

# Implementation of the process $gg(q\bar{q}) \rightarrow \bar{t}bH^+$ in PYTHIA

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## Masses in the Standard Model

Before spontaneous symmetry breaking:

$$\begin{array}{l} \text{Bosons:} \\ \text{Fermions:} \end{array} \begin{array}{l} \left( \begin{array}{c} \phi_1 \\ \phi_2 \end{array} \right) \\ \left( \begin{array}{c} \nu_{eL} \\ e_L \end{array} \right) \end{array} \begin{array}{l} W_\mu \\ \left( \begin{array}{c} u_L \\ d_L \end{array} \right) \end{array} \begin{array}{l} W_\mu^\dagger \\ e_R \end{array} \begin{array}{l} W_{3\mu} \\ u_R \end{array} \begin{array}{l} B_\mu \\ d_R \end{array}$$

After spontaneous symmetry breaking:

$$\begin{array}{l} \text{Bosons:} \\ \text{Fermions:} \end{array} \begin{array}{l} h \\ e \end{array} \begin{array}{l} W_\mu^+ \\ \nu_L \end{array} \begin{array}{l} W_\mu^- \\ u \end{array} \begin{array}{l} Z_\mu^0 \\ d \end{array} \begin{array}{l} A_\mu \end{array}$$

## The Higgs mechanism

- One of the Higgs components gets a vacuum expectation value (vev)  $v$
- Three of the four scalar degrees of freedom are absorbed by the three massive vector fields
- The down-type fields get mass through coupling to the Higgs doublet  $\Phi$ , the up-type fields through coupling to  $\tilde{\Phi} = -i [\Phi^\dagger \tau_2]^\top$ .

## Supersymmetric extensions

In a supersymmetric Lagrangean, one cannot make the transformation  $\tilde{\Phi} = -i [\Phi^\dagger \tau_2]^T$  of the Higgs doublet



Must have (at least) **two Higgs doublets** to give mass to both up-type and down-type fields

This is an example of a type II **Two Higgs Doublet Model (2HDM)**

## Two Higgs Doublet Models

- 8 scalar degrees of freedom  $\implies$  5 Higgs particles:

$h, H^0, H^+, H^-, A$  (pseudoscalar)

- Two parameters in MSSM (7 in general 2HDM):

$\tan(\beta) = \frac{v_1}{v_2}$       Ratio of vev's for the doublets

$M_A$       One of the masses, usually the pseudoscalar

- Finding a charged Higgs would be a clear signal of physics beyond the Standard Model!

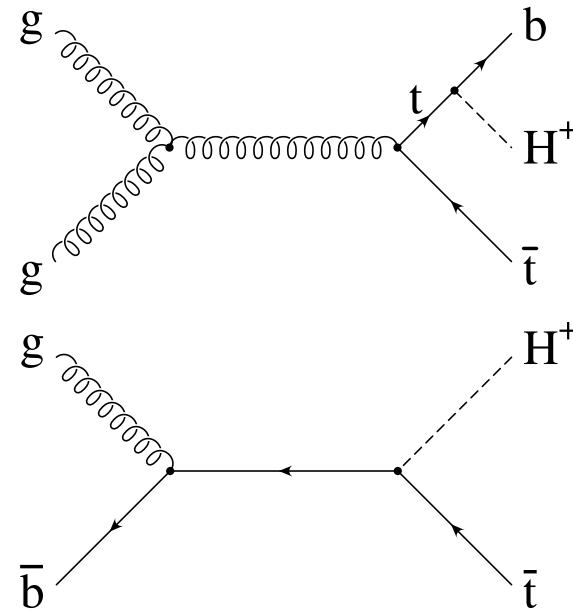
## Production of single charged Higgs

Three main production channels in  $pp$  ( $p\bar{p}$ ) collisions:

- $gg(q\bar{q}) \rightarrow t\bar{t} \rightarrow bH^+\bar{t} + \text{c.c.}$

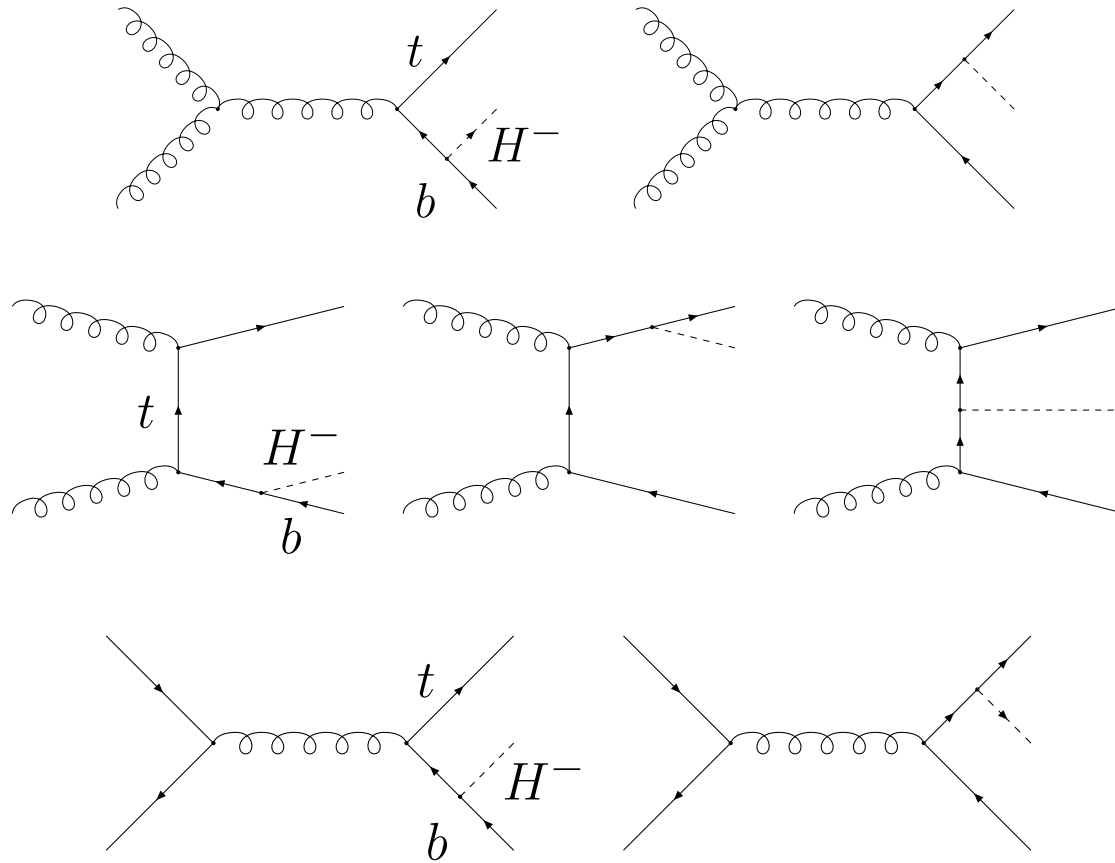
- $g\bar{b} \rightarrow \bar{t}H^+ + \text{c.c.}$

- $gg(q\bar{q}) \rightarrow \bar{t}bH^+ + \text{c.c.}$



see next slide...

