

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

Carole Weydert

LPSC Grenoble

PhD supervisors: B. Clément, M. Klasen

GDR Saclay

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 - Conclusion
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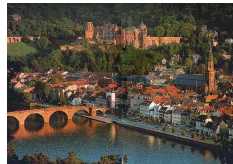
Collaboration



(a) Amsterdam



(b) Grenoble



(c) Heidelberg

E. Laenen,
G. Stavengar
C. White

M. Klasen
K. Kovarik
CW

T. Plehn

Charged Higgs production cross section @NLO

- Existing calculations

Shou-Hua Zhu (2001) [[hep-ph/0112109](#)],

Tilman Plehn (2002) [[hep-ph/0206121](#)]

- Results

- most optimistic choice of parameters gives ($10^{-2} < \sigma < 1$) pb
- important NLO QCD corections $1.2 < K\text{-factor} < 1.5$
- SUSY loop contributions negligible
- Phase-space slicing:
logarithmic dependence on the cut-off parameter, not optimized for a Monte Carlo (MC) event generator.

- Where we come in:

Do the NLO calculation again with another regularisation method and implement it in a MC!

The Charged Higgs Boson

- The 2 Higgs Doublet Model (2HDM)

Standard Model

$$\phi = \begin{pmatrix} \varphi_1 + i\varphi_2 \\ \varphi_3 + i\varphi_4 \end{pmatrix}$$

4 d.o.f.

$$\langle \phi \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}$$

→ 1 physical Higgs boson
 h^0

2HDM

$$\phi_1 = \begin{pmatrix} \varphi_1 + i\varphi_2 \\ \varphi_3 + i\varphi_4 \end{pmatrix} \quad \phi_2 = \begin{pmatrix} \varphi_5 + i\varphi_6 \\ \varphi_7 + i\varphi_8 \end{pmatrix}$$

8 d.o.f.

electroweak symmetry breaking

3 d.d.l. → m_{W^\pm}, m_Z

$$\langle \phi_1 \rangle = \begin{pmatrix} v_1 \\ 0 \end{pmatrix} \quad \langle \phi_2 \rangle = \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$$

→ $\tan \beta = \frac{v_2}{v_1}$

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

- Charged Higgs boson coupling (type II)

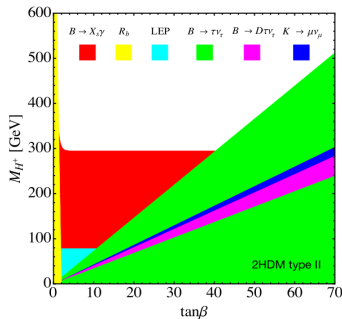
$$\mathcal{L} \propto H^+ \bar{u}_i \left(\frac{m_{u_i}}{\tan \beta} P_L + m_{d_j} \tan \beta P_R \right) d_j + \text{h.c.} \quad \text{with } P_{R/L} = 1/2(1 \pm \gamma^5)$$

Why are we doing this?

Experimental constraints (Courtesy of U. Haisch)

Theoretical constraints

- $\rho = \frac{m_W^2}{m_Z^2 \cos^2 \theta_W} = 1$ satisfied at leading order for singlets and doublets.
- Avoid flavor changing neutral currents (FCNC) by imposing the structure of the coupling to type II. (Glashow-Weinberg theorem)



Motivations for the 2HDM

- It is the **minimal extension** of the SM scalar sector.
- It is a **mandatory extension** if you want SUSY to be realised in Nature.

QCD cross section at NLO

● Hadronic cross section

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

Factorisation theorem



- * long distance physics \rightarrow non perturbative \rightarrow parton distribution functions $f_{i/j}$ (PDFs)
- * short distance physics \rightarrow perturbative \rightarrow partonic cross section

● Partonic cross section

$$\sigma_{ab} = \int \frac{1}{\mathcal{F}} |g_s \mathcal{M}_B + g_s^2 \mathcal{M}_R + g_s^3 \mathcal{M}_V + \dots|^2 dPS$$

where \mathcal{F} is the flux, g_s the strong coupling, \mathcal{M} the matrix element and dPS the final state phase space.

