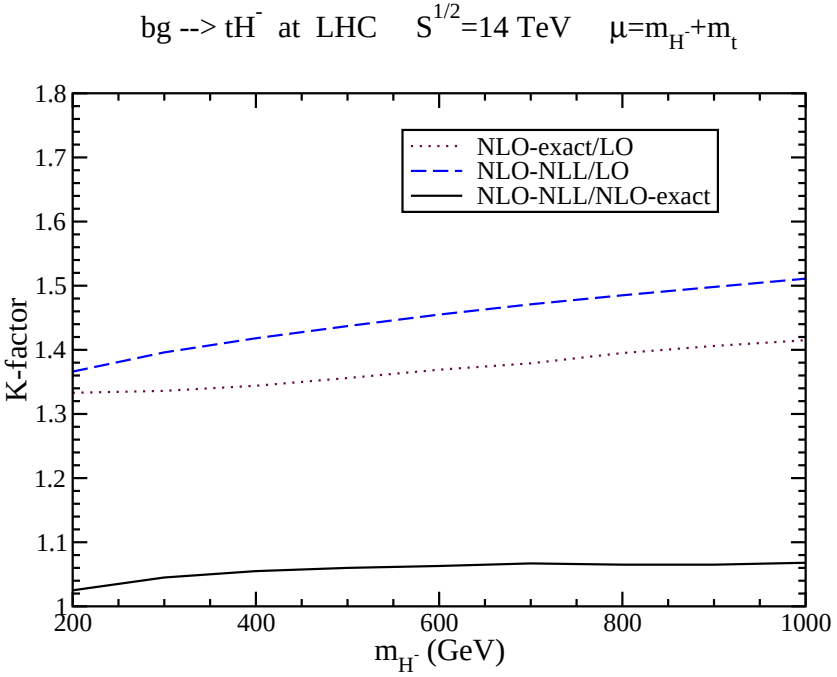
NNLO soft gluon corrections

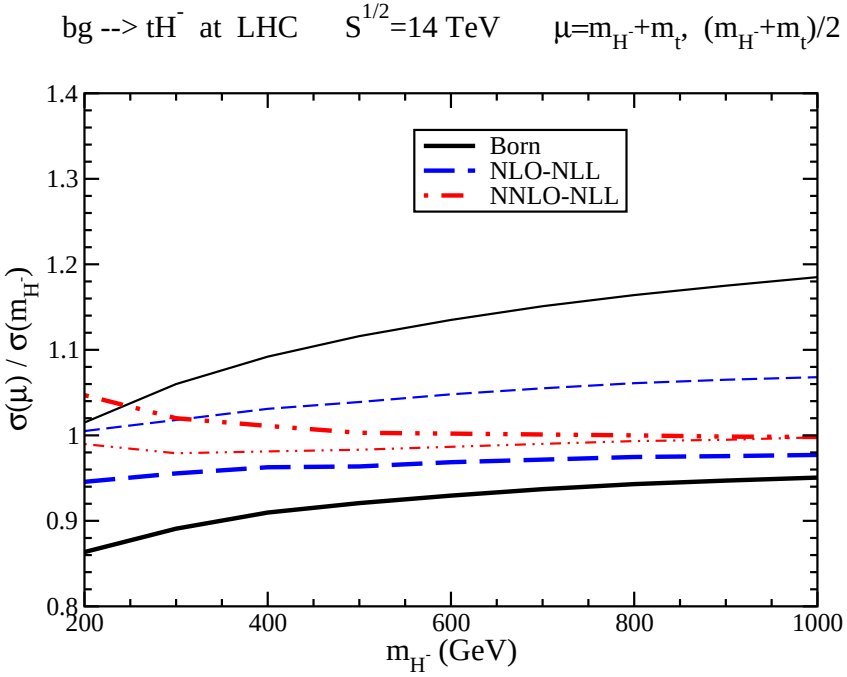
$$\hat{\sigma}^{(2)} = F^B \frac{\alpha_s^2(\mu_R^2)}{\pi^2} \left\{ \frac{1}{2} c_3^2 \left[\frac{\ln^3(s_4/m_H^2)}{s_4} \right]_+ + \left[\frac{3}{2} c_3 c_2 - \frac{\beta_0}{4} c_3 \right] \left[\frac{\ln^2(s_4/m_H^2)}{s_4} \right]_+ + \cdots \right\}$$

