$W^{\mp}H^{\pm}$ production and CP asymmetry at the LHC

DAO Thi Nhung

Based on

Wolfgang Hollik, Le Duc Ninh, D.T.N, Phys.Rev.D38:075003

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IMPRS colloquium

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Outline

1. Overview
   - Theoretical framework
   - Charged Higgs searches at colliders
2. $pp \to H^{\pm}W^{\mp}$
   - The lowest order
   - The effective bottom-Higgs couplings
   - Neutral Higgs propagator resummation
   - NLO corrections to $b\bar{b} \to H^{\pm}W^{\mp}$
   - Numerical results
3. Conclusions

Where charged Higgs bosons come from?

- What is the mechanism to generate particle masses? The Higgs mechanism is confirmed when Higgs bosons are found.
- No theoretical and experimental constraint on the number of Higgs bosons

$$\text{SM: one Higgs doublets} \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \xrightarrow{EWSB} h^0$$

- Two-Higgs-Doublet-Model (2HDM) is the simplest extension of the SM

$$\begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix} \text{ and } \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} \xrightarrow{EWSB} h^0, H^0 \text{ (CP even)}, A^0 \text{ (CP odd)}, H^\pm$$

  - Type I: fermions couple to one doublet → No FCNC at tree-level
  - Type II: down-type fermions couple to H_1, up-type fermions to H_2 (required by the MSSM) → No FCNC at tree-level
  - Type III: fermions couple to both H_1 and H_2

$H^\pm$ → clear signal of physics beyond the SM

The Minimal Supersymmetry Standard Model (MSSM) Higgs sector

compare to 2HDM type II:

- Two Higgs doublets with opposite hypercharge are required (analytic superpotential, anomaly free)
- Quartic coupling in Higgs potential is fixed

$$
\begin{aligned}
V &= m_1^2 H_{ui}^* H_{ui} + m_2^2 H_{di}^* H_{di} + \epsilon^{ij} (m_{12}^2 H_{ui} H_{dj} + \text{ H.c}) \\
&\quad + \frac{g_1^2 + g_2^2}{8} (H_{ui}^* H_{ui} - H_{di}^* H_{di})^2 + \frac{g_2^2}{2} |H_{ui}^* H_{di}|^2
\end{aligned}
$$

- Predict a light neutral Higgs boson: $m_{h^0} < 140$ GeV
- Number of Higgs-sector parameters are reduced

$$M_{H^\pm}(M_{A^0}), \tan\beta = \frac{v_2}{v_1}$$

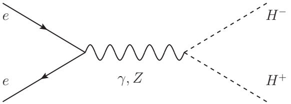
other good points of the MSSM: solve hierarchy problem, unification, darkmatter candidate, ...

Charged Higgs searches at colliders

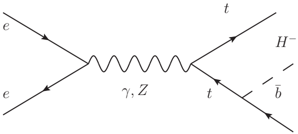
e^-e^+ colliders (LEP, future ILC,...)

- Two main production processes

1) $e^-e^+ \to H^-H^+$



2) $e^-e^+ \to H^-t\bar{b}$



- subsequence decays:
  - $M_{H^\pm} < m_t - m_b$: $H^- \to \tau\bar{\nu}_\tau$, $H^- \to \bar{c}s$
  - $M_{H^\pm} > m_t + m_b$: $H^- \to \bar{t}b$, $H^- \to h^0/AW$

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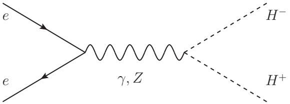

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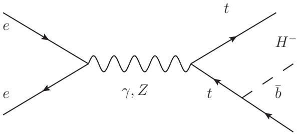

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LEP (192-209 GeV) analysis based on process 1):

- $M_{H^\pm} \geq 78.6$ GeV at 95% C.L for general 2HDM
- within MSSM, $M^2_{H^\pm} = M^2_A + M^2_W$, $M_A \geq 93.4$ GeV
  $\to M_{H^\pm} \geq 120$ GeV

Charged Higgs searches at colliders

Hadron colliders (Tevatron, LHC)

- Production processes
  1. $pp \to H^- t$ [Plehn, Shou, M. Beccaria, Elber, Dittmaier]
     largest production rate
  2. $pp \to H^\pm W^\mp$ [Kniehl, O. Brein, Hollik, Gao, Rauch, Yang]
  3. $pp \to H^- H^+$ [Eichten, Plehn, Hollik, Kniehl]

