Recent theoretical issues in Higgs production

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MCTP Spring Symposium on Higgs Physics
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The Higgs search from LEP to the LHC

- In early 2000:
  - $M_H < 113.4$ GeV excluded at 95% CL

- Fall 2008: first direct exclusion of the SM Higgs from the Tevatron
  - $M_H < 170$ GeV @ 95% CL

- $M_H = 170$ GeV is excluded at 95% CL
The Higgs search today

- Tevatron excess driven by $b\bar{b}$ channel
- LHC primarily $\gamma\gamma$
Discovery is the beginning

UnHiggs?  Private Higgs?  Guralnik's Higgs?
Gaugephobic Higgs?  Kibble's Higgs?  Little Higgs?
Buried Higgs?  Intermediate Higgs?  Littlest Higgs?
Composite Higgs?  Fat Higgs?  Slim Higgs?
Portal Higgs?  Peter's Higgs?  Higgsless?
Gauge-Higgs?  Brout-Englert's Higgs?  Lone Higgs?
Simplest Higgs?  Twin Higgs?  Phantom Higgs?

C. Grojean
Narrowing down the possibilities

- Current limits already strongly constrain what SM extensions possible

![Graph showing SM4, mH = 125 GeV](image1)

Kuflik, Nir, Volansky 2012

![Graph showing Adjoint Scalar Excluded Region](image2)

Boughezal 2011

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Measuring Higgs properties

• To pin down the underlying model, what are we interested in measuring?

The rate:

Carena, Gori, Shah, Wagner 2011

Angular distributions, of either jets or decay products

Zeppenfeld et al. 2006

\[ \mathcal{L} = -\frac{\kappa}{2} v H S^a S^a + \cdots. \]
Effects of theory uncertainties

- CMS PAS HIG-11-024: (WW channel) “The overall signal efficiency uncertainty... is dominated by the theoretical uncertainty due to missing higher-order corrections”
- ATLAS CERN-PH-EP-2012-013 (γγ): uncertainties due to QCD scale variation one of the two dominant systematic effects (along with photon reconstruction+ID efficiency)

<table>
<thead>
<tr>
<th>Source</th>
<th>Affected Processes</th>
<th>Typical uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDFs+αs (cross sections)</td>
<td>$gg \rightarrow H, , ttH, , gg \rightarrow VV$ $VBF , H, , VH, , VV@NLO$</td>
<td>±8% ±4%</td>
</tr>
<tr>
<td>Higher-order uncertainties on cross sections</td>
<td>total inclusive $gg \rightarrow H$ inclusive “$gg$” → $H + ≥ 1$ jets inclusive “$gg$” → $H + ≥ 2$ jets $VBF , H$ associated $VH$ $ttH$ uncertainties specific to high mass Higgs boson, see Section 2.1 $V$ $VV$ up to NLO $gg \rightarrow VV$ $t\bar{t}$, incl. single top productions for simplicity</td>
<td>±12% ±7% ±20% ±1% ±1% ±4% ±10% ±30% ±1% ±5% ±30%</td>
</tr>
<tr>
<td>acceptance</td>
<td>acceptance for $H \rightarrow WW \rightarrow \ell\ell\nu\nu$ events</td>
<td>±2%</td>
</tr>
<tr>
<td>phenomenology</td>
<td>modelling of underlying event and parton showering fake lepton probability ($W+jets \rightarrow \ell\ell^{fake}$)</td>
<td>±10% ±40%</td>
</tr>
<tr>
<td>luminosities</td>
<td>ATLAS and CMS uncertainties on their luminosity measurements</td>
<td>±3.7%, ±4.5%</td>
</tr>
</tbody>
</table>

from G. Rolandi, HCP 2011
Outline

- Review the theory going into this result and others used in analyses
- Discuss available tools, some of the tricky points in the calculations
- Brief summary of VH, VBF
- Longer discussion of gluon-fusion and its backgrounds; much recent work and still some unresolved issues in this analysis
Recent theoretical issues in Higgs production

A phenomenological profile

For SM Higgs, production primarily from $gg \rightarrow H$, with some contribution from VBF (VH for $b$ Yukawa measurement)

$\sqrt{s} = 7$ TeV

SM

$WW \rightarrow l^+vq\bar{q}$

$WW \rightarrow l^+v\bar{v}$

$ZZ \rightarrow l^+l^-q\bar{q}$

$ZZ \rightarrow l^+l^+v\bar{v}$

$WH \rightarrow l^+vb\bar{b}$

$ZH \rightarrow l^+b\bar{b}$

$VBF_{H} \rightarrow \tau^+\tau^-$

$H \rightarrow \tau^+\tau^-$

$l = e, \mu$

$\nu = \nu_e, \nu_\mu, \nu_\tau$

$q = uds$ cb
Associated VH production

- With bbar decay of Higgs, most important low-mass mode at Tevatron
- At LHC, boosted analysis possible
  Butterworth, Davison, Rubin, Salam 2008