NNNLO soft gluon corrections

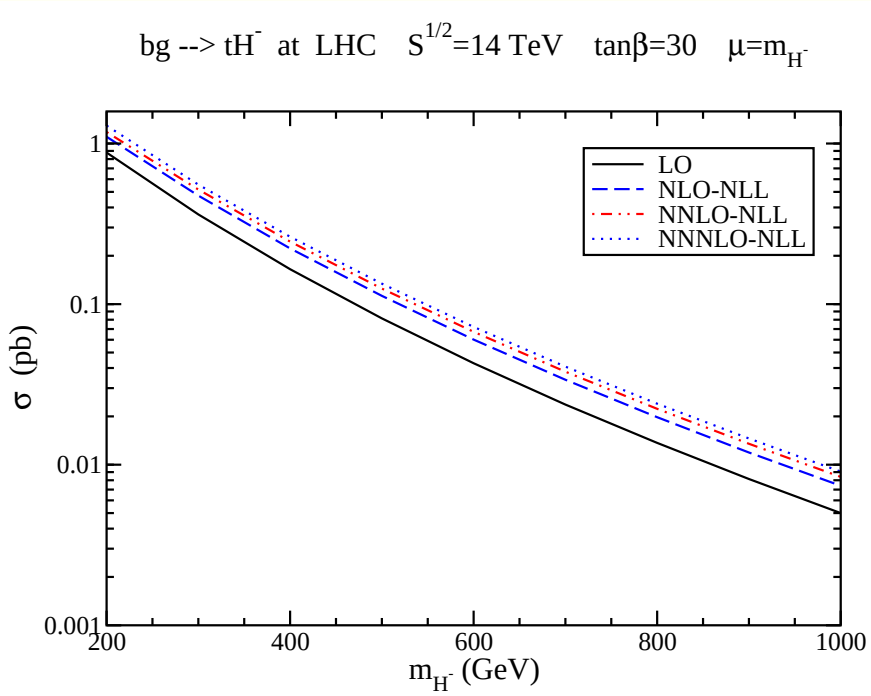
$$\hat{\sigma}^{(3)} = F^B \frac{\alpha_s^3(\mu_R^2)}{\pi^3} \left\{ \frac{1}{8} c_3^3 \left[\frac{\ln^5(s_4/m_H^2)}{s_4} \right]_+ + \left[\frac{5}{8} c_3^2 c_2 - \frac{5}{24} \beta_0 c_3^2 \right] \left[\frac{\ln^4(s_4/m_H^2)}{s_4} \right]_+ + \cdots \right\}$$