Perturbative series in $\alpha_s = \frac{g_s^2}{4\pi}$:

$$\sigma^{(NLO)} = \alpha_s \sigma^{LO} + \alpha_s^2 \sigma^{NLO} + \mathcal{O}(\alpha_s^3)$$

Leading Order LO /Born: $\mathcal{M}_B \mathcal{M}_B$

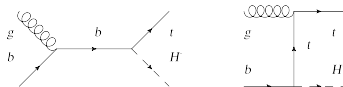
Next to Leading Order NLO : $\mathcal{M}_B \mathcal{M}_V$ et $\mathcal{M}_R \mathcal{M}_R$

- **NLO cross section** $\sigma^{NLO} = \sigma^V + \sigma^R$, σ^R : real contributions, σ^V : virtual contributions

Virtual contributions

- LO/Born:

Process $2 \rightarrow 2$: $gb \rightarrow tH^-$ (s- and t-channel)



- NLO: virtual contributions

Process $2 \rightarrow 2$: $gb \rightarrow tH^-$ + exchange of a virtual particle

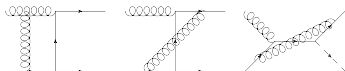
- Self-energies (bubbles)



- Vertex corrections (triangles)



- Boxes

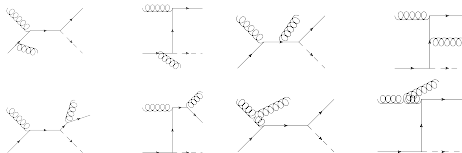


Real emission contributions

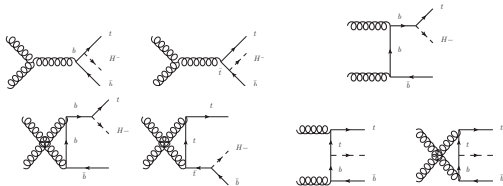
- NLO: real emission

Process 2 \rightarrow 3

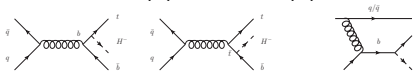
- $gb \rightarrow tH^-g$



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



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



Computing the NLO cross section

A job well done ...



- .. but ...

$$\sigma^{NLO} = \int_{2+1} d\sigma^R + \int_2 d\sigma^V$$

σ^{NLO} is finite, σ^R and σ^V are divergent and we need to separate the pieces in order to do the integration, since they involve different phase spaces.

- (Some) Solutions
 - **Phase space slicing**
separate the singular regions using a cut-off parameter in phase space
 - **Frixione-Kunszt-Signer formalism (FKS)**
extract the pole structure from the real part
 - **Catani-Seymour dipole subtraction (CS)**

Collaboration



(d) Amsterdam



(e) Grenoble



(f) Heidelberg

FKS

CS

phase space slicing

The massive Catani-Seymour dipole subtraction formalism

- Numerically integrable cross section

$$\sigma^{NLO} = \int_{m+1} [(d\sigma^R)_{\epsilon=0} - (d\sigma^A)_{\epsilon=0}] + \int_m \left[d\sigma^V + \int_1 d\sigma^A \right]_{\epsilon=0}$$

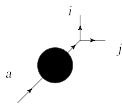
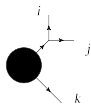
Define an auxiliary term $d\sigma^A$ which has the same pole structure as R (\rightarrow local counterterm) and is analytically integrable over the singular one-particle subspace.

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

Dipole construction

FS emitter, FS spectator

$$\mathcal{D}_{ij,k}$$

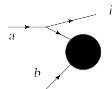
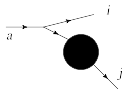


FS emitter, IS spectator

$$\mathcal{D}_{ij}^a$$

IS emitter, FS spectator

$$\mathcal{D}_j^{ai}$$



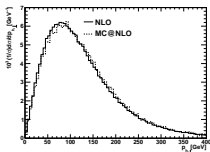
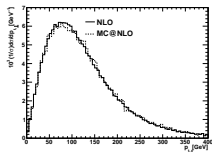
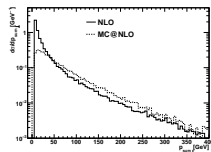
IS emitter, IS spectator

$$\mathcal{D}^{ai,b}$$

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

tH^- in MC@NLO

- FKS dipoles implementation by Amsterdam, relies heavily on Wt , all mass range available for m_{H^-} .
For $m_{H^-} < m_t$: diagram subtraction/removal
- Details can be found in [Weydert et al. 0912.3430 \[hep-ph\]](#)

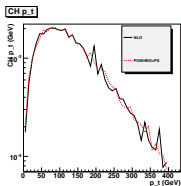
(g) charged Higgs p_T (h) top p_T (i) CH+top p_T

- Major drawbacks of MC@NLO
 - negative weight events
 - Parton-shower dependent, only HERWIG available

