# Associated Production of Top Quarks and Charged Higgs Bosons at the LHC

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# Outline

# The charged Higgs boson as a way to probe BSM physics

## The Project

(E. Laenen[1], M. Klasen[2], K. Kovarik[2], T. Plehn[3],C. Weydert[2], C. White[1])

Step 1: **Calculate the production cross section for $tH^-$ at the LHC with NLO QCD corrections using the Catani Seymour dipole formalism**

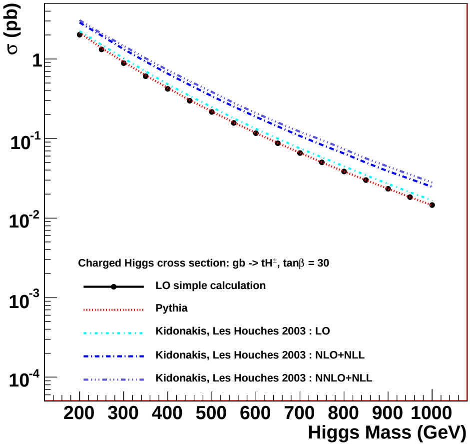
Step 2: Implement the process in a NLO Monte Carlo event generator (MC@NLO)

Step 3: Use the simulations for data analysis (at least for preparation) with the ATLAS detector

1: NIKHEF (Amsterdam), 2: LPSC (Grenoble), 3: ITP (Heidelberg)

# Existing vs. new calculations

- Shou-Hua Zhu (2001) [hep-ph/0112109]
- Tilman Plehn (2002) [hep-ph/0206121]
  - SUSY loop contributions are found to be negligible.
  - Both use phase-space slicing. Drawbacks: logarithmic dependence on the cut-off parameter, not optimized for a Monte Carlo generator.
  - $(10^{-2} < \sigma < 1)$ pb
  - $1.2 < \text{K-factor} < 1.5$



# Where does the charged Higgs boson come from?

- The Two-Higgs-Doublet Model (2HDM)
  - 2 complex $SU(2)_L$ scalar doublet fields $\phi_1$ and $\phi_2$ ($Y = 1$)

$$\phi_1 = \begin{pmatrix} \phi_1^0 \\ \phi_1^- \end{pmatrix} = \begin{pmatrix} \varphi_1 + i\varphi_2 \\ \varphi_3 + i\varphi_4 \end{pmatrix} \quad \phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix} = \begin{pmatrix} \varphi_5 + i\varphi_6 \\ \varphi_7 + i\varphi_8 \end{pmatrix} \quad \text{8 d.o.f.}$$

  - EWSB

$$< \phi_1 >= \begin{pmatrix} v_1 \\ 0 \end{pmatrix} \quad < \phi_2 >= \begin{pmatrix} 0 \\ v_2 \end{pmatrix} \rightarrow \tan\beta = \frac{v_2}{v_1} \quad \text{3 d.o.f.} \rightarrow m_{W^\pm}, m_Z$$

$\rightarrow$ 5 physical Higgs bosons $h^0, H^0, A^0, H^\pm$

- Charged Higgs boson coupling

$$\mathcal{L} = \frac{g V_{ij}^{CKM}}{\sqrt{2} m_W} H^+ \bar{u}_i \left( \frac{m_{u_i}}{\tan\beta} P_L + m_{d_j} \tan\beta P_R \right) d_j + h.c.$$

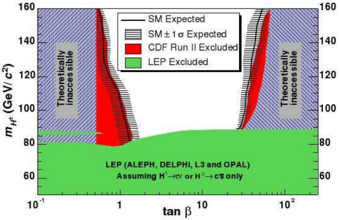
with $P_{R/L} = 1/2(1 \pm \gamma^5)$

# Why are we doing this?

## Theoretical constraints

- $\rho = \frac{m_W^2}{m_Z^2 \cos\theta_W} = 1$ automatically satisfied (at tree level) for Higgs singlets and doublets
- Avoid Flavor Changing Neutral Currents (FCNC)
  Impose the structure of the coupling (Glashow-Weinberg theorem)

## Experimental constraints



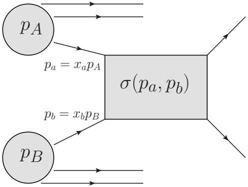

## Some advantages of Charged Higgs Physics

- 2HDM minimal extension of the SM Higgs sector
- Mandatory Higgs sector extension if you believe in SUSY
- Enhanced coupling to heavy particles $\rightarrow$ interesting probe for top physics

# QCD cross section at NLO (I)

- Hadronic cross section

$$\sigma(p_A, p_B) = \sum_{a,b} \int_0^1 dx_a f_{a/A}(x_a, \mu_F^2) \int_0^1 dx_b f_{b/B}(x_b, \mu_F^2) \sigma_{ab}(p_a, p_b)$$




