Associated Production of Top Quarks and Charged Higgs Bosons @LHC @NLO

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   - The Catani-Seymour dipoles
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4. Conclusion
   - Conclusion
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Collaboration

(a) Amsterdam

(b) Grenoble

(c) Heidelberg

E. Laenen
G. Stavengar
C. White

M. Klasen
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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 corrections $1.2 < \mathrm{K\text{-}factor} < 1.5$
  - 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	2HDM
$\phi = \begin{pmatrix} \varphi_1 + i\varphi_2 \\ \varphi_3 + i\varphi_4 \end{pmatrix}$	$\phi_1 = \begin{pmatrix} \varphi_1 + i\varphi_2 \\ \varphi_3 + i\varphi_4 \end{pmatrix}$ $\phi_2 = \begin{pmatrix} \varphi_5 + i\varphi_6 \\ \varphi_7 + i\varphi_8 \end{pmatrix}$
4 d.o.f.	8 d.o.f.

electroweak symmetry breaking

3 d.o.f. $\rightarrow m_{W^\pm}, m_Z$

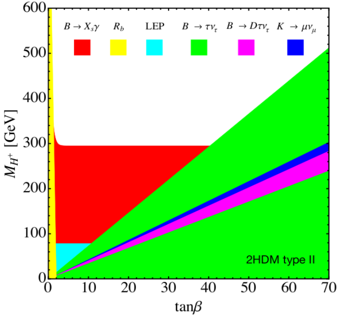
$< \phi >= \begin{pmatrix} 0 \\ v \end{pmatrix}$	$< \phi_1 >= \begin{pmatrix} v_1 \\ 0 \end{pmatrix}$ $< \phi_2 >= \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$
	$\rightarrow \tan\beta = \frac{v_2}{v_1}$
$\rightarrow$ 1 physical Higgs boson h^0	$\rightarrow$ 5 physical Higgs bosons $h^0, H^0, A^0, H^\pm$

- Charged Higgs boson coupling (type II)

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

Constraints for the 2HDM

Experimental constraints (Courtesy of U. Haisch)



Theoretical constraints

- $\rho = \frac{m_W^2}{m_Z^2 \cos\theta_W} = 1$ 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

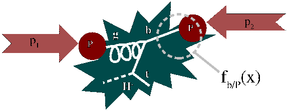
- It is the minimal extension of the SM scalar sector.
- It is a mandatory extension if you want SUSY to be realised in Nature.

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 → non perturbative → parton distribution functions $f_{i/I}$ (PDFS)
  * short distance physics → perturbative → partonic cross section

- Partonic cross section

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

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

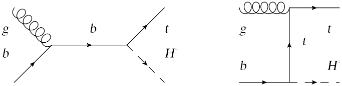
$$\sigma^{(NLO)} = \alpha_s \sigma^{LO} + \alpha_s^2 \sigma^{NLO} + \mathcal{O}(\alpha_s^3)$$

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

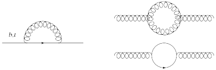
- NLO cross section $\sigma^{NLO} = \sigma^V + \sigma^R$, σ^R : real contributions, σ^V : virtual contributions

Virtual contributions

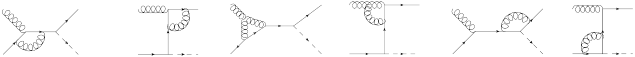
- LO/Born:
  Process 2 $\rightarrow$ 2: $gb \rightarrow tH^-$ (s- and t-channel)



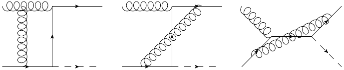
- NLO: virtual contributions
  Process 2 $\rightarrow$ 2: $gb \rightarrow tH^-$ + exchange of a virtual particle
  - Self-energies (bubbles)



  - Vertex corrections (triangles)



  - Boxes



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 ϵ after UV-Renormalization

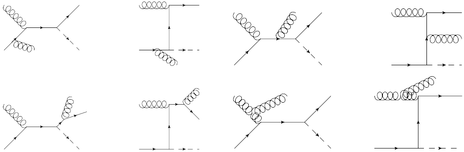
$$d\sigma^V \propto \left(\frac{A_2}{\epsilon^2} + \frac{A_1}{\epsilon} \right) d\sigma^B_{4-2\epsilon} + A_0$$

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

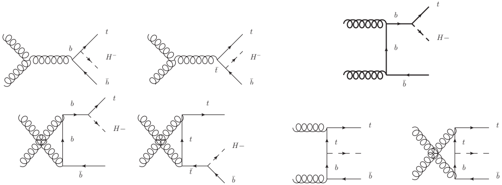
where s, t, u are the Mandelstam variables for a $2 \rightarrow 2$ process (kinematics).