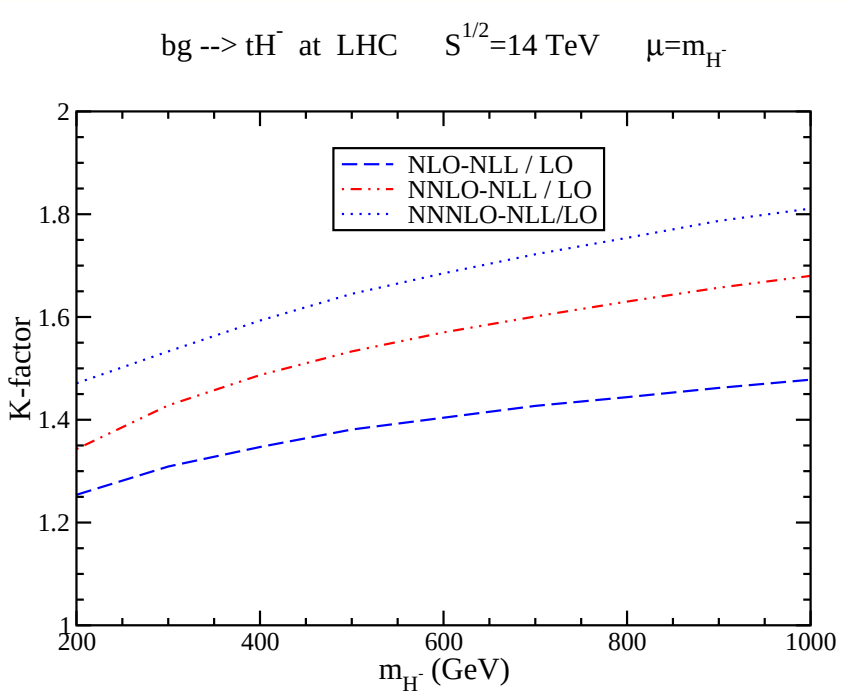
Charged Higgs production at the LHC





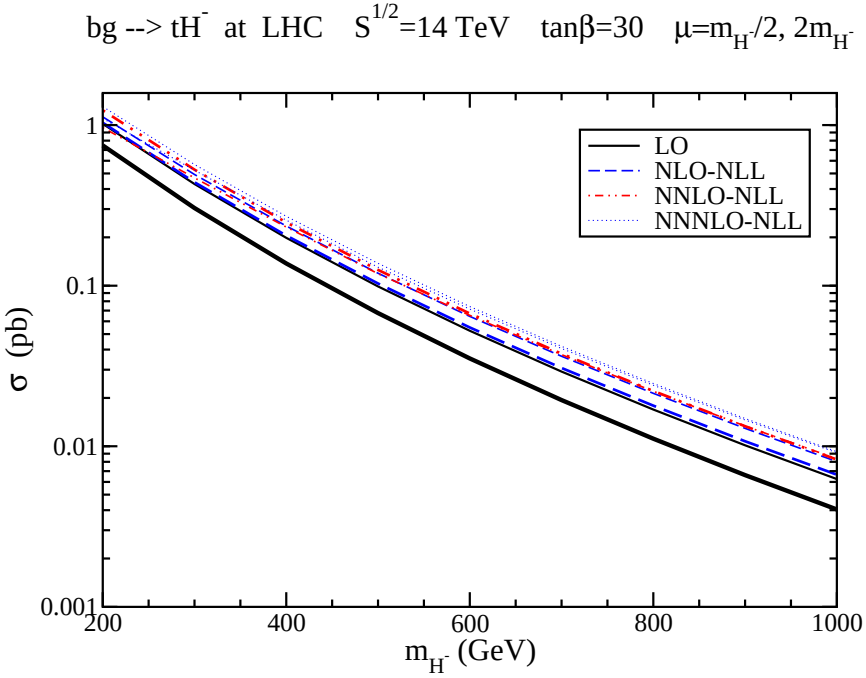
various choices of central scale in the literature