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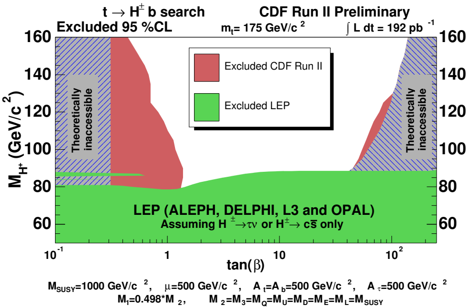
CDF analysis based on:

- $gg \to t\bar{t} \to (H^+\bar{b})\bar{t}$
- $M_{H^\pm} < m_t - m_b$
- important coupling Htb

Phys.Rev.Lett.96:042003



$pp \to H^\pm W^\mp$: What has been done?

Many studies are done in the real MSSM

- $gg \to H^\pm W^\mp$: loop induced

  [Barrientos Bendezu and Kniehl; Brein, Hollik and Kanemura]

- $b\bar{b} \to H^\pm W^\mp$: calculated at NLO
  - SM-QCD corrections [Hollik and Zhu; Gao, C.S. Li and Z. Li]
  - SUSY-QCD corrections [Zhao, C.S. Li and Z. Li; Rauch]
  - Yukawa corrections [Yang, C.S. Li, Jin and Zhu]
  - Full EW corrections: missing

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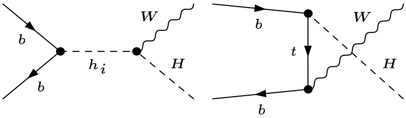
Our work:

- compute in general complex MSSM
- full EW corrections to $b\bar{b} \to H^{\pm}W^{\mp}$, consistently combine with QCD corrections,
- CP violating effects
- use the effective bottom-Higgs couplings
- use the neutral Higgs propagator resummation

- $b\bar{b} \to H^{\pm}W^{\mp}$



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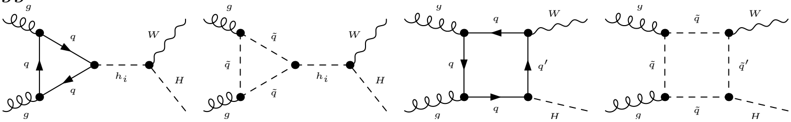
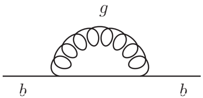


Importances

- bottom-Higgs couplings:
  $\lambda_{b\bar{b}h/H/A} \propto \frac{m_b}{\cos\beta}$, $\lambda_{b\bar{t}H^+} \propto (\frac{m_t}{\tan\beta} P_L + m_b \tan\beta P_R)$
- neutral Higgs propagator: $\frac{i}{p^2 - m_h{}^2}$, m_h^2?

The effective bottom-Higgs couplings

- Leading contribution $\alpha_s^n \ln^n(m_b/\mu_R)$ from SM-QCD are resumed into running $m_b^{\overline{\mathrm{DR}}}(\mu_R)$



$$m_b^{\overline{\mathrm{DR}}}(\mu_R) = m_b\left[1 - \frac{\alpha_s}{3\pi}\left(5 - 6\ln\frac{m_b}{\mu_R}\right)\right]$$

$\rightarrow$ SM-QCD corrections do not depend on $\ln m_b$
$\rightarrow$ ensure convergent property of perturbative expansion

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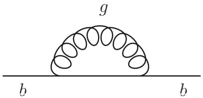

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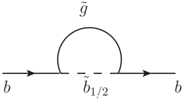
- Leading contribution $\Delta m_b \propto \tan\beta$ from SUSY corrections are resumed into bottom-Higgs couplings $\lambda_{bbh} \propto \frac{m_b}{1+\Delta m_b}$



$$\Delta m_b^{SQCD} = \frac{2\alpha_s}{3\pi} M_3^* \mu^* \tan\beta I(M_{\tilde{b}_1}^2, M_{\tilde{b}_2}^2, M_{\tilde{g}}^2)$$

$$I(a,b,c) = -\frac{ab\ln\frac{a}{b} + bc\ln\frac{b}{c} + ca\ln\frac{c}{a}}{(a-b)(b-c)(c-a)}$$

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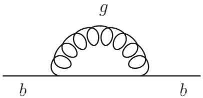

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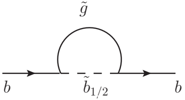