Real emission contributions

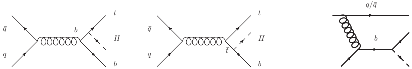
- NLO: real emission
  Process $2 \rightarrow 3$
  - $gb \rightarrow tH^- g$



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



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



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.

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)**

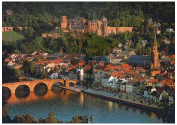
Collaboration

(d) Amsterdam

FKS

(e) Grenoble

CS



(f) Heidelberg

phase space slicing

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!

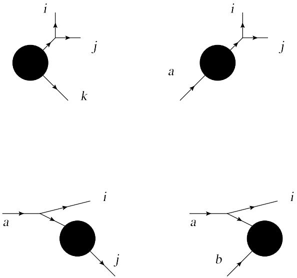
Dipole construction

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

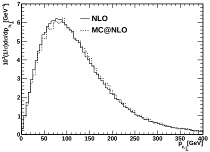
Virtual and real dipoles

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

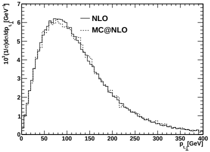
- Dipoles for the real part
  - gb initial states: $\mathcal{D}^g_{gt}$, $\mathcal{D}^b_{gt}$, $\mathcal{D}^{gg}_t$, $\mathcal{D}^{gg,b}$, $\mathcal{D}^{bg}_t$, $\mathcal{D}^{bg,g}$
  - gg initial states: $\mathcal{D}^{g_1 b, g_2}$, $\mathcal{D}^{g_1 b}_t$, $\mathcal{D}^{g_2 b, g_1}$, $\mathcal{D}^{g_2 b}_t$
  - $q(/\bar{q})b$ initial states: $\mathcal{D}^{qq,b}$, $\mathcal{D}^{qq}_t$

tH^- in MC@NLO

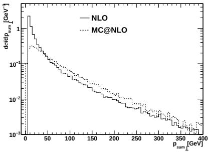
- FKS dipoles implementation by Amsterdam, relies heavily on Wt, all mass range available for m_{H^-}.
  For $m_{H^-} < m_t$: diagram subtraction/removal
- Details can be found in Weydert et al. 0912.3430[hep-ph]



(g) charged Higgs p_T



(h) top p_T



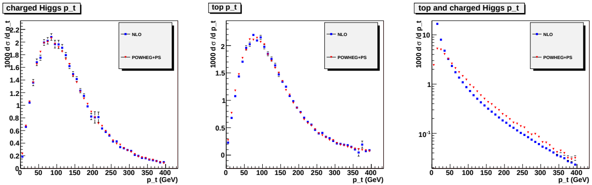
(i) CH+top p_T

- Major drawbacks of MC@NLO
  - negative weight events
  - Parton-shower dependent, only HERWIG available at the moment (PYTHIA under construction)

tH^- in POWHEG-BOX (Preliminary!!!)

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

Summary

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

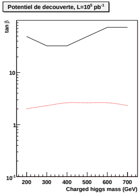
Example of a dipole

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

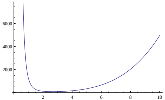
- $\frac{1}{2p_g \cdot p_t}$ responsible for the divergence in the soft/(quasi)-collinear limit
- $\frac{1}{x}$ permits a smooth interpolation between soft and (quasi)-collinear
- $\frac{\mathbf{T_a} \cdot \mathbf{T_{\tilde{t}}}}{\mathbf{T}_{\tilde{t}}^2}$ determines the color structure
- V_{gt}^{b} 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

Outlook

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



(m) Discovery potential



(n) $\tan\beta$ dependence

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

$\rightarrow$ 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