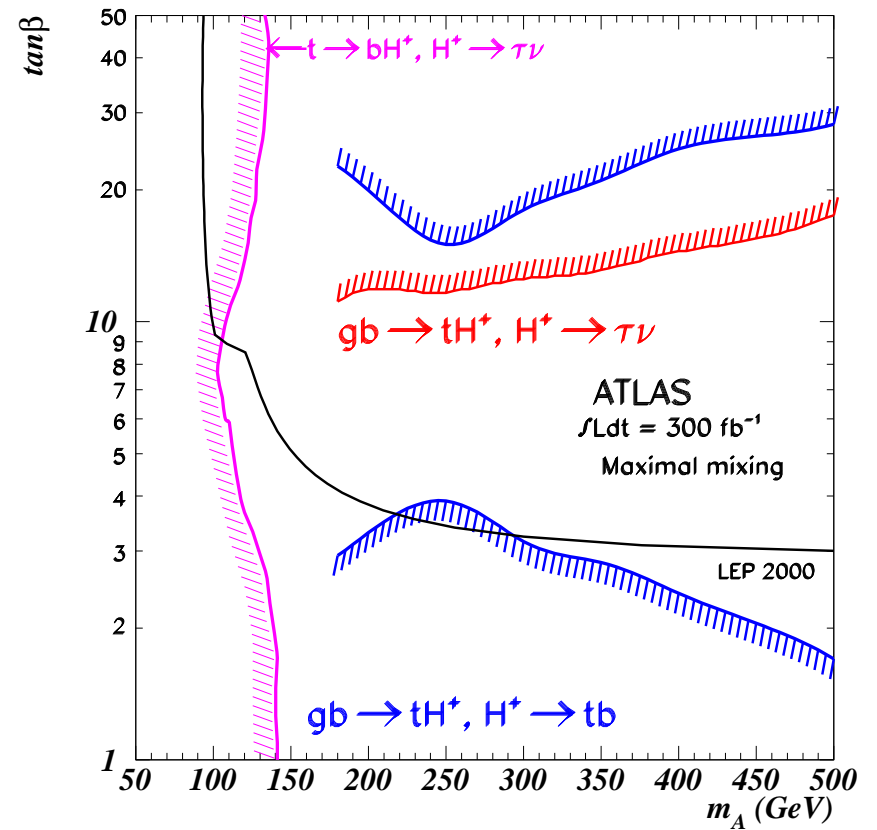
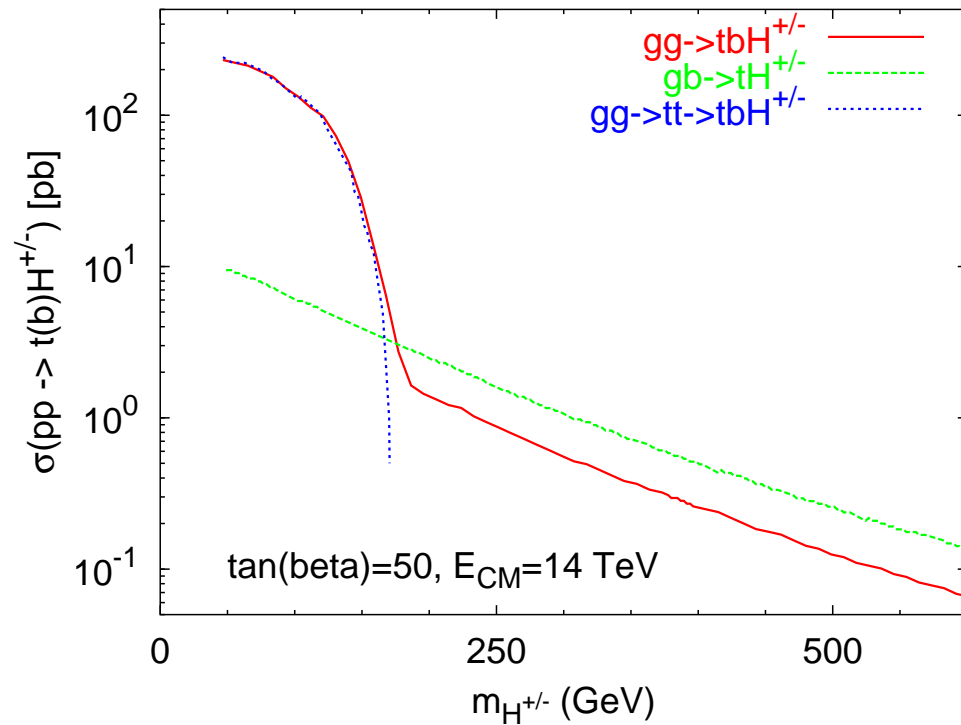
# Diagrams for $gg(q\bar{q}) \rightarrow \bar{t}bH^+$



