Top asymmetry in top-charged Higgs production as a probe of the parameter $\tan\beta$

Julien Baglio

Institut für Theoretische Physik (KIT), Karlsruhe (Germany)

in coll. with M. Beccaria, A. Djouadi, G. Macorini, E. Mirabella, N. Orlando, F.M. Renard and C. Verzegnassi, [Phys.Lett. **B705** (2011) 212-216]

Forshung seminar, November 3$^{\rm rd}$, 2011

Karlsruher Institut für Technologie

Outline

1. The context of the study: Two Higgs doublets models
2. Top–charged Higgs production at hadron colliders
3. Scale and PDF uncertainties at the LHC
4. SUSY vs non–SUSY predictions
5. Conclusion

Motivations for Two Higgs doublet models

Two Higgs doublet models (2DHMs): the minimal gauge invariant Standard Model (SM) extension of the Higgs sector with two Higgs doublets instead of a single one

Why looking at 2DHMs models? Several reasons:

- Scalar sector of SM yet to be discovered: no experimental proof that we should restrict to the most simple 1 Higgs doublet even in the context of SM
- SUSY, one of the most well-known BSM frameworks, needs a 2HDM to describe its Higgs sector
- Allows for a richer phenomenology with additionnal new states without contradicting the $\rho \simeq 1$ constraint

Karlsruher Institut für Technologie

The scalar potential in 2HDMs

Two Higgs $SU(2)_L$ doublets introduced:

$$\Phi_1 = \begin{pmatrix} \phi_1^0 \\ \phi_1^- \end{pmatrix}, \; \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix} \quad Y_{\Phi_1} = -1, \;\; Y_{\Phi_2} = +1$$

The most general **CP–conserving** general 2HDM scalar potential is:

$$\begin{aligned} V(\Phi_1, \Phi_2) \;\; = \;\; & \lambda_1 \left(|\Phi_1|^2 - v_1^2 \right)^2 + \lambda_2 \left(|\Phi_2|^2 - v_2^2 \right)^2 + \lambda_3 \left[|\Phi_1|^2 + |\Phi_2|^2 - v_1^2 - v_2^2 \right]^2 + \\ & \lambda_4 \left[|\Phi_1|^2 |\Phi_2^2|^2 - (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \right] + \lambda_5 \left(\mathrm{Re}(\Phi_1^\dagger \Phi_2) - v_1 v_2 \right)^2 + \\ & \lambda_6 \, \mathrm{Im}(\Phi_1^\dagger \Phi_2)^2 \end{aligned}$$

with the 6 λ_i as real parameters;
C–invariance as well as a global $\Phi_2 \to e^{\imath\chi}\Phi_2$ $U(1)$ invariance (no tree–level FCNC)

Φ_1, Φ_2 get vacuum expectation values (vev):

$$\langle \Phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_1 \\ 0 \end{pmatrix}, \; \langle \Phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$$

with $\tan\beta \equiv \dfrac{v_2}{v_1}$ and $v^2 (\equiv v_{\rm SM}^2) = v_1^2 + v_2^2 \simeq 246$ GeV

Karlsruher Institut für Technologie

Electroweak symmetry breaking and Higgs spectrum

Rewrite $\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \mathrm{Re}\,\phi_1^0 + \imath\,\mathrm{Im}\,\phi_1^0 + v_1 \\ \sqrt{2}\phi_1^- \end{pmatrix}$, $\Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\phi_2^+ \\ \mathrm{Re}\,\phi_2^0 + \imath\,\mathrm{Im}\,\phi_2^0 + v_2 \end{pmatrix}$

- 2 CP–even neutral Higgs bosons h, H with

$$\begin{aligned} h &= \mathrm{Re}\,\phi_1^0 \cos\alpha + \mathrm{Re}\,\phi_2^0 \sin\alpha \\ H &= -\mathrm{Re}\,\phi_1^0 \sin\alpha + \mathrm{Re}\,\phi_2^0 \cos\alpha \end{aligned}$$

- 1 CP–odd neutral Higgs boson A (and a Goldstone G) with

$$\begin{aligned} A &= -\mathrm{Im}\,\phi_1^0 \sin\beta + \mathrm{Re}\,\phi_2^0 \cos\beta \\ G &= \mathrm{Im}\,\phi_1^0 \cos\beta + \mathrm{Im}\,\phi_2^0 \sin\beta \end{aligned}$$

