SM$_{(\text{-like})}$ Higgs production: theoretical progress

John Campbell, Fermilab
State of play in 2014

How could this figure be updated now?

What about knowledge beyond $\sigma(pp\rightarrow H+X)$?

What good is it all?

(and apologies to all work that I have overlooked in this subjective review)
2015: a banner year

A fantastic year that has led to a significantly better theoretical understanding of Standard Model Higgs boson production at the LHC.

- improved predictions for cross-sections and observables;
- development of better Monte Carlo tools;
- new ideas for additional channels and improved analyses.

Headlined by new theoretical calculations of Higgs boson processes at NNLO and beyond.

- both total cross-sections and accounting for required fiducial cuts.
- control of both absolute normalization and remaining uncertainty.

Bottom line: extraction of Higgs boson couplings and properties at an unprecedented level of precision.
Headlines
Gluon-fusion production at $N^3$LO

Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Lazopoulos, Mistlberger

- Focus of great theoretical scrutiny.
  - dominant production mode at the LHC;
  - a “simple” $2 \rightarrow 1$ process.

- Exact calculation only known to NLO at present; higher orders tractable through EFT.

- Capture dominant effects through scaling with exact treatment at LO.

Compute $N^3$LO cross-section as an expansion around the soft limit, to arbitrary order.

$z = \frac{m_H^2}{\hat{s}} \quad \rightarrow \quad (1 - z)$ is distance from threshold
Convergence of soft expansion

F. Dulat, Dec 2015, CERN

small residual effect in low-z (high-energy) region

excellent convergence

terms in expansion

$N^3LO$ coefficient [pb]
Fruits of theoretical labor: scale uncertainty

Cross-section increases by \( \sim 2\% \) compared to NNLO and within scale uncertainty \( \rightarrow \) negligible impact on value of coupling extracted so far.

Level of precision mandates careful analysis of other effects, approximations and remaining sources of uncertainty.

- \( \text{N}^3\text{LO pdfs not available and not accounted for by pdf uncertainties; can estimate uncertainty by equivalent at NNLO: } \sim 1\% . \)

- **finite mass effects** only known approximately beyond NLO, do not include all important interference effects; estimate of total uncertainty: \( \sim 2\% \).

- **electroweak corrections** to the LO process known, dominant mixed NLO effects computed in EFT; estimated uncertainty from missing NLO: \( \sim 1\% \)

\[ \rightarrow \text{F. Dulat Dec 2015, CERN} \]
Best prediction at 13 TeV, combining all sources of uncertainty, promises spectacular precision:

\[ \sigma = 48.48 \pm 2.60 \, \text{pb} = 48.48 \, \text{pb} \pm 5.36\% \]

Current uncertainty budget points the way for further theoretical improvements.

In addition:

- paves way for similar approaches to related Higgs processes, e.g. associated production.
- application to rapidity distributions too?
The Higgs boson radiates additional jets prolifically …

- according to our theoretical tools;
- and (even more so?) in the 7 and 8 TeV data taken so far.

Important source of additional events;

- to exploit, need more differential information.
Previous approximate results included only NNLO corrections to gluonic channels.

Boughezal, Caola, Melnikov, Petriello, Schulze (2013)
Chen, Gehrmann, Glover, Jaquier (2014)

This year, multiple new fully-differential results at NNLO:

- dominant gg and qg channels, sub-dominant (1% effect) qq at NLO;
  Boughezal, Caola, Melnikov, Petriello, Schulze, arXiv: 1504.07922

- extension to include Higgs boson decays for fiducial comparisons;
  Caola, Melnikov, Schulze, arXiv: 1508.02684

- all channels included at NNLO.
Corrections modest, dominant effects already captured at NLO.; predictions already stabilized (c.f. inclusive production).

- NNLO ~15% for typical LHC cuts ($p_T \sim 30$ GeV), decrease as $p_T$ increases.
- Residual scale uncertainty $\sim 5\%$.

Calculation uses powerful new SCET-based technique, “jettiness subtraction”.

**Impact of NNLO corrections**

**BCMPS, arXiv: 1504.07922**

**BFGLP, arXiv: 1505.03893**
Consistent calculation, $O(\alpha_s^5)$, for jet multiplicities from one to three.
- $k$-jet rate known to $N^{(3-k)}$LO.
- Also true for zero-jet bin in absence of fiducial cuts.