*Factorization theorem*
long-distance physics→ non perturbative → parton distribution functions $f_{i/I}$
short-distance physics → perturbative → partonic cross section

- Partonic cross section

$$\sigma_{ab}(p_a, p_b) = \sigma_{ab}^{LO}(p_a, p_b) + \sigma_{ab}^{NLO}(p_a, p_b; \mu_F^2)$$

- NLO cross section

$$\sigma^{NLO} = \int_{m+1} d\sigma^R + \int_m d\sigma^V + \int_m d\sigma^C$$

- Soft poles cancel between $R$ and $V$ (Bloch-Nordsieck)
- Collinear initial state singularities of $R + V$ cancel with $C$ $\rightarrow \sigma^{NLO}$ finite!

# QCD cross section at NLO (II)

- Problem

$$\sigma^{NLO} = \int_{m+1} d\sigma^R + \int_m d\sigma^V + \int_m d\sigma^C$$

  We need to separate the pieces in order to do the integration, since they involve different phase spaces.

- (Some) Solutions
  - phase space slicing
  - Frixione-Kunszt-Signer formalism
  - Catani-Seymour dipole subtraction

# The **massive** Catani-Seymour dipole subtraction formalism

- Numerically integrable cross section

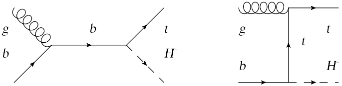
$$\sigma^{NLO} = \int_{m+1} \left[ \left( d\sigma^{R} \right)_{\epsilon=0} - \left( d\sigma^{A} \right)_{\epsilon=0} \right] + \int_{m} \left[ d\sigma^{V} + \int_{1} d\sigma^{A} \right]_{\epsilon=0}$$

  Define an auxiliary term $d\sigma^{A}$ which has the same pole structure as $R$ ( $\rightarrow$ local counterterm ) and is analytically integrable over the singular one-particle subspace.

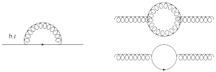
- Since the divergencies come from universal splitting kernels $\rightarrow$ process-independent method!

# Feynman Diagrams for the partonic cross section (I)

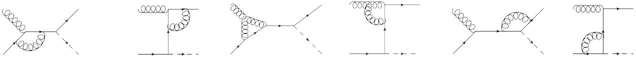
- LO contributions: $gb \rightarrow tH^-$ (s- and t-channel)



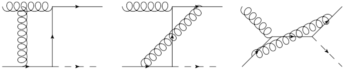

- NLO contributions: virtual contributions
  - Self-energies




  - Vertex corrections



  - Boxes



# UV-Renormalization

- Virtual part of the cross section $d\sigma^V = \frac{1}{\mathcal{F}} 2Re(\mathcal{M}^V \mathcal{M}^B) dPS^{(2)}$
- Dimensional Regularization: $D = 4 \rightarrow D = 4 - 2\epsilon$ dimensions
- Renormalization
  - Counterterms by redefining the parameters in the Lagrangian $(g_s, m, g_{yuk})$
    Schemes: On-shell for the top quark, $\bar{MS}$ for the b quark

$$d\sigma^V(\epsilon_{uv}^{-1}, \epsilon_{IR}^{-2}, \epsilon_{IR}^{-1}) \rightarrow d\sigma^V(\epsilon_{IR}^{-2}, \epsilon_{IR}^{-1})$$

# Virtual contributions

- Double and simple poles in $\epsilon$ after UV-Renormalization

$$d\sigma^V = \frac{\alpha_s}{2\pi}\frac{(4\pi)^\epsilon}{\Gamma(1-\epsilon)}\left(\frac{\mu^2}{m_t^2}\right)^\epsilon\left(\frac{A_2}{\epsilon^2}+\frac{A_1}{\epsilon}+A_0\right)d\sigma^B_{4-2\epsilon}$$

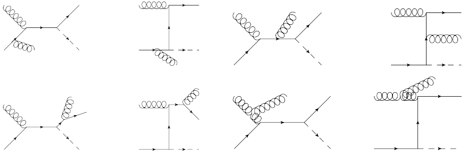
$$\begin{aligned}
A_2 &= \frac{1}{2N_C}-\frac{3}{2}N_C \\
A_1 &= \frac{1}{4N_C}\left[5-4\ln\left(\frac{m_t^2-u}{m_t^2}\right)\right] \\
&+ \frac{N_C}{12}\left[-37+12\ln\left(\frac{s}{m_t^2}\right)+12\ln\left(\frac{m_t^2-t}{m_t^2}\right)\right] \\
&+ \frac{1}{3}N_F
\end{aligned}$$

