Higgs-boson phenomenology:
from discovery to precision studies

Laura Reina

MASS 2014, Odense, May 20, 2014
Outline

• Higgs-boson physics, from discovery to precision studies: an overview.

• Nature of current and future theoretical studies, with emphasis on:
  → accurate description of signal (new physics) and background (SM):
    theory cannot be the limiting factor;
  → new ideas to enhance signal vs background (ex: boosted regimes, spin
    correlations);
  → systematic parametrization of BSM effects: looking for indirect effects.

• Looking forward and getting ready for more LHC physics.
Overview

If Run I of the LHC has brought us one of the most exciting times of the last several decades with

$\rightarrow$ the Higgs-boson discovery

... an equally exciting time may await us in Run II, looking for

$\rightarrow$ anomalies w.r.t. SM-Higgs couplings
$\rightarrow$ direct signals of new physics

Unprecedented experimental means and expertise matched by the results of decades of theoretical efforts to provide the most accurate description of collider data

$\rightarrow$ has been a winning synergy in Higgs-boson discovery
$\rightarrow$ will be essential for Higgs-boson precision studies

as shown by LHC-Run I results.
Theoretical predictions for the LHC

Higher-order terms in QCD/EW essential to:

- stability and predictivity of theoretical results, since less sensitivity to unphysical renormalization/factorization scales;
- more realistic modelling of parton level since higher parton multiplicity (distributions, jets, ...);
- first step towards matching with resummed calculations and parton shower Monte Carlo programs.
• **NLO QCD**, challenges have largely been met:
  → traditional approach (FD’s) made more efficient to handle high multiplicity;
  → new techniques based on unitarity methods and recursion relations offers a powerful alternative, particularly suited for automation;
  → interface with parton shower MC well advanced (MC@NLO, POWHEG, Sherpa);
  → automation mostly achieved (aMC@NLO, BlackHat, GoSam, ...).

• **NLO EW and EW+QCD**: corrections known for most processes relevant for Run I of the LHC.

• **NNLO QCD**: conquered or under way for a variety of $2 \rightarrow 2$ processes (e.g. $pp \rightarrow Q\bar{Q}$, and $pp \rightarrow H + j$). Essential when:
  → processes involve multiple scales, leading to large logarithms of the ratio(s) of scales;
  → new parton level subprocesses first appear at NLO;
  → new dynamics first appear at NLO.
• N$^3$LO results for $2 \to 1$ processes ($gg \to H$ in $m_t \to \infty$ limit)

• Developed systematic resummation techniques for multiscale processes to account for:
  → large corrections from dominant kinematic regions (soft/collinear);
  → large corrections induced by exclusive cuts/vetos.

• PDF: constant development, NNLO is now the state of the art. Enormous effort to optimize PDF sets for LHC physics.
More than a proof of concept: Higgs discovery and beyond

(LHC Higgs Cross Sections Working Group, arXiv:1101.0593,1201.3084 and 1307.1347)

- all channels combined in a coherent way;
- all orders of calculated higher orders corrections included consistently (tested with all existing calculations);
- theory errors (scales, PDF, $\alpha_s$, ...) combined according to a common recipe.
The exclusion/discovery process would have been different, if at all possible, had we not had the most important inclusive corrections under control.

**Ex.**: large impact of QCD corrections on $gg \rightarrow H$ (determine expected SM signal).

Harlander, Kilgore, Anastasiou, Melnikov, Ravindran, Smith, van Neerven, 2002-2003
Signal strength now measured in several channels:

- Observed both bosonic and fermionic decays (both ATLAS and CMS)
- Each measurement is the result of several analyses, where specific kinematics cuts/vetos have been applied.
- Notice how the theoretical errors are about to become the limiting uncertainty.
From signal strength to couplings

The experiments measure signal strengths and can only fit the product:

\[ \mu_p^i = \mu_p \cdot \mu_{BR}^i \]

where \( \mu_p = \sigma_p / \sigma_p^{SM} \) (production) and \( \mu_{BR}^i = BR_i / BR_i^{SM} \) (decay) (n.w.a.)

Taking one decay mode at a time one can go one step further and fit the ratio per channel:

\[ \frac{\mu_{VBF+VH}^i}{\mu_{ggF+ttH}^i} = \frac{\mu_{VBF+VH}}{\mu_{ggF+ttH}} \]

under the assumption

\[ \mu_{VBF+VH} \simeq g_{VVH}^2 \]
\[ \mu_{ggF+ttH} \simeq g_{ttH}^2 \]
Relation to couplings only under specific assumptions

Define the normalized couplings $\kappa$ such that:

$$\mu^i_p = \sigma_p \cdot BR_i = \sigma_p^{SM} \cdot BR_i^{SM} \cdot \frac{\kappa_p \cdot \kappa_i}{\kappa_H}$$

where $\kappa_H = \Gamma_H / \Gamma_H^{SM}$.