Key observables, e.g. dilepton azimuthal separation in $H \rightarrow WW$ decays: not significantly changed.

Ratios of fiducial cross-sections display excellent convergence.

$$R_{WW/\gamma\gamma} = \frac{\sigma_{WW \rightarrow e^+\mu^-\nu\bar{\nu},13\text{ TeV}}}{\sigma_{H+j,13\text{ TeV}}} \approx 2.39_{-0.06}^{+0.04}, \quad 2.33_{-0.05}^{+0.04}, \quad 2.32_{-0.02}^{+0.04}$$
Differential VBF production at NNLO
Cacciari, Dreyer, Karlberg, Salam, Zanderighi, arXiv: 1506.02660

- Critical test of the Standard Model: largest production process that involves tree-level interactions.

- Cross-section known at NNLO (total) and NLO (differential).

- Innovative “projection-to-Born” method that exploits structure function approach to merge two existing calculations:

**NNLO inclusive rate**

**NLO VBF+jet**

- Bolzoni, Maltoni, Moch, Zaro (2010, 2012)
- Figy, Zeppenfeld, Oleari (2003)
- Figy, Hankele, Zeppenfeld (2008)
- Jager, Schissler, Zeppenfeld (2014)
Can now assess effect of NNLO corrections under fiducial cuts used to tag VBF events; contrast with inclusive case.

**Impact: differential VBF at NNLO**

- Invaluable information for future precision studies of this process.

<table>
<thead>
<tr>
<th></th>
<th>inclusive $\sigma^{(\text{no cuts})}$ (pb)</th>
<th>fiducial $\sigma^{(\text{VBF cuts})}$ (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LO</td>
<td>$4.032^{+0.057}_{-0.069}$</td>
<td>$0.957^{+0.066}_{-0.059}$</td>
</tr>
<tr>
<td>NLO</td>
<td>$3.929^{+0.024}_{-0.023}$</td>
<td>$0.876^{+0.008}_{-0.018}$</td>
</tr>
<tr>
<td>NNLO</td>
<td>$3.888^{+0.016}_{-0.012}$</td>
<td>$0.826^{+0.013}_{-0.014}$</td>
</tr>
</tbody>
</table>

- Effect of NNLO:
  - Normalization: -1%
  - Uncertainty: 0.4%

- Normalization: -6%
  - Uncertainty: 1.7%
Even bigger impact on differential distributions
- corrections up to O(10%);
- outside NLO uncertainty estimate from scale variation.

Motivation for N³LO calculation; may be possible with this technique.
Gluon-fusion
Inclusion of finite mass effects (top and bottom loops) at NLO in NNLOPS generator: effects of order a few percent. 


New analytic calculation of leading interference effects at NLO, as expansion in powers of $m_b$.


Opens up possibility of similar method at NNLO, to reduce one of the leading uncertainties that remains.
The Higgs boson $p_T$ and jets

- Investigations of the Higgs transverse momentum distribution in parton showers, at NNLO+NNLL and including some BSM effects.
  - Bagnaschi, Vicini, arXiv: 1505.00735
  - Bagnaschi, Harlander, Mantler, Vicini, Wiesemann, arXiv: 1510.08850

- Phenomenology of H+2/3 jets (GF and VBF) in GOSAM/SHERPA.
  - Greiner, Hoeche, Luisoni, Schoenherr, Winter, Yundin, arXiv: 1506.01016

- Very recently, jet-veto analysis taking into account new $N^3$LO inclusive result.
  - also includes NNLL jet pt and LL jet radius resummation.
    - Banfi, Caola, Dreyer, Monni, Salam, Zanderighi, Dulat, arXiv: 1511.02886
  - increase in central value and new scale uncertainty both 2%
Primarily of interest for BSM but closely related to other developments discussed here.

- $N^3LO$ predictions for a pseudoscalar Higgs in the threshold limit.
  
  Ahmed, Kumar, Mathews, Rana, Ravindran, arXiv: 1510.02235

- NNLL soft/collinear resummation for pseudoscalar Higgs boson ($N^3LL$ for scalar).
  
  Schmidt, Spira, arXiv: 1509.00195

Heavy-quark annihilation channels:

- FONLL scheme for $b\bar{b}$ annihilation;
  
  Forte, Napoletano, Ubiali, arXiv: 1508.01529

- NNLO for neutral, charged Higgs production.
  