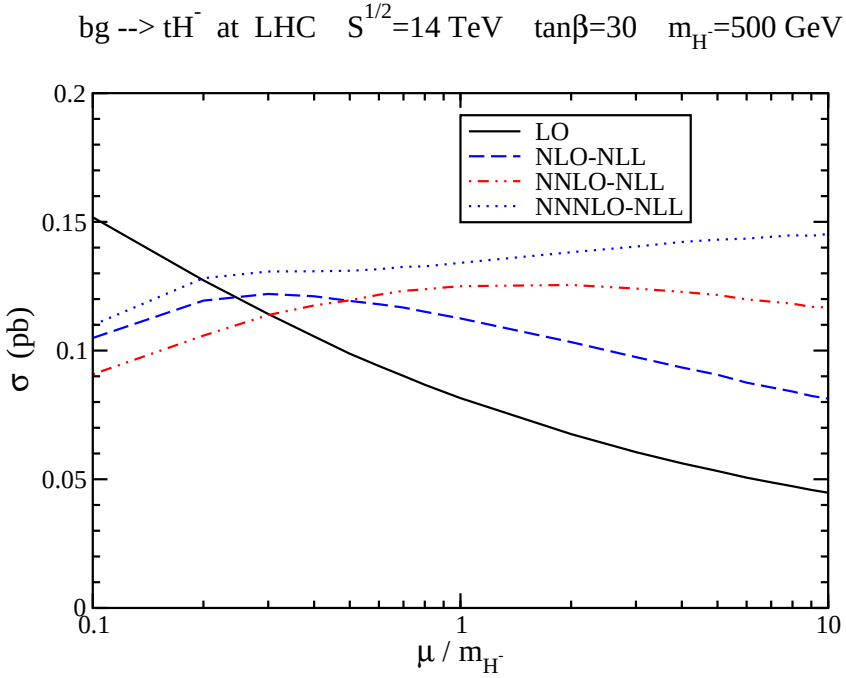




K factors		
Mass (GeV)	**NNLO-NLL**	**NNNLO-NLL**
200	**1.34**	**1.47**
300	**1.43**	**1.53**
400	**1.49**	**1.59**
500	**1.53**	**1.65**
600	**1.57**	**1.69**
700	**1.60**	**1.72**
800	**1.63**	**1.75**
900	**1.66**	**1.79**
1000	**1.68**	**1.81**

Scale dependence of the cross section





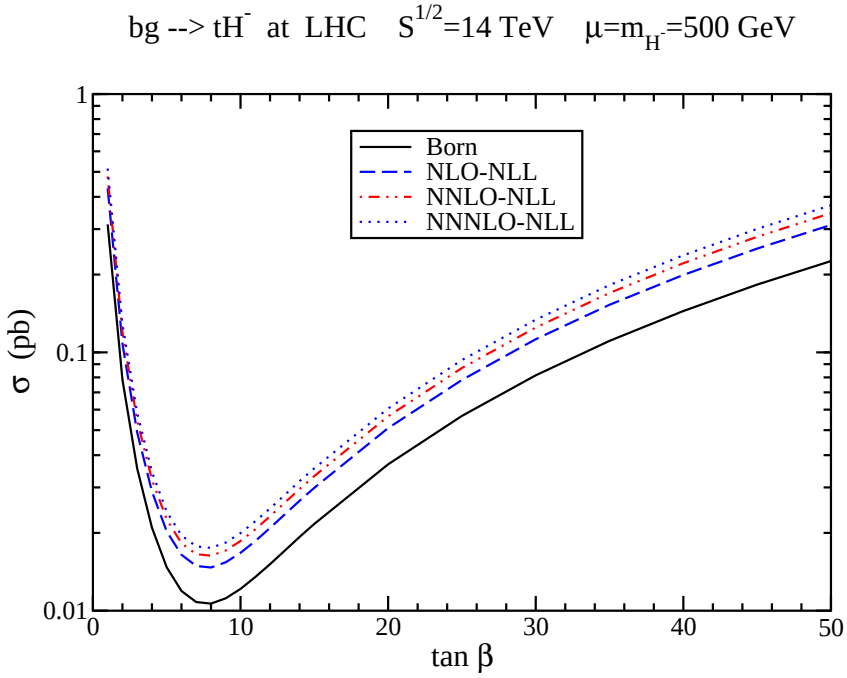
Reduced scale dependence over large range of scale $0.1 < \mu/m_{H-} < 10$

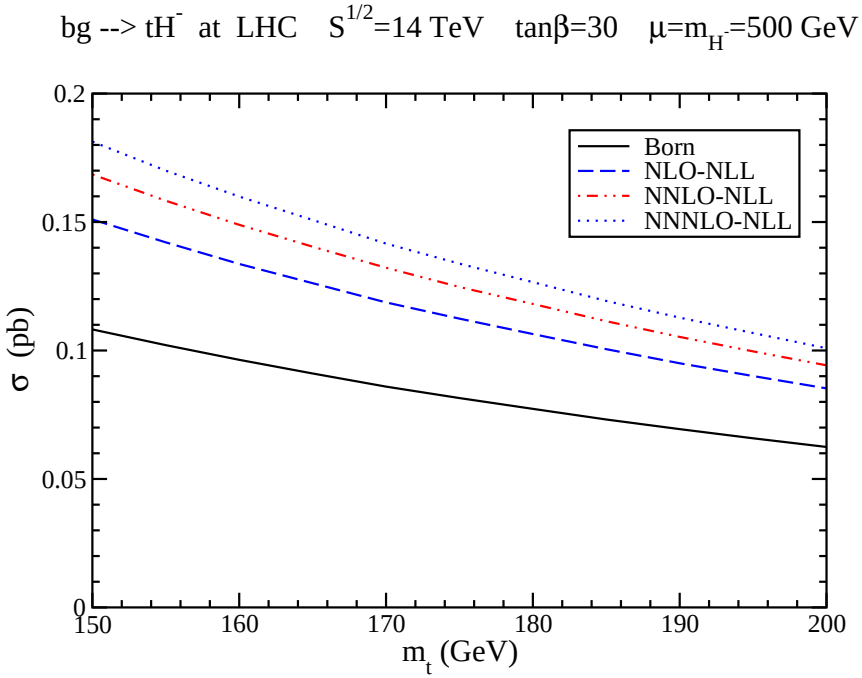
$\sigma_{\max}/\sigma_{\min} = 3.39 \quad 1.50 \quad 1.38 \quad 1.32$