One can then consider different scenarios of increasing complexity:

- $\kappa_V = \kappa_W = \kappa_Z$ and $\kappa_f = \kappa_t = \kappa_b = \kappa_\tau$
- $\kappa_Z$, $\lambda_{WZ} = \kappa_W / \kappa_Z$, and $\kappa_f$
- $\kappa_t$, $\lambda_{du} = \kappa_d / \kappa_u$, and $\kappa_V$
- $\ldots$

with $\kappa_{g,\gamma,H} = \kappa_{g,\gamma,H}(\kappa_f, \kappa_V, \ldots)$, or just independent effective parameters.

Ultimately to be rephrased in terms of effective BSM interactions:

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_i \frac{1}{\Lambda_{d_i-4}} c_i \mathcal{O}_i$$

already implemented in public codes:
eHDECAY $\rightarrow$ Contino et al. $\rightarrow$ for $H$ decays
SUSYFit $\rightarrow$ Ciuchini et al. $\rightarrow$ as part of global EW fit.
Example: \((\kappa_V, \kappa_f)\) fit

\[
\kappa_V = 1.15 \pm 0.08
\]
\[
\kappa_f = 0.99^{+0.17}_{-0.15}
\]

\[
\kappa_V = [0.81, 0.97]
\]
\[
\kappa_f = [0.71, 1.11]
\]

with less constraining bounds obtained in other scenarios.
First measurement of $t\bar{t}H$ production

**ATLAS preliminary**

Data

- SR+CR background fit
- SM signal ($m_H = 126.8\text{ GeV}$)
- SR-only background fit

**Leptonic channel**

**ATLAS preliminary**

$\gamma\gamma\to H, H t$

Data 2012 $\sqrt{s} = 8\text{ TeV}$

$\int L dt = 20.3\text{ fb}^{-1}$

$\frac{\sigma}{\sigma_{SM}}$ at $m_H = 125.7\text{ GeV}$

**Combination**

Same-Sign 2l

CMS Preliminary

$\sqrt{s} = 7\text{ TeV}, L = 5.0\text{ fb}^{-1}$; $\sqrt{s} = 8\text{ TeV}, L = 19.5\text{ fb}^{-1}$

**CMS Preliminary**

$\sqrt{s} = 8\text{ TeV}, L = 19.5\text{ fb}^{-1}$

$\kappa_V$

- $\Delta\ln L$

$\kappa_V$

$m_H = 125.7\text{ GeV}/c^2$
How can we still improve theoretical predictions?

The main outstanding issue is now the measurement of couplings, looking for deviations from the SM-Higgs paradigm:

- different production channels need to be disentangled (via cuts/vetos)
  - from each other
  - from background
- exclusive modes need to be calculable with sufficient accuracy and flexibility:
  - provide accurate interface to specific decay channels;
  - investigate need for resummation of induced large logarithmic effects in selection process (via cuts/vetos);
  - investigate accurate matching between various selection channels (e.g.: \( H + N \) jets, \( N = 0, 1, 2, \ldots \));
- large fixed-order corrections still need to be investigated;
- assumptions need to be revisited (e.g. \( m_t \to \infty \) in \( gg \to H \))

Some important developments presented in the following
**$gg \rightarrow H$ beyond NNLO, including Higgs decays**

Resummation of multiple soft-gluon emission at small transverse momentum

- HqT → no decay
- HRes → includes $H \rightarrow WW, ZZ, \gamma\gamma$

*(de Florian, Ferrera, Grazzini, Tommasini, 2012-13)*
$gg \to H$ beyond existing NNLO calculation

- Studied impact of HQ mass in $gg \to H$ (going beyond $m_t \to \infty$) (Grazzini, Sargsyan, arXiv:1306.4581)

- $N^3$LO inclusive cross section computed in soft limit $\to$ threshold production (Anastasiou, Duhr, Dulat, Furlan, Gerhmann, Herzog, Mistlberger, arXiv:1403.4616)
$H + j$, including NNLO QCD corrections

(Boughezal, Caola, Melnikov, Petriello, Schulze, arXiv:1302.6216)

- large $K$ factors: $\sigma_{NLO}/\sigma_{LO} = 1.6$ and $\sigma_{NN:P}/\sigma_{NLO} = 1.3$
- scale dependence significantly reduced to $\simeq 4\%$