- 2 charged Higgs bosons $H^\pm$ (and 2 Goldstones $G^\pm$)

$$\begin{aligned} H^\pm &= -\phi_1^\pm \sin\beta + \phi_2^\pm \cos\beta \\ G^\pm &= \phi_1^\pm \cos\beta + \phi_2^\pm \sin\beta \end{aligned}$$

with α mixing angle (see later)

Karlsruher Institut für Technologie

Higgs spectrum: masses and mixing angle

We have four masses and a CP–even Higgs mixing angle α:

- $$\tan(2\alpha) = \frac{4\tan\beta(4\lambda_3 + \lambda_5)}{4\lambda_1 - 4\lambda_2\tan^2\beta + (\tan^2\beta - 1)\lambda_5}$$

- $m_A^2 = \lambda_6(v_1^2 + v_2^2)$, $m_{H^\pm}^2 = \lambda_4(v_1^2 + v_2^2)$

- $$\begin{cases} m_h = \frac{1}{2}\left[(4\lambda_3 + \lambda_5)(v_1^2 + v_2^2) + 4\lambda_1 v_1^2 + 4\lambda_2 v_2^2\right] - \frac{1}{2}\sqrt{R_\lambda} \\ m_H = \frac{1}{2}\left[(4\lambda_3 + \lambda_5)(v_1^2 + v_2^2) + 4\lambda_1 v_1^2 + 4\lambda_2 v_2^2\right] + \frac{1}{2}\sqrt{R_\lambda} \end{cases}$$

  where we have

$$R_\lambda = \left[(4\lambda_3 - \lambda_5)(v_1^2 - v_2^2) + 4\lambda_1 v_1^2 - 4\lambda_2 v_2^2\right]^2 + 4v_1^2 v_2^2(4\lambda_3 + \lambda_5)^2$$

Karlsruher Institut für Technologie

Type I and type II 2HDMs

Depending on the Higgs couplings to fermions, two main discussed classes of 2HDM:

1. Type I: only one doublet couples to all fermions:

$$\mathcal{L}_{\text{Yukawa, I}} = -\frac{\lambda_u}{v_2}\left(\bar{u}P_L u\phi_2^0 - \bar{u}P_L d\phi_2^+\right) - \frac{\lambda_d}{v_2}\left(\bar{d}P_L d\tilde{\phi}_2^0 - \bar{d}P_L u\tilde{\phi}_2^-\right) + \text{h.c.}$$

$$m_{u,d} = \frac{\lambda_{u,d} M_W \sqrt{2}\sin\beta}{g}$$

2. Type II: one doublet couples to up–type fermions, the other couples to down–type fermions:

$$\mathcal{L}_{\text{Yukawa, II}} = -\frac{\lambda_u}{v_2}\left(\bar{u}P_L u\phi_2^0 - \bar{u}P_L d\phi_2^+\right) - \frac{\lambda_d}{v_1}\left(\bar{d}P_L d\phi_1^0 - \bar{d}P_L u\phi_1^-\right) + \text{h.c.}$$

$$m_u = \frac{\lambda_u M_W \sqrt{2}\sin\beta}{g},\ m_d = \frac{\lambda_d M_W \sqrt{2}\cos\beta}{g}$$

Karlsruher Institut für Technologie

Constraints on 2HDMs

Theoretical constraints (some examples):

- Unitarity constraints: unitarity in $V_L V_L \to V_L V_L$, $f\bar{f} \to V_L V_L$ imply sum rules:

$$\sum_i g^2_{h_i VV} = g^2_{h_{\rm SM} VV}, \quad \sum_i g_{h_i VV} g_{h_i f\bar{f}} = g_{h_{\rm SM} VV} g_{h_{\rm SM} f\bar{f}}, \ \text{etc.}$$

- Perturbativity and stability constraints: λ_i perturbative at the EW scale $\Rightarrow \tan\beta \leq 50$

  nearly no general bounds on masses, for specific cases see e.g. [JHEP 0908 (2009) 069] or MSSM limits

Experimental constraints:

Model–dependant limits, see type II limits within the MSSM for example

MSSM: the SUSY example of a type II 2HDM

In the minimal supersymmetric extension of the SM (the MSSM), two Higgs doublets required in the theory because:

- Gauge anomalies cancellation: with only one Higgs doublet the charged higgsino superparter anomaly remains
- Analytic superpotential: 2 Higgs doublets needed to give mass to up and down–type quarks

A type II 2HDM required, with the λ_i parameters dictated by the SUSY relations in the gauge sector, the soft SUSY breaking terms ($m_1^2, m_2^2, m_{12}^2 \equiv B\mu$) and the superpotential

$$\mathcal{W}_{\rm MSSM} = -\mu \Phi_2 \cdot \Phi_1 - \lambda_{ij}^e (\Phi_1 \cdot L_i)\overline{E}_j - \lambda_{ij}^d (\Phi_2 \cdot Q_i)\overline{D}_j - \lambda_{ij}^u (Q_i \cdot \Phi_2)\overline{U}_j$$

λ_i parameters read

$$\begin{aligned}
\lambda_2 &= \lambda_1 & \lambda_3 &= \tfrac{1}{8}(g_Y^2 + g^2) - \lambda_1 \\
\lambda_4 &= 2\lambda_1 - \frac{1}{2} g_Y^2 & \lambda_5 &= \lambda_6 = 2\lambda_1 - \tfrac{1}{2}(g_Y^2 + g^2) \\
m_1^2 &= -|\mu|^2 + 2\lambda_1 v_2^2 - \frac{1}{2} m_Z^2 & m_2^2 &= -|\mu|^2 + 2\lambda_2 v_1^2 - \tfrac{1}{2} m_Z^2 \\
m_{12}^2 &= -\frac{1}{2} v_1 v_2 (g_Y^2 + g^2 - 4\lambda_1)
\end{aligned}$$

Karlsruher Institut für Technologie

Charged Higgs couplings to fermions

Type I 2HDM: with K CKM element, $m_{U,D}$ up and down–type quark masses, the charged Yukawa lagrangian read:

$$\mathcal{L}_{\text{Yukawa, I}} = \frac{g}{\sqrt{2}M_W \sin\beta}\left(m_U K \bar{U} P_L D \phi_2^+ + m_D K^* \bar{D} P_L U \tilde{\phi}_2^-\right) + \text{h.c.}$$

With physical Higgs states:

$$g^{\text{I}}_{H^- t\bar{b}} = \frac{g\cot\beta}{2\sqrt{2}M_W} K^*_{tb}\left[m_t(1+\gamma_5) + m_b(1-\gamma_5)\right]$$

Type II 2HDM: up and down–type quarks have different couplings:

$$\mathcal{L}_{\text{Yukawa, II}} = \frac{g}{\sqrt{2}M_W}\left(\frac{m_U}{\sin\beta} K \bar{U} P_L D \phi_2^+ + \frac{m_D}{\cos\beta} K^* \bar{D} P_L U \phi_1^-\right) + \text{h.c.}$$

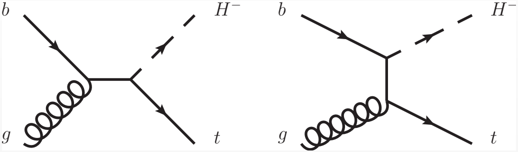
With physical Higgs states:

$$g^{\text{II}}_{H^- t\bar{b}} = \frac{g}{2\sqrt{2}M_W} K^*_{tb}\left[\cot\beta\, m_t(1+\gamma_5) + \tan\beta\, m_b(1-\gamma_5)\right]$$

Karlsruher Institut für Technologie

Top–charged Higgs production at hadron colliders

$bg \to tH^-$ LO calculation in the s and t channels:



- Use $\overline{m}_b(\mu_F^2)$ in $\overline{\text{MS}}$ scheme to stabilize the calculation
  $\overline{m}_b(\overline{m}_b^2) = 4.16$ GeV and $\overline{m}_b(\mu_F^2) \simeq 3$ GeV

- LO $\alpha_s(\mu_F^2)$ evolution, $\alpha_S(M_Z^2) = 0.130$ in CTEQ6L1 and ABKM PDF sets, $\alpha_S(M_Z^2) = 0.139$ in MSTW PDF set (see later)