↑ ↑ ↑ ↑

LO NLO-NLL NNLO-NLL NNNLO-NLL

Dependence of the cross section on $\tan\beta$ and top quark mass

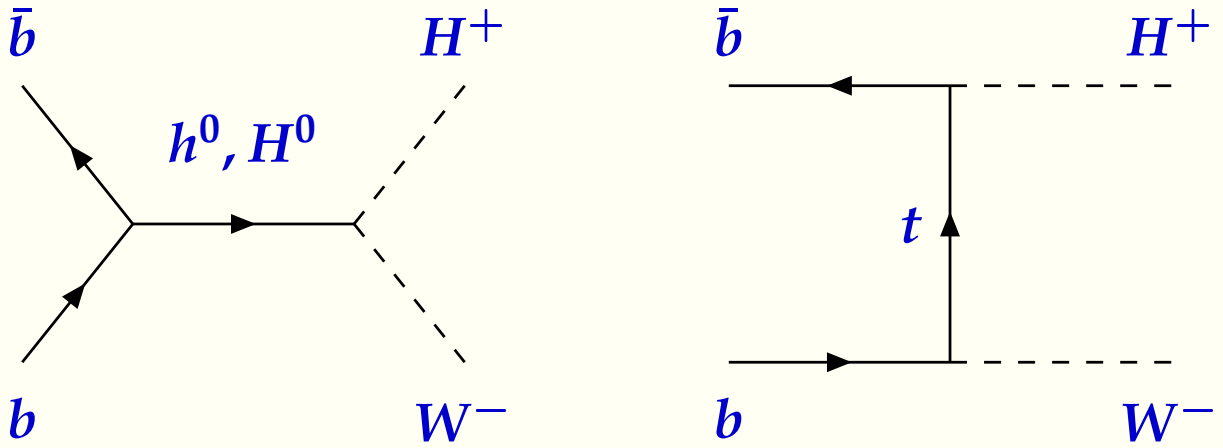


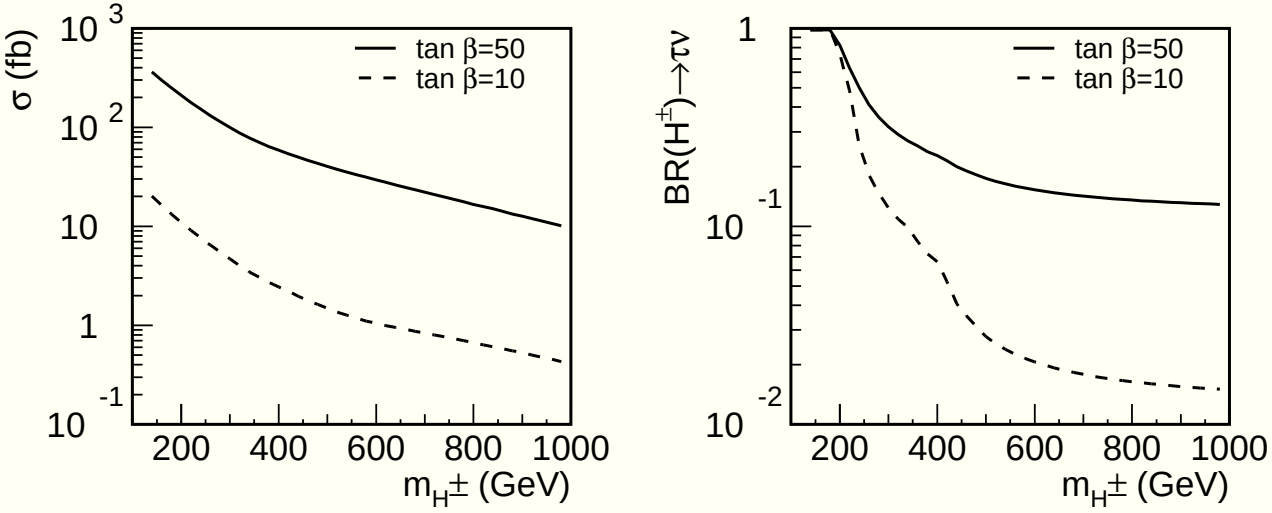


$\tan\beta$ shape same for all curves