- Dipole for the virtual part

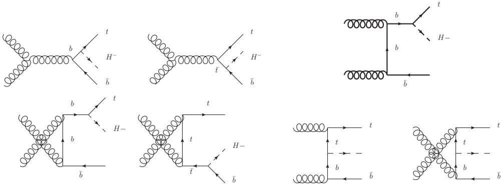
$\int_1 d\sigma^A = d\sigma^B \bigotimes \mathbf{I}$ with $\mathbf{I} = -\frac{\alpha_s}{2\pi}\frac{(4\pi)^\epsilon}{\Gamma(1-\epsilon)}\left(\frac{\mu^2}{m_t^2}\right)^\epsilon\left(\frac{A_2}{\epsilon^2}+\frac{A_1}{\epsilon}+A_0'\right)$

# Feynman Diagrams for the partonic cross section (II)

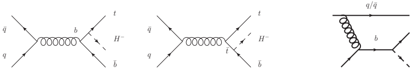
- NLO contributions: Real Emissions
  - $gb \to tH^- g$



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




  - $q\bar{q} \to tH^- \bar{b}$, $q(\bar{q})b \to tH^- q(\bar{q})$



# A Real Emission Result

- Example of the double pole structure of $gb \to tH^- g$

$$|\mathcal{M}_{2\to3}|^2 \propto |\mathcal{M}_{2\to2}|^2 \left[\frac{1}{N_C}\left(\frac{m_t^2}{s_4^2} - \frac{t_1}{s_4 t'}\right) + N_C\left(\frac{s}{t' u'} + \frac{u_1}{s_4 t'} - \frac{m_t^2}{s_4^2}\right)\right]$$

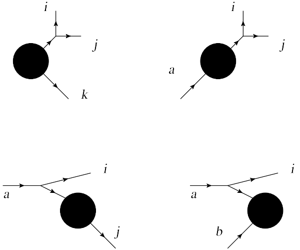
where $s_4, t_1, u_1, t', u'$ are Mandelstam variables for the $2 \to 3$ process.

# The dipoles for the real part

- General structure

FS emitter, FS spectator $\mathcal{D}_{ij,k}$

FS emitter, IS spectator $\mathcal{D}_{ij}^{a}$




IS emitter, FS spectator $\mathcal{D}_{j}^{ai}$

IS emitter,IS spectator $\mathcal{D}^{ai,b}$

For a specific pole $\rightarrow$ collect contributions from all the spectators $\rightarrow$ color sub-structures rather than pole sub-structures

- $gb$ initial states: $\mathcal{D}_{gt}^{g}$, $\mathcal{D}_{gt}^{b}$, $\mathcal{D}_{t}^{gg}$, $\mathcal{D}^{gg,b}$, $\mathcal{D}_{t}^{bg}$, $\mathcal{D}^{bg,g}$
- $gg$ initial states: $\mathcal{D}^{g_1 b,g_2}$, $\mathcal{D}_{t}^{g_1 b}$, $\mathcal{D}^{g_2 b,g_1}$, $\mathcal{D}_{t}^{g_2 b}$
- $q(/\bar{q})b$ initial states: $\mathcal{D}^{qq,b}$, $\mathcal{D}_{t}^{qq}$

# Example of a dipole

$$\mathcal{D}^{b}_{gt} = -\frac{1}{2p_g \cdot p_t}\frac{1}{x} < \cdots, \tilde{t}, \cdots; \tilde{b}, \cdots | \frac{\mathbf{T_a} \cdot \mathbf{T_{\tilde{t}}}}{\mathbf{T^2_{\tilde{t}}}} \mathbf{V^b_{gt}} | \cdots, \tilde{t}, \cdots; \tilde{b}, \cdots >$$

- $\frac{1}{2p_g \cdot p_t}$ responsible for the divergence in the soft/(quasi)-collinear limit
- $\frac{1}{x}$ permits a smooth interpolation between soft and (quasi)-collinear
- $\frac{\mathbf{T_a} \cdot \mathbf{T_{\tilde{t}}}}{\mathbf{T^2_{\tilde{t}}}}$ determines the color structure
- $V^b_{gt}$ contains the Altarelli-Parisi splitting kernel
- $< \cdots, \tilde{t}, \cdots; \tilde{b}, \cdots | \cdots | \cdots, \tilde{t}, \cdots; \tilde{b}, \cdots >$ is the Born amplitude squared with modified kinematics

# Conclusions and outlook

- Calculation
  - Virtual and real emission amplitudes calculated and cross-checked.
  - Integration with dipoles converges.
  - Final checks are in progress.
- Implementation in MC@NLO
  - In progress (relies heavily on the already available $Wt$ implementation ).