Inclusive NLO QCD: +30% (Han, Wilenbrock 1990), NLO EW: +5-10% (Ciccolini, Dittmaier, Denner 2003)

NNLO QCD: 1-2% in bulk of phase space (Ferrera, Grazzini, Tramontano 2011)

- Original boosted analysis vetoes additional jets to remove ttbar background
- Negative impact on stability of expansion (jet vetoes are theoretically dangerous!)
- Original paper mentions possibility of top-veto instead, likely safer from QCD perspective
**Vector boson fusion**

- Important for the low-mass Higgs in both the $\tau\tau$ and $\gamma\gamma$ modes
- NLO QCD the same as for DIS, increase by 5-10%
- NLO QCD+EW in VBFNLO (Oleari, Zeppenfeld et al., partial EW) and HAWK (Denner, Dittmaier, Mueck, full EW)

- DIS-like NNLO contributions also calculated, at the percent-level (Bolzoni, Maltoni, Moch, Zaro 2010)

- Important distributions under theoretical control
Gluon fusion

- Famously sensitive to large QCD corrections; difficult to calculate to requisite order in perturbation theory. The subject of enormous theoretical effort over the years.

Dawson; Djouadi, Graudenz, Spira, Zerwas, 1991, 1995
Effective interactions

• Getting the next terms requires new techniques
• Effective field theory: exploit heavy mass of virtual particles

Two scales: \( M_{\text{Higgs}}, m_{\text{top}} \)

\[
\mathcal{L}_{\text{eff}} = \alpha_s \frac{C_1}{4v} H G_{\mu\nu} G^{\mu\nu}
\]
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The Wilson coefficient

\[ C_1 = -\frac{1}{3\pi} \left\{ 1 + \alpha_s C_1 t + \alpha_s^2 C_2 t + \lambda_{EW} [1 + C_1 w] \right\} \]

Inami, Kubota, Okada 1982

Chetyrkin, Kniehl, Steinhauser 1997

EW terms: Actis, Passarino, Sturm, Uccirati 2008; Anastasiou, Boughezal, FP 2009

Clear separation of new physics effects into Wilson coefficient, QCD into corrections to the effective vertex
Unreasonably effective EFT

NLO in the EFT:

\[ \Delta \sigma = \sigma_0 \frac{\alpha_s}{\pi} \left\{ \left( \frac{11}{2} + \pi^2 \right) \delta(1 - z) + 12 \left[ \frac{\ln(1 - z)}{1 - z} \right] \right\} - 12z(-z + z^2 + 2)\ln(1 - z) \]

eikonal emission of soft gluons

Identical factors in full theory with \( \sigma_0 \rightarrow \sigma_{\text{LO, full theory}} \)

NNLO study of \( 1/m_t \) suppressed operators, matched to large s-hat limit, large indicates this persists

Harlander, Mantler, Marzani, Ozeren; Pak, Rogal, Steinhauser 2009

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NNLO in the EFT

• Success of the EFT over almost entire interesting mass range motivates NNLO calculation

Harlander, Kilgore; Anastasiou, Melnikov; Ravindran, Smith, van Neerven 2002-2003

FEHiP: Anastasiou, Melnikov, FP 2005

HNNLO: Catani, Grazzini 2007-2008
Gluon-fusion: inclusive

Effects of soft-gluon resummation at Next-to-next-to leading logarithmic (NNLL) accuracy (about 6-15%)

Partial N$^3$LO corrections known (considerably reduced scale dependence)

Two-loop EW corrections are also known (effect is about O(5%))

Mixed QCD-EW effects evaluated in EFT approach

support “complete factorization”: EW correction multiplies the full QCD corrected cross section

EW effects for real radiation (effect O(1%))
The jet-veto in gluon fusion

- Toughest cut from theoretical perspective is the jet veto
- Required in WW channel due to background composition
- 25-30 GeV jet cut envisioned; restriction of radiation leads to large logs

Inclusive scale variation 10%; with a 25 GeV jet veto, 5-6%!