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  - if Δm_b close to -1, λ can be very large

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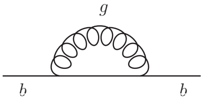

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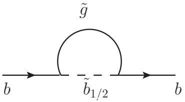

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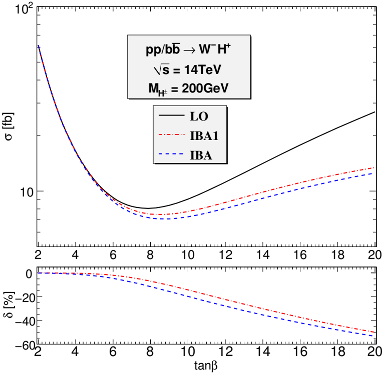
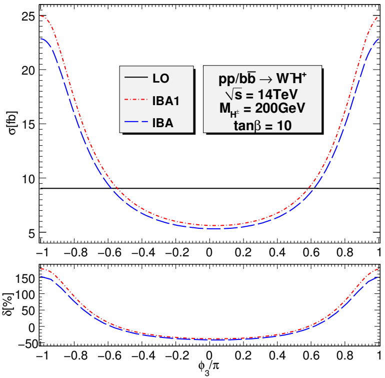
  - Δm_b in general is complex
  - if Δm_b close to -1, λ can be very large
  - To avoid double counting, we have to subtract the Δm_b-related corrections in one-loop calculation

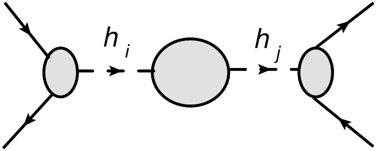
Δm_b resummation effects





- $\delta = (\sigma_{\rm IBA} - \sigma_{\rm LO})/\sigma_{\rm LO}$
- 50% at $\tan\beta = 20$
- even 150% at $\phi_3 = \pm\pi$

Neutral Higgs propagator resummation



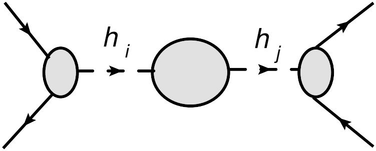
$$\mathcal{A}(p^2) = \sum_{ij} \Gamma_i \, \Delta_{ij}(p^2) \, \Gamma_j, \quad i = h, H, A,$$

$\Gamma_{i,j}$ are one-particle irreducible Higgs vertices.

$$\Delta(p^2) = i[p^2 - \mathcal{M}(p^2)]^{-1},$$

$$\mathcal{M}(p^2) = \begin{pmatrix} m_h^2 - \hat{\Sigma}_{hh}(p^2) & -\hat{\Sigma}_{hH}(p^2) & -\hat{\Sigma}_{hA}(p^2) \\ -\hat{\Sigma}_{hH}(p^2) & m_H^2 - \hat{\Sigma}_{HH}(p^2) & -\hat{\Sigma}_{HA}(p^2) \\ -\hat{\Sigma}_{hA}(p^2) & -\hat{\Sigma}_{HA}(p^2) & m_A^2 - \hat{\Sigma}_{AA}(p^2) \end{pmatrix}.$$

- m_i ($i = h, H, A$) are the lowest-order Higgs-boson masses
- $\hat{\Sigma}_{ij}$ the renormalized self-energies, $\hat{\Sigma}_{h/HA}$ vanish in real MSSM,
- Loop-corrected masses are obtained by diagonalizing $\mathcal{M}(p^2)$



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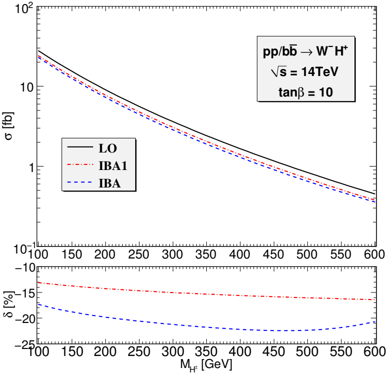
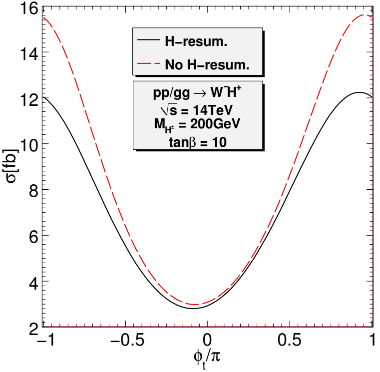
- To avoid double counting, we have to discard all $h_i h_j$ self-energies diagrams in NLO EW corrections