## Importance of the $H^+$ production processes

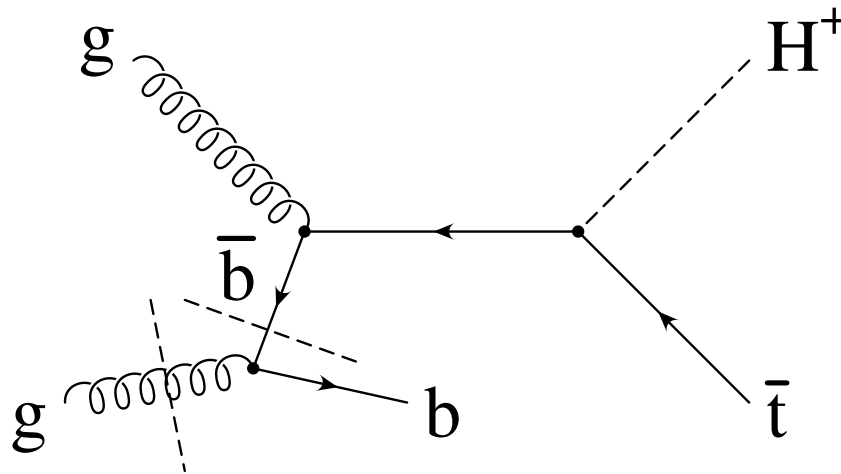
- $gg(q\bar{q}) \rightarrow t\bar{t} \rightarrow bH^+\bar{t}$  is an approximation of  $gg(q\bar{q}) \rightarrow \bar{t}bH^+$  which works well for small Higgs masses  $m_{H^+} < m_t$ , when the main contribution comes from  $t$  close to the mass shell
- For large Higgs masses,  $g\bar{b} \rightarrow \bar{t}H^+$  gives larger cross-section than  $gg(q\bar{q}) \rightarrow \bar{t}bH^+$  and similar  $p_\perp$ -distributions for the  $t$  and  $H^+$
- If one wants to tag the extra  $b$  quark for  $m_{H^+} > m_t$ ,  $gg(q\bar{q}) \rightarrow \bar{t}bH^+$  is necessary
- For  $H^+$  masses close to the  $t$  mass,  $gg(q\bar{q}) \rightarrow \bar{t}bH^+$  is necessary

# Importance of the $H^+$ production processes (contd.)



## Summing the $2 \rightarrow 2$ and $2 \rightarrow 3$ processes

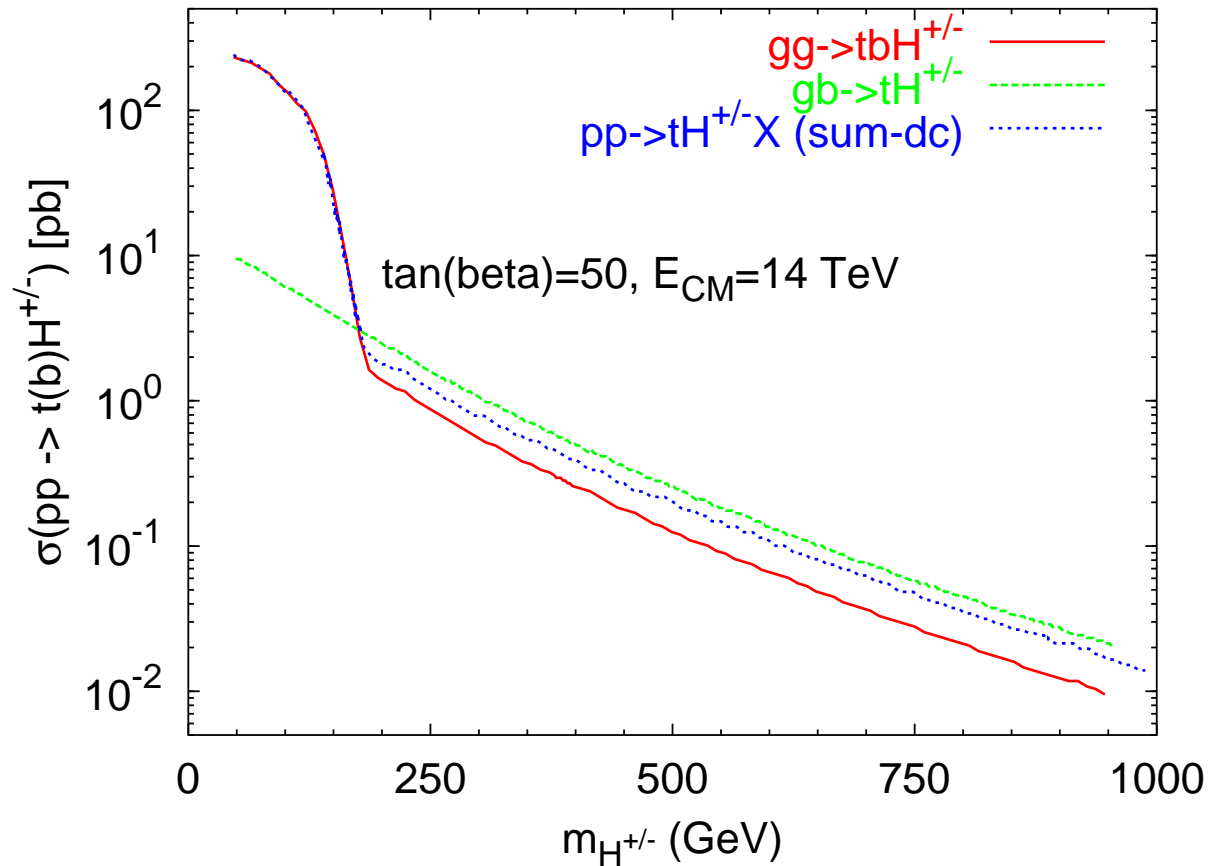
The  $g\bar{b} \rightarrow \bar{t}H^+$  ( $2 \rightarrow 2$ ) and  $gg \rightarrow \bar{t}bH^+$  ( $2 \rightarrow 3$ ) processes overlap when the  $b$  of the  $2 \rightarrow 3$  process is collinear with the beam