Having $\Delta \sigma_{\text{veto}} < \Delta \sigma_{\text{tot}}$ doesn’t seem correct; $\sigma_{\text{veto}}$ has a more complicated structure and a larger expansion parameter, $\alpha_S \ln^2(m_H/p_{T,\text{cut}})$ rather than $\alpha_S$
Cancellations

• Study of cross section structure (Stewart, Tackmann 2011)

\[
\sigma_0(p_{\text{cut}}) = \sigma_{\text{total}} - \sigma_{\geq 1}(p_{\text{cut}})
\]

\[
\simeq \sigma_B \left\{ [1 + \alpha_s + \alpha_s^2 + O(\alpha_s^3)] - [\alpha_s(L^2 + L + 1) + \alpha_s^2(L^4 + L^3 + L^2 + L + 1) + O(\alpha_s^3 L^6)] \right\}
\]

\[
\sigma_{\text{total}} = (3.32 \text{ pb}) [1 + 9.5 \alpha_s + 35 \alpha_s^2 + O(\alpha_s^3)],
\]

\[
\sigma_{\geq 1}(p_T^{\text{jet}} \geq 30 \text{ GeV}, |\eta^{\text{jet}}| \leq 3.0) = (3.32 \text{ pb}) [4.7 \alpha_s + 26 \alpha_s^2 + O(\alpha_s^3)].
\]

• Accidental cancellation between large corrections to total cross section and logarithms, leading to reduced scale error. No reason to persist at higher orders.
Explicit demonstration

- Further evidence: three ways of extending the calculation of the 0-jet event fraction that differ by $O(\alpha_s^3)$ w.r.t. leading order

$\frac{\sigma(0) + \sigma(1) + \sigma(2)}{\sigma(0)}$

- Gives results differing from 0.5 to 0.85 for a 30 GeV veto

Banfi, Salam, Zanderighi 2012
Error prescription

• A solution using fixed-order results pointed out (Stewart, Tackmann 2011)

In the limit of \( \ln(m_H/p_{T,\text{cut}}) \) large, \( \sigma_{\text{tot}} \) and \( \sigma_{\geq 1} \) have independent expansions.

Gives expected result, that \( \Delta \sigma_{\text{veto}} > \Delta \sigma_{\text{tot}} \).

The current prescription used in LHC analyses (phrased in terms of jet fractions)

First consider *inclusive* jet cross sections

\[
\begin{align*}
\sigma_{\text{total}}, \sigma_{\geq 1}, \sigma_{\geq 2} & \Rightarrow C = \begin{pmatrix}
\Delta^2_{\text{total}} & 0 & 0 \\
0 & \Delta^2_{\geq 1} & 0 \\
0 & 0 & \Delta^2_{\geq 2}
\end{pmatrix}
\end{align*}
\]

Transform to *exclusive* jet cross sections

\[
\begin{align*}
\sigma_0 &= \sigma_{\text{total}} - \sigma_{\geq 1} \\
\sigma_1 &= \sigma_{\geq 1} - \sigma_{\geq 2} \\
\sigma_{\geq 2} &= \sigma_{\geq 1}
\end{align*}
\]

\[
\Rightarrow C = \begin{pmatrix}
\Delta^2_{\text{total}} + \Delta^2_{\geq 1} & \Delta^2_{\geq 1} & 0 \\
-\Delta^2_{\geq 1} & \Delta^2_{\geq 1} + \Delta^2_{\geq 2} & -\Delta^2_{\geq 1} \\
0 & -\Delta^2_{\geq 1} & \Delta^2_{\geq 2}
\end{pmatrix}
\]

<table>
<thead>
<tr>
<th>cut</th>
<th>( \frac{\Delta \sigma_{\text{total}}}{\sigma_{\text{total}}} )</th>
<th>( \frac{\Delta \sigma_{\geq 1}}{\sigma_{\geq 1}} )</th>
<th>( \frac{\Delta \sigma_{\geq 2}}{\sigma_{\geq 2}} )</th>
<th>( \frac{\Delta \sigma_0}{\sigma_0} )</th>
<th>( \frac{\Delta \sigma_1}{\sigma_1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_T^{\text{cut}} = 30 \text{ GeV}, \eta^{\text{cut}} = 3 )</td>
<td>10%</td>
<td>21%</td>
<td>45%</td>
<td>17%</td>
<td>29%</td>
</tr>
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</table>
Jet-veto resummed

- Very recent NLL resummation of the jet-vetoed cross section
  Banfi, Salam, Zanderighi 2012

Numbers not much reduced from those estimated using previous prescription
(error defined here as envelope of methods a, b, c from before)

Can’t use HqT reweighted POWHEG to estimate uncertainty! Central also value off by 10-15%.
**Di-photon Higgs background**

- Major interest in di-boson production as background to Higgs

\[ \sqrt{s} = 7 \text{ TeV} \]