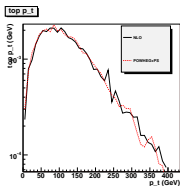
tH^- in POWHEG-BOX

1002.2581 [*hep - ph*]

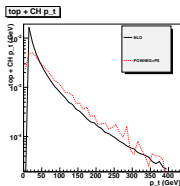
- User-friendly implementation framework
 - provide polarized Born $B^{\mu\nu}(p^i)$, finite part of the virtual corrections $V_{fin}(p^i)$ and the real corrections $R(p^i)$
- automated calculation of FKS-dipoles
- coupled to HERWIG for the parton shower, FASTJET for jet reconstruction to compare with the MC@NLO implementation
- currently testing different parameter sets



(j) charged Higgs p_T



(k) top p_T



(l) CH+top p_T

- General comparison between MC@NLO and POWHEG see Paolo Nason's talk tomorrow!

Summary

- Calculation
 - NLO codes using phase space slicing, FKS dipoles and CS dipoles all agree
- Implementation in ...
 - ... MC@NLO: should be available soon
 - ... POWHEG: final checks are in progress

Outlook

- study PS and jet reconstruction
- compare to existing implementations
- add the $m_{H^-} < m_t$ case (diagram subtraction/removal)
- Resummation

Backup slides

UV-Renormalization

- Virtual part of the cross section $d\sigma^V = \frac{1}{\mathcal{F}} 2\text{Re}(\mathcal{M}^V \mathcal{M}^B) dPS^{(2)}$
- 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 ϵ after UV-Renormalization

$$d\sigma^V \propto \left(\frac{A_2}{\epsilon^2} + \frac{A_1}{\epsilon} \right) d\sigma_{4-2\epsilon}^B + A_0$$

$$A_2 = \frac{1}{2N_C} - \frac{3}{2}N_C$$

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

where s, t, u are the Mandelstam variables for a $2 \rightarrow 2$ process (kinematics).

A Real Emission Result

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

$$|\mathcal{M}_{2 \rightarrow 3}|^2 \propto |\mathcal{M}_{2 \rightarrow 2}|^2 \left[\frac{1}{N_C} \left(\frac{m_t^2}{s_4^2} - \frac{t_1}{s_4 t'} \right) + N_C \left(\frac{s}{t' u'} + \frac{u_1}{s_4 t'} - \frac{m_t^2}{s_4^2} \right) \right]$$

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

Virtual and real dipoles

- Dipole for the virtual part

$$\int_1 d\sigma^A = d\sigma^B \otimes \mathbf{I} \text{ with } \mathbf{I} = -\frac{\alpha_s}{2\pi} \frac{(4\pi)^\epsilon}{\Gamma(1-\epsilon)} \left(\frac{\mu^2}{m_t^2}\right)^\epsilon \left(\frac{A_2}{\epsilon^2} + \frac{A_1}{\epsilon} + A'_0\right)$$

- Dipoles for the real part

- 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: $\mathcal{D}^{g_1 b, g_2}$, $\mathcal{D}_t^{g_1 b}$, $\mathcal{D}^{g_2 b, g_1}$, $\mathcal{D}_t^{g_2 b}$
- $q(/q) b$ initial states: $\mathcal{D}^{qq,b}$, \mathcal{D}_t^{qq}

Example of a dipole

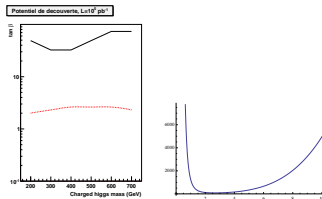
$$\mathcal{D}_{gt}^b = -\frac{1}{2p_g \cdot p_t} \frac{1}{x} \langle \dots, \tilde{t}, \dots; \tilde{b}, \dots \mid \frac{\mathbf{T}_a \cdot \mathbf{T}_{\tilde{t}}}{\mathbf{T}_{\tilde{t}}^2} \mathbf{V}_{gt}^b \mid \dots, \tilde{t}, \dots; \tilde{b}, \dots \rangle$$

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

Outlook

- Experiment

- Discovery potential for $\sqrt{s} = 14\text{TeV}$ with a very basic analysis for $H^+ \rightarrow tb$
→ very challenging channel, high luminosity mandatory



(m) Discovery potential (n) $\tan\beta$ dependence

- Studies in CMS and ATLAS also for $H^- \rightarrow \tau\nu$

→ very challenging topology in either case (b-tag, tau identification, neutrinos, huge QCD background, ...) What we can/plan to do with the first data: background studies