Higgs mixing resummation effects

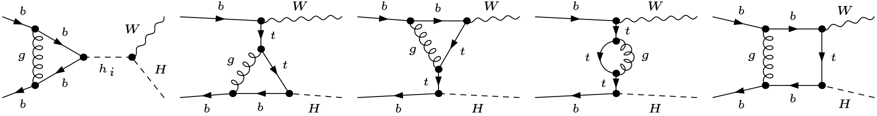




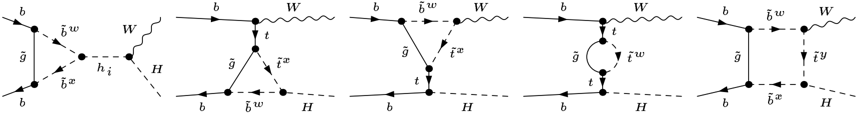
- less than 10% in subprocesses $b\bar{b} \to W^{\mp}H^{\pm}$
- large effects (30% at $\phi_t = \pm\pi$) in subprocesses $gg \to W^{\mp}H^{\pm}$

Virtual contributions:

- SM-QCD

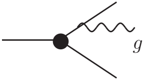


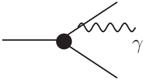
- SUSY-QCD



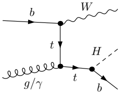
- EW part consists of 352 self-energies + 440 triangles + 153 boxes

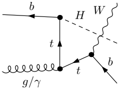
Real contributions:





Gluon induce, photon induce:

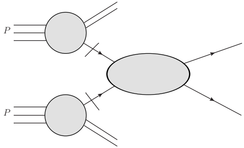




Divergencies:

- UV divergencies are cured by renormalization,
  - OS-scheme for W-boson, M_{H^+}, m_t
  - DR-scheme for $\tan\beta$, m_b, $H^{\pm}$ wave function
- IR divergencies are cancelled between the virtual part and the gluon and photon radiations
- Mass singularities of the type $\alpha_s \ln(m_b)$ and $\alpha \ln(m_b)$ are absorbed into (anti-) bottom PDF
- In the gluon- and photon-induced precesses, the top quark can be on-shell then $t \to Wb$ ($t \to Hb$). This contribution belongs to tH (tW) production so it needs to be subtracted in a gauge-invariant way.

Drell-Yan process



$$\sigma^{pp} = \sum_{i,j} \int \mathrm{d}x_1 \mathrm{d}x_2 [F_i^p(x_1, \mu_F) F_j^p(x_2, \mu_F) \hat{\sigma}^{ij}(\mu_R) + i \leftrightarrow j)],$$

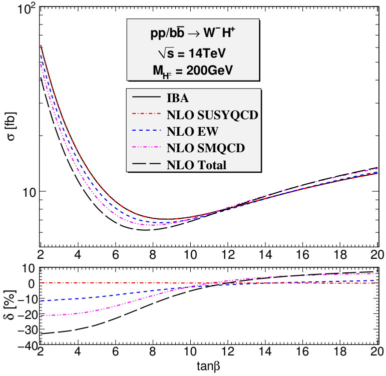
PDF: MRST2004qed

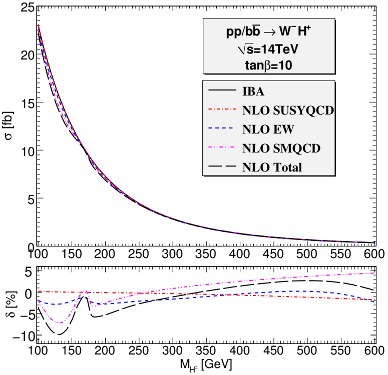
CP asymmetry

$$\delta_{pp}^{\text{CP violation}} = \frac{\sigma(pp \to W^- H^+) - \sigma(pp \to W^+ H^-)}{\sigma(pp \to W^- H^+) + \sigma(pp \to W^+ H^-)}.$$