<table>
<thead>
<tr>
<th>( \sigma^{LO}(\gamma\gamma) ) [pb]</th>
<th>( \sigma^{NLO}(\gamma\gamma) ) [pb]</th>
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<td>35.98(0)</td>
<td>47.0(1)(\pm5%) (\pm6%)</td>
</tr>
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- Staggered’ momentum cuts change \( K = 1.3 \rightarrow 3 \)
- At LO, \( p_T^1 = p_T^2 \), cut effectively 40 GeV
- Region between 25-40 GeV first opens at NLO, leading to large corrections
- Are the staggered cuts experimentally necessary? They complicate QCD background predictions

\[ p_T^\gamma > 25 \text{ GeV} , \quad |\eta_\gamma| < 5 \]

from MCFM: Campbell, Ellis, Williams 2011
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Di-photon Higgs background

• Major interest in di-boson production as background to Higgs

• ‘Staggered’ momentum cuts change $K=1.3 \rightarrow 3$

• At LO, $p_{T1}=p_{T2}$, cut effectively 40 GeV

• Region between 25-40 GeV first opens at NLO, leading to large corrections

• Are the staggered cuts experimentally necessary? They complicate QCD background predictions

Catani, Cieri, de Florian, Ferrera, Grazzini 2011

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<th>$\sqrt{s}$ [TeV]</th>
<th>$\sigma^{LO}(\gamma \gamma)$ [pb]</th>
<th>$\sigma^{NLO}(\gamma \gamma)$ [pb]</th>
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<tr>
<td>7</td>
<td>35.98 (0)</td>
<td>47.0 (1) $^{+5%}_{-6%}$</td>
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$p_{T\gamma} > 25$ GeV, $|\eta_\gamma| < 5$
**Recent theoretical issues in Higgs production**

**gg → VV(g) background**

- Formally NNLO, but enhanced by both large gluon luminosity and experimental cuts ($\Delta \varphi_{ll}$ looks like Higgs signal)

Binoth, Ciccolini, Kauer, Kraemer 2006

![Diagram](image)

<table>
<thead>
<tr>
<th>$\sigma(pp \to W^* W^* \to \ell \bar{\nu} \ell' \bar{\nu}' )$ [fb], LHC</th>
<th>$gg$</th>
<th>$q\bar{q}$</th>
<th>$\sigma_{NLO}^{\sigma_{LO}}$</th>
<th>$\sigma_{NLO+gg}^{\sigma_{NLO}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{tot}$</td>
<td>$60.00(1)$</td>
<td>$875.8(1)$</td>
<td>$1373(1)$</td>
<td>$1.57$</td>
</tr>
<tr>
<td>$\sigma_{std}$</td>
<td>$29.798(6)$</td>
<td>$270.5(1)$</td>
<td>$491.8(1)$</td>
<td>$1.82$</td>
</tr>
<tr>
<td>$\sigma_{bkg}$</td>
<td>$1.4153(3)$</td>
<td>$4.583(2)$</td>
<td>$4.79(3)$</td>
<td>$1.05$</td>
</tr>
</tbody>
</table>

• Relevant for the 1-jet bin; not known even at LO!

• Result coming soon... M. Schulze et al.
Conclusions

• We will soon move beyond the discovery stage of the Higgs and begin analyzing the newest discovered particle
• SM predictions for the Higgs are the benchmark against which all other possibilities will be compared.
• After years of work by a large community, predictions under fairly good control
• The few lingering issues occur in the interplay of experimental cuts with QCD... a good idea to discuss the intended cuts with theorists (in general, jet vetoes are bad)
• Many tools exist; recent new ones for both signal and background, and some poised to hit the market soon
• We’re prepared for the next stage after discovery!
Jet fractions

- Can be easily translated to be in terms of fractions of events in 0, 1, 2 jet bins

\[
\delta(f_0)^2 = \left(\frac{1}{f_0} - 1\right)^2 (\delta_{\text{total}}^2 + \delta_{\geq 1}^2),
\]

\[
\delta(f_1)^2 = \delta_{\text{total}}^2 + \left(\frac{1 - f_0}{f_1}\right)^2 \delta_{\geq 1}^2 + \left(\frac{1 - f_0}{f_1} - 1\right)^2 \delta_{\geq 2}^2,
\]

\[
\rho(f_0, \sigma_{\text{total}}) = \left[1 + \frac{\delta_{\geq 1}^2}{\delta_{\text{total}}^2}\right]^{-1/2},
\]

\[
\rho(f_1, \sigma_{\text{total}}) = -\frac{\delta_{\text{total}}}{\delta(f_1)},
\]

\[
\rho(f_0, f_1) = -\left(1 + \frac{1 - f_0}{f_1} \frac{\delta_{\geq 1}^2}{\delta_{\text{total}}^2}\right) \left(\frac{1}{f_0} - 1\right) \frac{\delta_{\text{total}}^2}{\delta(f_0)\delta(f_1)}.
\]