  Harlander, arXiv: 1512.04901
Associated VH production
Useful to consider contributions separately for purposes of MC multi-jet merging (different QCD emission patterns).

gg→VH enhanced by gluon pdf, large top Yukawa and effect of $2m_t$ threshold;

- especially important for invisible decays, e.g. Higgs-portal models.

Improved Monte Carlo modelling

Goncalves, Krauss, Kuttimalai, Maierhofer, arXiv: 1509.01597
(see also: Hespel, Maltoni, Vryonidou, arXiv: 1503.01656)
Impact

- Important for application of jet veto, e.g. to suppress background.
- Imperative for application to boosted search for $H \rightarrow bb$ decays.

\[ \text{Impact} \]

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\[ \text{Imperative for application to boosted search for } H \rightarrow bb \text{ decays.} \]
Other new tools

- NLO parton shower (POWHEG) including effects of anomalous couplings in linear EFT:
  Mimasu, Sanz, Williams, arXiv: 1512.02572

\[ \frac{ig}{m_W^2} \left[ \Phi^\dagger T_{2k} \vec{D} \mu \Phi \right] D^\nu W_{\mu\nu}^k + \]
\[ \frac{2ig}{m_W^2} \left[ D^\mu \Phi^\dagger T_{2k} D^\nu \Phi \right] W_{\mu\nu}^k \]

- Fully-differential NNLO including both DY and $y_t$ contributions.
  Ellis, JC, Williams, arXiv: 1601.00658

  Also includes effects of radiation in decay at NLO for $H \rightarrow bb$.

- Recalculation of $H \rightarrow bb$ at NNLO.
  Del Duca et al, arXiv: 1501.07226
Associated top production
Beyond NLO: parton showers and resummation

Public NLO parton shower available in POWHEG-BOX.  
Hartanto, Jager, Reina, Wackeroth, arXiv: 1501.04498

First steps beyond NLO: soft-gluon resummation for approximate NNLO.  
Broggio, Ferroglia, Pecjak, Signer, Yang, arXiv: 1510.01914

- caveat: how well does this capture behavior of full corrections?
- estimate of uncertainty by including additional contributions that are formally sub-leading in the soft limit.
- justified by comparison of exact and approximate NLO.
Less approximations at NLO

Denner, Feger, arXiv: 1506.07448

Full treatment of all diagrams that lead to the same final state: non-resonant contributions, off-shell and interference effects.

Calculation performed in limit of massless b-quarks; infrared safety therefore requires two hard b-jets.

- difference with on-shell calculation < 1%.
- would be much bigger in regions where one bottom quark is not observed, but requires massive b-quarks.
Other production modes
Small total cross-section $\sim 75\text{fb}$ at 13 TeV (mostly $t$-); strong destructive interference due to unitarity, very sensitive to non-standard couplings.

Thorough analysis of theoretical uncertainty and sensitivity to CP-violating Yukawa in aMC@NLO.

Demartin, Maltoni, Mawatari, Zaro, arXiv: 1504.00611

$$\mathcal{L} = -\frac{y_t}{\sqrt{2}} \bar{\psi}_t \left( \cos \alpha + i \gamma_5 \frac{2}{3} \sin \alpha \right) \psi_t X_0$$

ensures GF cross-section remains at observed SM level
Associated production with a pair of weak bosons.

Baglio, arXiv: 1512.05787

rates at 13 TeV in 2-10 fb range, better prospect for FCC ...

Production in association with b-jets: probe of extended Higgs sectors.

Jager, Reina, Wackeroth, arXiv: 1509.05843
Decays
Full calculation of complete NLO weak and QED corrections, combined with multiple-photon emission through QED parton shower.

* stand-alone package can be interfaced with any generator.
Higgs pair production

- gg → HH: 33.9 fb
- VBF HH: 1.8 fb
- VHH: 0.7 fb
Cross-section known at NNLO in infinite top quark mass limit; now extended by threshold resummation to NNLL.

Beyond NNLO in gluon fusion

probe of Higgs potential (self-coupling)

de Florian, Mazzitelli
arXiv: 1505.07122

Fixed order

Resummed
Exact dependence on top mass only known at LO; at NLO, expansion to \((1/m_t)^{12}\) supplemented by factoring LO result.