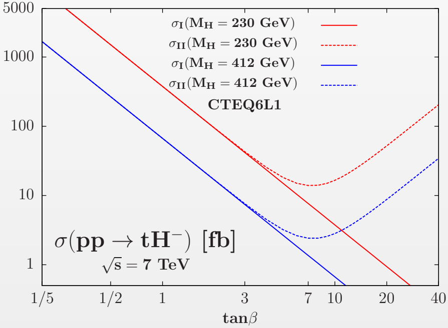
- Central scale $\mu_F = \mu_0 = \frac{1}{6}(M_{H^-} + m_t) \Rightarrow$ minimize the higher order QCD corrections (see Plehn, Phys.Rev. **D67** (2003) 014018)

Karlsruher Institut für Technologie

Top–charged Higgs production at hadron colliders

With λ kinetic phase–space term and $x_{ht}^2 = (M_{H^-}^2 - m_t^2)/\hat{s}$, the partonic cross section is:

$$\hat{\sigma}_{\mathrm{I}/\mathrm{II}} = \frac{G_F\,\alpha_s(\mu_F^2)}{24\sqrt{2}\,\hat{s}}\left(m_t^2\cot^2\beta + \overline{m}_b^2(\mu_F^2)\,\cot^2\beta/\tan^2\beta\right)$$
$$\left[2\left(1-2x_{ht}^2(1-x_{ht}^2)\right)\ln\left(\frac{1-x_{ht}^2+\lambda}{1-x_{ht}^2-\lambda}\right) - (3-7x_{ht}^2)\lambda\right]$$

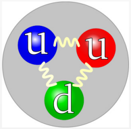


PDF convolution

Parton Distribution Functions (PDFs)

Probability density of a given parton (quarks, gluons) to be extracted from the (anti)proton with a fraction x of the (anti)proton momentum

Non–perturbative quantity, fitted on data by different collaborations
$\Rightarrow$ different sets on the market: MSTW, ABKM, CTEQ, etc.



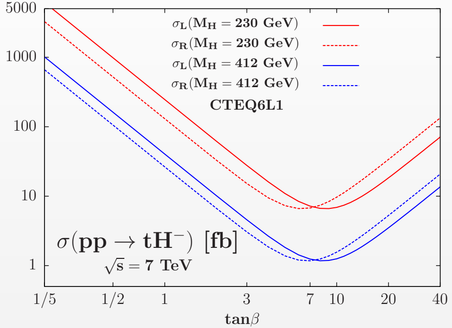
Hadronic cross section

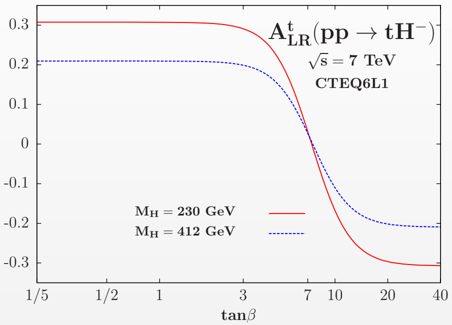
$$\sigma\left(pp \to tH^-\right) = \sum_{i,j=g,q} \int_0^1 dx_1 \int_0^1 dx_2 f_i(x_1) f_j(x_2) \hat{\sigma}_{ij}\left(\hat{s} = x_1 x_2 S\right) \Theta\left(\hat{s} \geq \left(m_t + m_{H^-}\right)^2\right)$$

Karlsruher Institut für Technologie

Top polarization asymmetry in $bg \to tH^-$

Left (-1 helicity) and Right (+1 helicity) polarized top quarks : $A_{LR} \equiv \dfrac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$





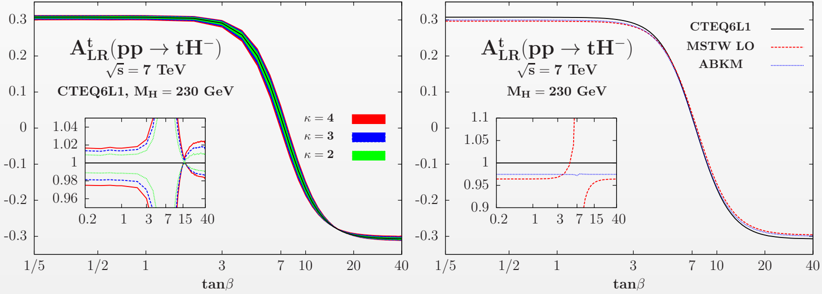
- $g_{H^- t\bar{b}} \propto \cot\beta$ in type I 2HDM:
  $A^{\rm I}_{LR}$ constant in type I 2HDM, $A^{\rm I}_{LR} = A^{\rm II}_{LR}(\tan\beta = 1)$
- $A^{\rm II}_{LR} = 0$ for $\tan\beta = \sqrt{m_t/\overline{m}_b} \simeq 7$ in type II 2HDM
- Easy to distinguish low and high $\tan\beta$ regimes in type II 2HDM; **combine $\sigma(bg \to tH^-)$ & A_{LR} to distinguish type I and type II 2HDMs**