$\implies$  Must subtract **double counting term**.

Borzumati et al., Phys.Rev. D60,115011, Belyaev et al., hep-ph/0203031

## Summing the $2 \rightarrow 2$ and $2 \rightarrow 3$ processes (cont)



## 2 → 3 processes in PYTHIA

Phase space for a 2 → 3 process:

$$d(PS) = \left( \prod_{i=3}^5 \frac{1}{(2\pi)^3} \frac{d^3 p_i}{2E_i} \right) (2\pi)^4 \delta^{(4)}(p_3 + p_4 + p_5 - p_1 - p_2)$$

In PYTHIA:

$$d(PS) = \frac{1}{(2\pi)^5} \frac{\pi^2}{4\sqrt{\lambda_{\perp 34}}} dp_{\perp 3}^2 \frac{d\varphi_3}{2\pi} dp_{\perp 4}^2 \frac{d\varphi_4}{2\pi} dy_5 ,$$

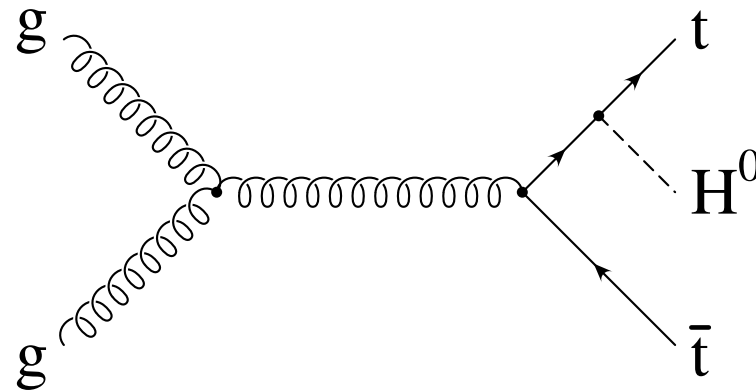
where  $\lambda_{\perp 34} = (m_{\perp 34}^2 - m_{\perp 3}^2 - m_{\perp 4}^2)^2 - 4m_{\perp 3}^2 m_{\perp 4}^2$

+ variables  $\tau = \frac{m_{H^+}^2}{s}$ ,  $\tau' = x_1 x_2$ ,  $y^* = \frac{1}{2} \ln \frac{x_1}{x_2}$

⇒ Events chosen from distribution in **8 variables**

## Implementation of $gg(q\bar{q}) \rightarrow \bar{t}bH^+$

I have basically followed the implementation of  $gg(q\bar{q}) \rightarrow \bar{t}tH^0$ ,



Difference: 3 final-state particles with different masses  
(first process in PYTHIA)

All features of existing processes, such as width of  $H^+$  mass.

## Activities so far

- Checks against Herwig and publications
- Efficiency tests: 10000 events with full fragmentation etc. ~ 16 min on standard PC,  $m_{H^+} = 250$  (670 tries/event)
- Test of differences between  $gg(q\bar{q}) \rightarrow t\bar{t} \rightarrow bH^+\bar{t}$  and  $gg(q\bar{q}) \rightarrow \bar{t}bH^+$  together with Johan Rathsman and Andre Sopczak
- Properly matching the  $2 \rightarrow 2$  and  $2 \rightarrow 3$  processes (work in progress)

## Results

Results on difference between  $gg(q\bar{q}) \rightarrow t\bar{t} \rightarrow bH^+\bar{t}$  and  $gg(q\bar{q}) \rightarrow \bar{t}bH^+$  at the Tevatron,  $m_{H^+} = 165$  GeV.