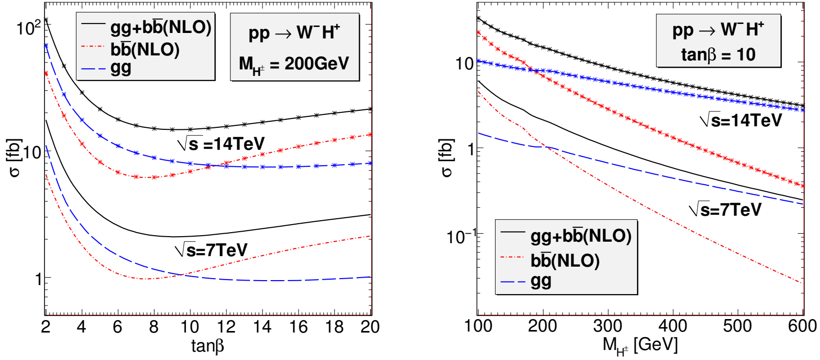
Use CPX scenario for numerical studies

NLO corrections to $b\bar{b} \to H^{\pm}W^{\mp}$

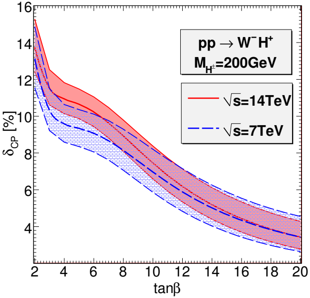


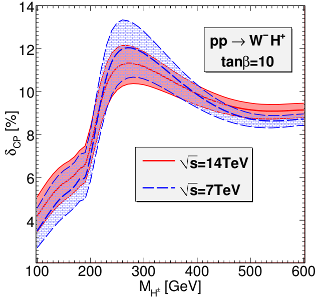


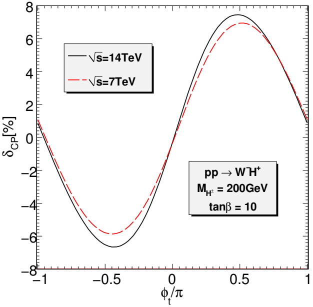
Total hardronic cross section

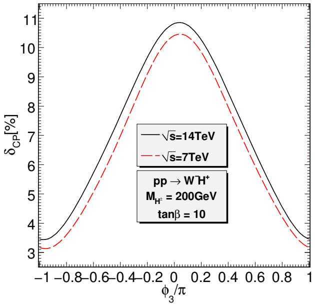


CP asymmetry



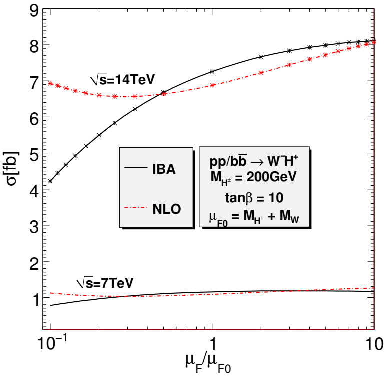


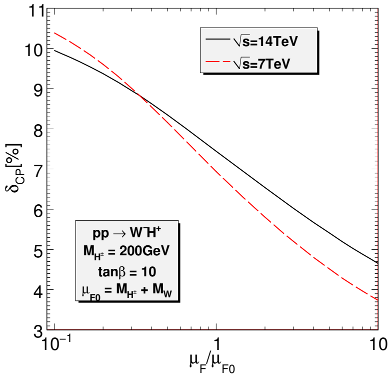




Scale dependence

- $\delta = [|\sigma(\mu_{F0}/2) - \sigma(\mu_{F0})| + |\sigma(2\mu_{F0}) - \sigma(\mu_{F0})|]/\sigma(\mu_{F0})$
- $\mu_R = \mu_F,\ \mu_{F0} = M_W + M_{H^\pm}$





- NLO: $\delta = 9\%(9\%)$
- IBA: $\delta = 14\%(7\%)$

- 14 TeV $\delta = 24\%$
- 7 TeV: $\delta = 34\%$

Conclusions

- $pp \to W^{\mp}H^{\pm}$ have been studied in general complex MSSM
- NLO EW, QCD corrections to $b\bar{b} \to W \mp H^{\pm}$ are important for precision searches
- NLO corrections significantly reduce scale dependence
- Large CP asymmetry is mainly induced from gg fusion
- The effective bottom-Higgs couplings have significant effects on $b\bar{b}$ annihilation
- The Higgs mixing resummation gives large effects on gg fusion, and CP asymmetry
- Production rates and CP asymmetry strongly depend on $\tan\beta$, $M_{H^{\pm}}$, ϕ_t, ϕ_3

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THANK YOU FOR YOUR ATTENTION