Exact calculation feasible at NLO but out of reach at NNLO;

- improved NNLO approximation including mass effects to \((1/m_t)^4\); strictly valid only for \(\sqrt{s} \lesssim 2m_t\)

Grigo, Hoff, Steinhauser, arXiv: 1508.00909

estimate of remaining finite-mass uncertainty:

NLO \(\pm 10\%\)
NNLO \(\pm 5\%\)
Off-shell / interference effects
Higgs boson line-shape in $H \to VV$ decays

- Reveals a significant off-shell component (real vector bosons, top threshold).
- Sensitive to cancellation of longitudinal modes in SM.

![Graph showing 4-lepton invariant mass distribution](image)

- $d\sigma/dm_\ell$: differential cross section per lepton pair [fb/GeV]
- $m_\ell$: lepton pair invariant mass [GeV]
- $ZZ \to 4\ell$: ZZ decay into four leptons
- GF total: total cross section from gluon fusion
- GF Higgs: Higgs contribution to gluon fusion
- VBF Higgs: Higgs contribution to VBF (vector boson fusion)
- VBF total: total cross section from VBF
Use high-mass events to bound off-shell Higgs couplings/width.

- larger rate in GF, requires additional theoretical assumptions (particles in the loop).
- constraints in Run 2 from tree-level vector boson scattering processes (not just VBF), significant backgrounds from QCD.

- Best information from like-sign W channels that have only small backgrounds.

JC, Ellis, arXiv: 1502.02990

Run I estimate (ATLAS data): $\kappa_V < 2.8$

Ballestrero, Maina, arXiv: 1506.02257
- SM+singlet extension

Englert, McCullough, Spannowsky, arXiv: 1504.02458
- combination with LEP
Higgs couplings
Novel ideas for constraining the charm Yukawa coupling.

- recasting $VH(\to bb)$, taking advantage of bottom/charm mis-tagging and new production channels that are normally pdf-suppressed;
- re-interpreting direct bound on total width;
- bounds on exclusive decay, $H\to J/\psi \gamma$
- indirect bound from global analysis of Higgs couplings.
… or through Higgs + charm

Brivio, Goertz, Isidori, arXiv: 1507.02916

- Can take advantage of clean Higgs decay modes and only need to tag one charm jet.
- More events, but larger intrinsic “background”.
- Expected constraint from HL-LHC similar to previous slide.
  - theoretical uncertainty based on NLO calculation ~ 20%
Include radiative corrections, resum large logarithms, account for flavor mixing.

Indirect contributions must be predicted with precision and accounted for, without assuming SM, in order to extract information on Yukawa; achieve by taking ratio: $\text{Br}(h \rightarrow V\gamma)/\text{Br}(h \rightarrow \gamma\gamma)$.

SM branching ratios of order $10^{-6}$ or smaller; long-term prospects ($3000\text{fb}^{-1}$):

- $h \rightarrow \phi\gamma$ yields $O(30)$ constraint on $y_s$
- $h \rightarrow J/\psi\gamma$ gives $O(1)$ constraint on $y_c$
- $h \rightarrow \gamma(nS)\gamma$ and $h \rightarrow bb$ complementary.


Original idea in:
- Bodwin et al, 1306.5770
- Kagan et al, 1406.1722
Complementary information on bottom Yukawa

Weak boson fusion with Higgs decays to bottom quarks.

- small signal to background ratio
- lack of typical cuts to ameliorate analysis, e.g. central jet veto.

New proposal to use:

- fat jets to identify $H \rightarrow bb$ decay;
- matrix element method combined with shower deconstruction;
- data-driven approach.

Englert, Mattelaer, Spannowsky, arXiv: 1512.03429

Sensitivity to SM value after LHC accumulates $\sim 100\text{fb}^{-1}$;

- with $600\text{fb}^{-1}$, constrain SM value at $\sim 20\%$ level.
finite mass!
17%

EW!
10%

N3LO pdfs!
12%

duration
13%

pdf!
19%

precision total cross-sections

theoretical progress on SM Higgs production

improved Monte Carlo tools

precision fiducial predictions

new ideas to test SM Higgs
(Un-)fortunately this talk has a short shelf-life, due to the rapid pace of theoretical developments.

Huge, ongoing effort in the LHC Higgs Cross Section Working Group.
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG

next meeting later this week, Jan 13-15 at CERN.
http://indico.cern.ch/event/407347/overview

The great strides being made now will surely be reflected in sharper constraints on the Higgs boson, and in greater number, later this year.