Single top plus Higgs production at the LHC

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Outline

- Motivations
- Cross sections at hadron colliders
- $t$-channel production at the LHC
- Conclusions
The guest for an intermediate-mass Higgs at the LHC
study the relative phase of the couplings $W$ and the top 

The Higgs couples to both the (spacelike) $W$ and the top such as a forward jet

Shares similar dynamical features with single top production,

Interesting features:

Balistero and Medina (1993), Bordes and van Elst (1993), Diaz-Cruz and Sampaio (1992), Shilling and Summers (1992),

This process with the $h$ has been discussed by:

Consider single top production in the $W$-channel (spacelike $W$ boson)

t-channel Production
Other channels for single top + Higgs

The $s$-channel:

- Higgs couples to a timelike $W$ boson ($q^2 > 0$)
- Cross section is small at $pp$ colliders for single top only
- For an intermediate-mass Higgs, it gives the largest contribution at the Tevatron

The $W$-associated channel:

- Higgs couples to an on-shell $W$ boson ($q^2 = M_W$)
- Complicated final state
- Always smaller than the $t$-channel
Single Top + Higgs at the Tevatron

- $p\bar{p} @ \sqrt{s} = 2$ TeV
- the s-channel is favoured (valence quarks and anti-quarks)
- s-channel cross section is around $1/50$ of $\sigma(t\bar{t}h)$ for $m_h = 115$ GeV

Conclusion: cross section far too small to have any events produced in Run II
Single top + Higgs production at the LHC

- $pp \oplus \sqrt{s} = 14\text{ TeV}$
- the $t$-channel gives the largest contribution, about one order of magnitude smaller than $t\bar{t}h$ (note the different fall off, though)
- for $m_h < 120\text{ GeV}$ we expect a cross section of about 100 femtobarns
  $\Rightarrow$ no hope for $h \rightarrow \gamma\gamma$, but what about $h \rightarrow b\bar{b}$?
Interference in the t-channel

The interference is destructive and accounts for the smallness of the cross section.

\[ q' \quad W \quad h \quad t \]

\[ q \quad b \]
Unitarity cancellations in the t-channel

The largest contribution from the $t$-channel comes from the emission of longitudinal $W$’s. Using the effective-$W$ approximation:

For $s \sim -t \sim -u \sim E^2 \gg m_h^2, m_W^2, m_t^2$, each of the two diagrams behaves like

$$\mathcal{A} \sim g^2 \frac{m_t E}{m_W^2}$$

This entails a violation of unitarity at a scale $\Lambda \sim m_W^2/m_t g^2$. The divergent terms cancel if the following relation between the Higgs couplings holds:

$$\frac{g_W - W^+}{2} m_t + g_{tih} m_W = 0.$$ 

True in the standard model!
Interference in the s-channel

The interference is constructive. $th$ production is suppressed by around 1/11 compared to $q\bar{q} \rightarrow t\bar{t}h$. Part of it ($\sim 1/3$) is due to p.d.f. effects, the rest ($\sim 1/4$) is due to the smallness of the Higgs coupling to the bottom.
t-channel production with $h \to b\bar{b}$ at the LHC

To simulate the detector acceptance we have used:

| cut     | $p_b^T$ | $p_{\ell,\nu}^T$ | $p_j^T$ | $|\eta_{b,\ell}|$ | $|\eta_j|$ | $\Delta R_{ij}$ | $\sigma_{3b}$ |
|---------|---------|-----------------|---------|-----------------|----------|----------------|----------------|
| value   | 15 GeV  | 20 GeV          | 30 GeV  | 2.5             | 5        | 0.4            | 4.7 fb        |

Cuts applied to the $t$-channel signal, for $m_h = 115$ GeV.
Branching ratios $\text{Br}(h \to b\bar{b})$ as well as $\text{Br}(W \to \ell\nu)$ are included.
Detector efficiencies are not included.
The probability ($\frac{e}{\text{mc}^2} = 10\%$) of misidentifying a $t$-quark as a $b$-quark is included in the $t\bar{t}$ and $tZ$ cross sections. In the number of events, expected the $b$-tagging and lepton-tagging efficiencies are included ($\frac{e}{\text{mc}^2} = 60\%$). The $s$-quark jet is

<table>
<thead>
<tr>
<th>Event with $30 fb^{-1}$</th>
<th>00</th>
<th>970</th>
<th>27</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1 $\frac{f \bar{f}}{d} &lt; 2.4 \text{ GeV}$</td>
<td>77</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.0 $</td>
<td>m_{t\bar{t}} - m_{t\bar{t}}</td>
<td>&gt; 22 \text{ GeV}$</td>
<td>130</td>
<td></td>
</tr>
</tbody>
</table>

**Signal vs. Background with 3 $b$-tags**

**Selectable cuts**

- $tt\bar{t}$: reducible background
- $tt\bar{t}$: irreducible background
- $tZ$: reducible background
- $tZ$: irreducible background
<table>
<thead>
<tr>
<th>Events with 30 fb$^{-1}$</th>
<th>Detector cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2 3.2 18 11</td>
<td>$\nu &lt; 2.1 , \text{GeV}$</td>
</tr>
<tr>
<td>0.94 0.95 4.7 2.8</td>
<td>$p_{\text{T}} &lt; 25 , \text{GeV}$</td>
</tr>
<tr>
<td>1.8 1.7 10 45</td>
<td>$</td>
</tr>
<tr>
<td>2.1 4.3 15 63</td>
<td>Detector cuts</td>
</tr>
</tbody>
</table>

Values in parentheses

**ttH:** Reducible b-fakes

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**Zh:** Reducible b-fakes

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**Signal:** 4 b-fakes

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Single Top + SUSY Higgs production at the LHC

- $M_{\text{SUSY}} = 1$ TeV, maximal stop mixing.
- The red line is the cross section for a standard model Higgs.
- The enhancement of the cross section is modest:
  for $m_h = m_A = 115$ GeV and $\tan \beta \approx 50 \Rightarrow \sigma(th) + \sigma(tA) = 5 \sigma(th_{\text{SM}})$
Unitarity cancellations in the t-channel in the 2HDM (type II)

For $s \sim -t \sim -u \sim E^2 \gg m_h^2, m_{H^+}, m_W^2, m_t^2$, each diagram behaves like

$$A_i \sim g^2 \frac{m_f E}{m_W^2}, \quad \text{with} \quad f = t, b.$$

This entails a violation of unitarity at a scale $\Lambda \sim m_W^2/m_f g^2$. The divergent terms cancel if the following relations hold true:

$$\frac{g_{W-W+h}}{2} m_b + g_{W-H+h} \tan \beta \, m_b + g_{b\bar{b}h} \, m_W = 0,$$

$$-\frac{g_{W-W+h}}{2} m_t + g_{W-H+h} \cot \beta \, m_t - g_{t\bar{t}h} \, m_W = 0.$$

True in the 2HDM also!
Is single top plus Higgs production doomed to never be detected?

- \( \tan \beta \) and \( m_A > 120 \text{ GeV} \) in the SUSY Higgs sector.
- Moderate enhancements of the signal are found for large Higgs masses.
- Backgrounds from \( t\bar{t} + jets \) are at least one order of magnitude larger.
- Gives a fair amount of signal events at the LHC, but t-channel production with the Higgs decaying into \( bq \).

The cross sections are smaller than one would expect from comparison with \( H \) and \( tt\bar{t} \).

The cross sections are smaller than one would expect from comparison with a Higgs at hadron colliders.

**Summary**