Mild m_t dependence

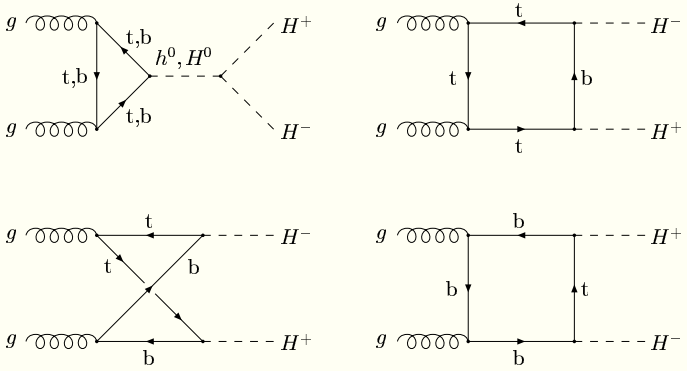
Associated H^+ and W^- production, $b\bar{b} \to H^+W^-$

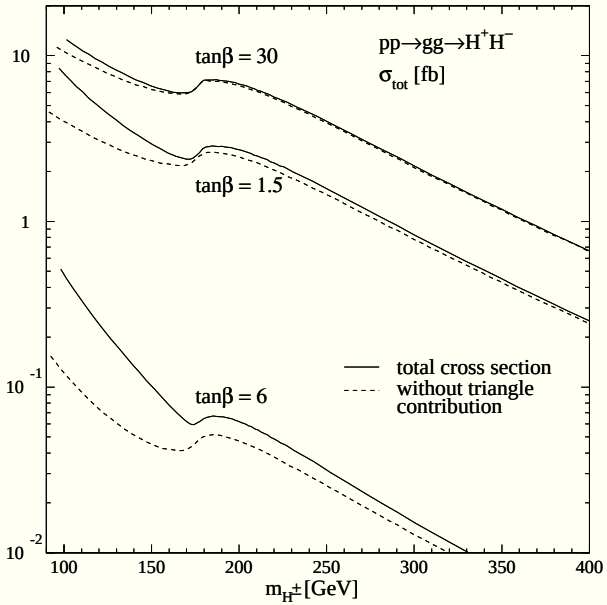


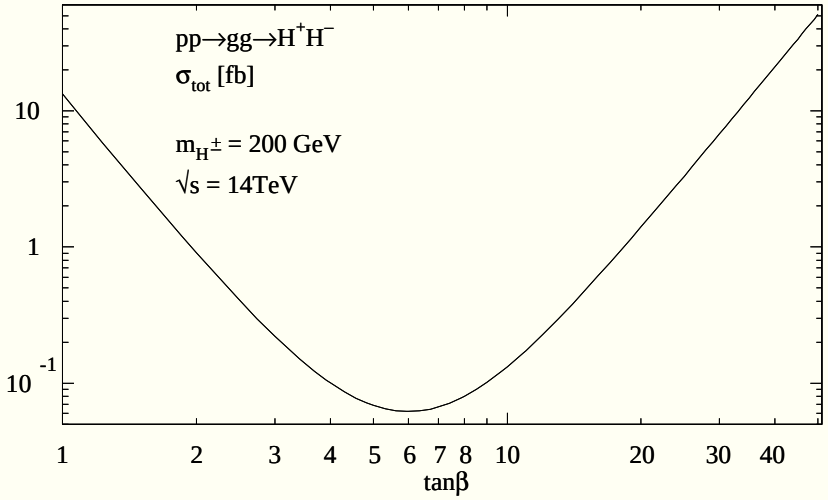


Eriksson, Hesselbach, Rathsman ('06)