New: matching of resummed results in different jet bins: $H + 0$ jet (NNLO) and $H + 1$ jet (NLO)

(Boughezal, Liu, Petriello, Tackmann, Walsh, arXiv:1312.4535)
$t\bar{t}H$: towards more accurate theoretical predictions

NLO QCD corrections to $pp \rightarrow t\bar{t}H$ from:


used to estimate the theoretical uncertainties currently used in Higgs searches

→ Higgs Cross Section Working Group (HXSWG-$t\bar{t}H$)
  (First Yellow Report, arXiv:1101.059)

\[ \begin{align*}
    m_H &\simeq 125 \text{ GeV}, \quad \sqrt{s} = 14 \text{ TeV} \\
    \delta\sigma_{NLO}^{scale}(\%) &\simeq [+5.9, -3.3] \\
    \delta\sigma_{NLO}^{PDF+\alpha_s} &\simeq \pm 8.9 \\
\text{where} & \quad \mu_0/2 < \mu < 2\mu_0 \\
\text{PDF:} & \quad \text{MSTW08, CTEQ6.6, NNPDF2.0}
\end{align*} \]
Matched at NLO to Parton Shower Monte Carlo generators

NLO calculation (by Dawson et al.) interfaced with Parton Shower Monte Carlo generators (PYTHIA/HERWIG) within

- POWHEG-BOX
- Sherpa

and successfully compared to PowHel (HELAC-NLO+POWHEG-BOX)

Gerzelli, Kardos, Trócsányi; Jäger, Hartanto, Reina, Wackeroth

for a standard choice of selection cuts, and assuming $H \rightarrow \gamma \gamma$ (all decays implemented through the PS MC, e.g. Pythia in following plots),

- $p_T^{jet} > 20$ GeV, $|y^{jet}| < 4.5$
- $p_T^l > 20$ GeV, $|y^l| < 2.5$
- $\Delta R_{l,jet} > 0.4$
(Garzelli, et al., arXiv:1405.1067)
(Garzelli, et al., arXiv:1405.1067)
Independent calculation from aMC@NLO, also successfully compared with PowHel (both $t\bar{t}H$ and $t\bar{t}A$)

$\rightarrow$ Garzelli, Kardos, Trócsányi; Frederix
(HXSWG-$t\bar{t}H$, Yellow Report II, arXiv:1201.3084)
Background: $t\bar{t}b\bar{b}$

NLO QCD corrections to $pp \rightarrow t\bar{t}b\bar{b}$ calculated in:

→ Bevilacqua et al. (arXiv:0907.4723)
→ Bevilacqua et al. (arXiv:1403.2046): ratio $t\bar{t}b\bar{b}/t\bar{t}jj$

updated in the context of HXSWG-$t\bar{t}H$ ($\sqrt{s} = 7, 8$ GeV) (Yellow Report 3, arXiv:1307.1347)

Now interfaced with PS Monte Carlo (Sherpa) in the context of OPENLOOP+Sherpa

Powhel: $ttH$ vs $ttbb$

HELAC-NLO calculation (Bevilacqua et al.) interfaced with PS Monte Carlo using POWHEG

$\leftrightarrow$ Kardos, et al. (arXiv:1303.6291)

$\leftrightarrow$ Garzelli, et al. (HXSWG, Yellow Report 3, arXiv:1307.1347)
New: study of spin correlation in $t\bar{t}H$

Spin-correlation effects can be used to distinguish scalar vs pseudoscalar associated production, i.e. SM from non-SM effects

$\rightarrow$ Artoisenet, Frederix, Mattelaer, Rietkerk, arXiv:1212.3460

and can be very visible in decay product’s kinematic distributions,

$\rightarrow$ Ellis, Hwang, Sakurai, Takeuchi, arXiv:1312.5736

and even more can be used to improve the separation of signal (tt$H$) and some irreducible backgrounds (e.g. $t\bar{t}\gamma\gamma$)

$\rightarrow$ Biswah, Frederix, Gabrielli, Mele, arXiv:1403.1790
Summary and Outlook

• After the discovery of a SM-like Higgs boson during Run I of the LHC, precision studies of its couplings could bring very important indirect evidence of non SM physics. It’s a unique time!

• The close interaction between theory and experiment and the comparable level of accuracy reached on both sides has been instrumental to the discovery.

• Precision studies needs this process to continue and to be broadened to include new techniques and ideas.

• The field is moving fast and this will have positive repercussions on a broad spectrum of LHC-Run II physics.