Karlsruher Institut für Technologie

Scale and PDF uncertainties on the asymmetry

Scale uncertainty: estimated with factorization scale varied in the interval $\mu_0/\kappa \leq \mu_F \leq \kappa\mu_0$ with $\kappa = 2, 3, 4$

PDF uncertainty: estimated as the difference between the various central predictions (ABKM, CTEQ6L, MSTW)



- Even with $\kappa = 4$: scale uncertainty below 2%
- PDF uncertainty estimated below 4%

Side remark: PDF uncertainty accounts also for the $\alpha_s(M_Z^2)$ uncertainty

Karlsruher Institut für Technologie

SUSY corrections to top–charged Higgs production

SUSY scenarios only investigated through the loop structure of $bg \to tH^-$ process in type II 2HDMs

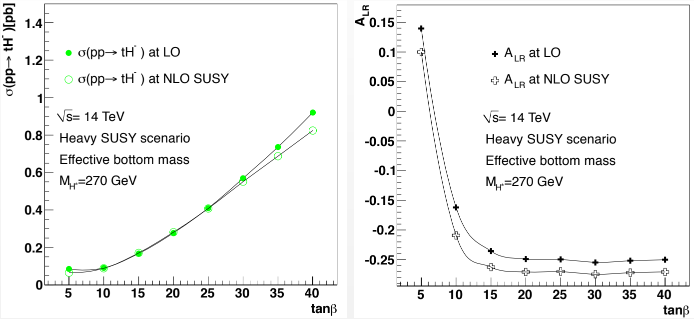
- NLO SUSY QCD corrections sizeable and negative for large $\tan\beta$, $\Delta\sigma_{\rm tot}/\sigma_{\rm tot} \simeq -15, -20\%$ (Dittmaier *et al.*, Phys.Rev. **D83** (2011) 055005)
- NLO EW corrections also negative and decreasing for large $\tan\beta$ (Beccaria *et al.*, Phys.Rev. **D80** (2009) 053011)

Impact of the SUSY spectrum:

- NLO EW corrections enhanced in a light SUSY spectrum
- The bulk of SUSY corrections accounted for in the effective Δ_b approximation, $m_b \to m_b/(1-\Delta_b)$, for heavy SUSY spectrum

SUSY results

The effect of SUSY NLO corrections is hardly seen on the production cross section $\sigma(bg \to tH^-)$:



Sizeable correction in the asymmetry: allow to distinguish between SUSY and non–SUSY Type II 2HDM

We have used mSUGRA scenario of type LS2: $m_0 = 300$ GeV, $m_{1/2} = 150$ GeV, $A_0 = -500$ GeV, $\mu > 0$ (see Beccaria *et al.*, Phys.Rev **D80** (2009) 053011)

Karlsruher Institut für Technologie

Summary

Top–charged Higgs production at the LHC:

- Rich Higgs sector in Two Higgs doublet models: two CP–even neutral Higgs h, H, one CP–odd neutral Higgs A and 2 charged Higgs $H^{\pm}$
- We can define a **top polarization asymmetry** A_{LR} in the charged Higgs production channel $bg \to tH^{-}$ which:
  - is nearly **insensitive to scale uncertainty**
  - **hardly depends on the PDF choice**, implying that the PDF uncertainty is very small
- A_{LR} helps to **distinguish large** $\tan\beta$ **and low** $\tan\beta$ **regimes** and type II models versus type I models (except in the low $\tan\beta$ region)
- The SUSY corrections are sizeable: **we can distinguish between SUSY and non-SUSY 2HDMs**

We then have good prospects to have a clean measure of the parameter $\tan\beta$ **at the LHC**

Karlsruher Institut für Technologie