Associated pair production $gg \to H^+H^-$

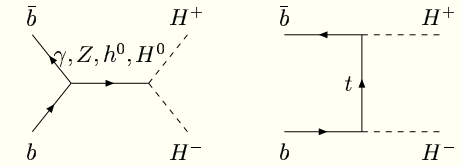


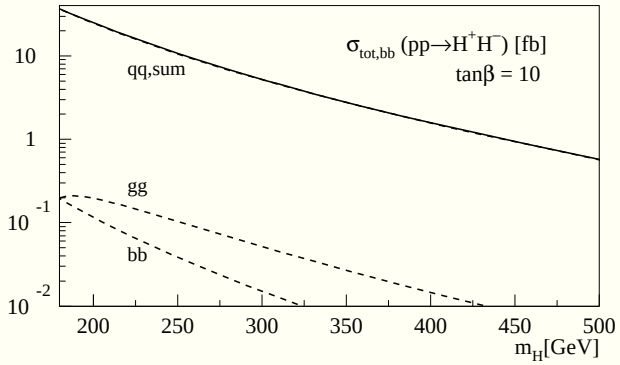


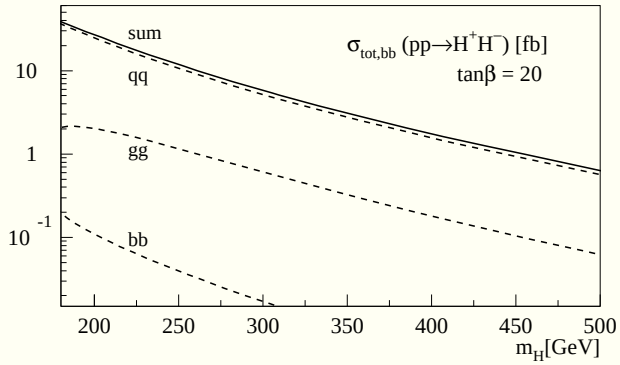


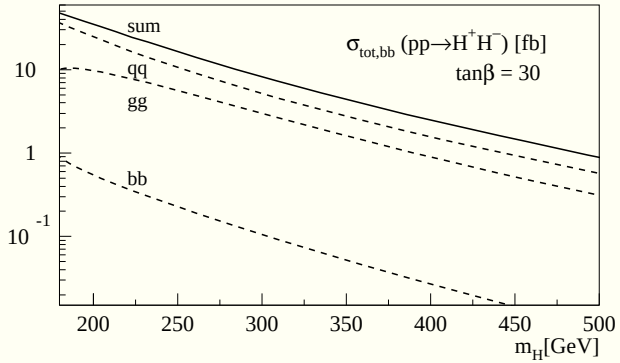
Krause, Plehn, Spira, Zerwas ('97)

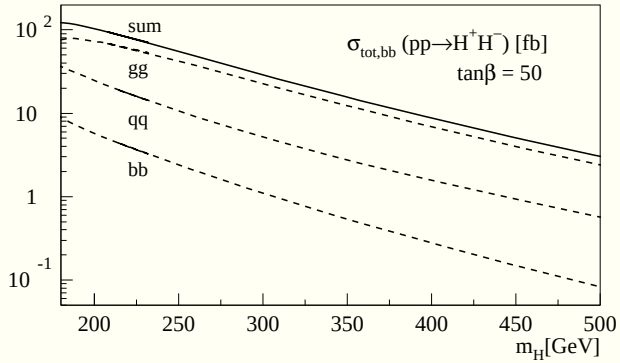
Associated pair production $b\bar{b} \to H^+H^-$











Alves, Plehn ('05)

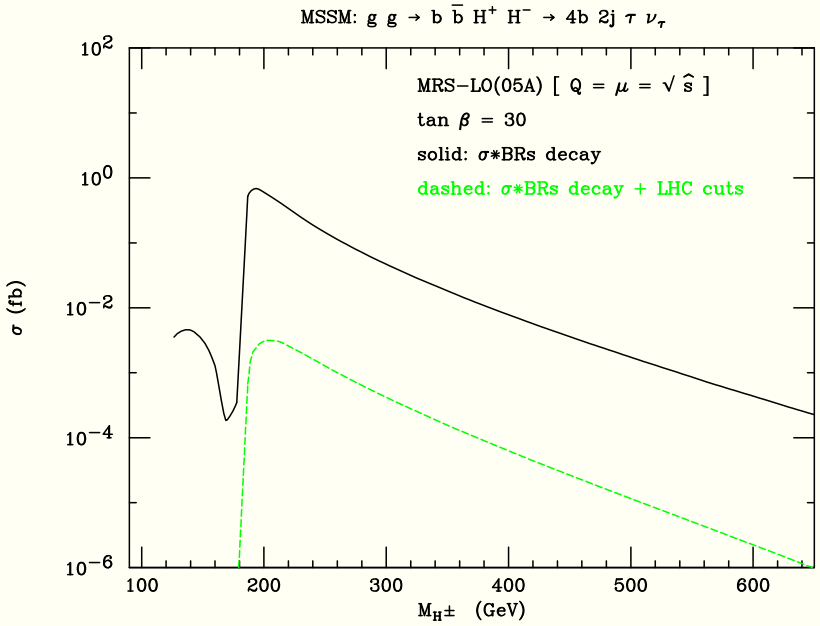
$gg \to b\bar{b}H^+H^-$

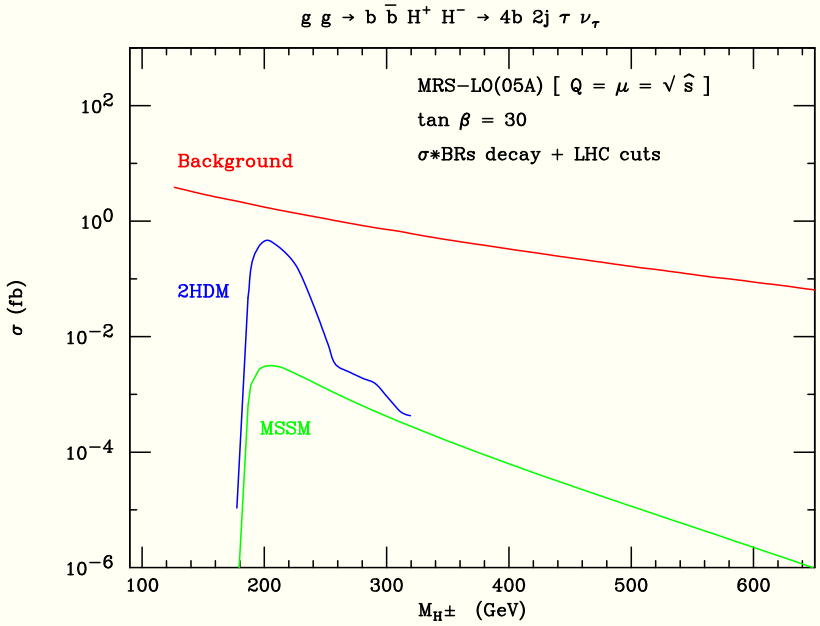
dominant pair production mode at large $\tan\beta$

relevant for triple-Higgs couplings

consider signature: 4 b-jets + 2 q-jets+ τ +p_T^{miss}

Moretti, Rathsman ('03)





Summary

- **Several production processes for $H^{\pm}$ at the LHC**
- **NLO QCD and SUSY corrections**
- **$bg \to tH^-$, $gg \to \bar{b}tH^-$ at the LHC - matching**
- **$bg \to tH^-$ Soft and collinear corrections through NNNLO**
- **$bg \to tH^-$ Large K factors -reduced scale dependence**
- **Associated production with a W**
- **Charged Higgs pair production**