Higgs Boson Physics
from indirect constraints to direct searches

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Unveiling the origin of Electroweak Symmetry Breaking (EWSB): top priority of both the Tevatron and the LHC,
  ➞ Tevatron: can set exclusion limits;
  ➞ LHC: can discover related particles and their dynamics.

Spectrum of ideas to explain EWSB: based on weakly or strongly coupled dynamics embedded into some more fundamental theory at a scale \( \Lambda (\sim \text{TeV}) \):
  ➞ Elementary Higgs: SM, 2HDM, SUSY (MSSM, NMSSM,...), ...
  ➞ Composite Higgs: technicolor, little Higgs models, ...
  ➞ Extra Dimensions: flat,warped, ...
  ➞ Higgsless models
  ➞ ...

SM Higgs boson, our learning ground:
  - \( \mathcal{L}_{Higgs}^\text{SM} = (D^\mu \phi)^\dagger D_\mu \phi - \mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2 (\mu^2 < 0) : 
  - scalar particle, neutral, CP even, \( m_H^2 = -2\mu^2 = 2\lambda v^2 ; 
  - minimally coupled to gauge bosons \( \rightarrow M_W = g \frac{v}{2}, M_Z = \sqrt{g^2 + g'^2} \frac{v}{2} ; 
  - coupled to fermions via Yukawa interactions \( \rightarrow m_f = y_f \frac{v}{2} ; 
  \rightarrow mass constrained by EW precision fits.
SM Higgs-boson mass range: constrained by EW precision fits
Increasing precision will continue to provide an invaluable tool to test the consistency of the SM and its extensions.

$m_W = 80.399 \pm 0.023$ GeV

$m_t = 173.3 \pm 1.1$ GeV

$M_H = 89^{+35}_{-26}$ GeV

$M_H < 158$ (185) GeV

plus exclusion limits (95% c.l.):

$M_H > 114.4$ GeV (LEP)

$M_H \neq 158 - 175$ GeV (Tevatron)

focus is now on exclusion limits and discovery!
• **New Precision Program**: for signal and background processes in Higgs-boson production,
  ▶ theoretical predictions: stability and control of the systematic errors;
  ▶ theoretical predictions: test validity of existing results in different regimes and under different exclusive cuts;
  ▶ enforce standards in multi-process studies/analyses (e.g.: combining different production channels, comparing signal and background, etc.);
  ▶ make experimental selection process more transparent;
  ▶ . . .

• **Explore new techniques and new ideas** to fully exploit the discovery potential,
  ▶ boosted regimes (used for \( WH/ZH \), and \( t\bar{t}H \));
  ▶ jet substructure (used for \( WH/ZH \), and \( t\bar{t}H \));
    (Butterworth, Davison, Rubin, Salam, arXiv:0802.2470),
    (Piacquadio, CERN-THESIS-2010-027, 2010),
    (Plehn, Salam, Spannowski, arXiv:0802.2470)
  ▶ new variables (lower theoretical uncertainty, . . .).
Tevatron: great potential for a light SM-like Higgs boson

Lower mass region:
\[ q\bar{q}' \rightarrow WH, H \rightarrow b\bar{b} \]

Higher mass region:
\[ gg \rightarrow H, H \rightarrow W^+W^- \]

(smaller impact:
\[ q\bar{q} \rightarrow q'\bar{q}'H, q\bar{q}, gg \rightarrow t\bar{t}H \])

Exclusion region very important for LHC search strategies.
LHC: entire SM Higgs-boson mass range accessible

Many channels have been studied:

Below 130-140 GeV:

\( gg \rightarrow H, \ H \rightarrow \gamma\gamma, WW, ZZ \)
\( qq \rightarrow qqH, \ H \rightarrow \gamma\gamma, WW, ZZ, \tau\tau \)
\( q\bar{q}, gg \rightarrow t\bar{t}H, \ H \rightarrow \gamma\gamma, b\bar{b}, \tau\tau \)
\( q\bar{q}' \rightarrow WH, \ H \rightarrow \gamma\gamma, b\bar{b} \)

Above 130-140 GeV:

\( gg \rightarrow H, \ H \rightarrow WW, ZZ \)
\( qq \rightarrow qqH, \ H \rightarrow \gamma\gamma, WW, ZZ \)
\( q\bar{q}, gg \rightarrow t\bar{t}H, \ H \rightarrow \gamma\gamma, WW \)
\( q\bar{q}' \rightarrow WH, \ H \rightarrow WW \)

(M. Spira, Fortsch.Phys. 46 (1998) 203)
With $\sqrt{s} = 7$ TeV and a few fb$^{-1}$ ...

Combining only $H \rightarrow W^+W^-$, $H \rightarrow ZZ$, $H \rightarrow \gamma\gamma$, ATLAS and CMS indicate that,

- if no signal, the SM Higgs can be excluded in the range $140 - 200$ GeV;
- a 5$\sigma$ significance for a SM Higgs in the $160 - 170$ GeV mass range;
- in the low mass region ($\leftarrow$ new strategies, new ideas).

where also $WH, H \rightarrow b\bar{b}$ (highly boosted) and VBF with $H \rightarrow \tau\tau$ were used.
LHC: high luminosity projections (old)

- Low mass region still difficult at low luminosity.
- Channels like $WH, H \rightarrow b \bar{b}$ absent even at $30 \text{ fb}^{-1}$.
- Updated studies would probably show very different features.
Crucial to have access to the best theoretical predictions for Higgs-boson cross sections and branching ratios.

The LHC Higgs Cross Sections Working Group (https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections)

Two stages:
- inclusive observables (studies done in 2010) (arXiv:1101.0593→ Yellow Book);
- exclusive observables (studies started in 2011).

Ten subgroups:
- 4 SM production modes + 2 MSSM subgroups;
- branching ratios;
- PDF;
- NLO Monte Carlo;
- Higgs pseudo-observables.

Goals:
- implementing a coherent Higgs precision program;
- provide working tools to the experiments in a timely fashion.
all orders of calculated higher orders corrections included (tested with all existing calculations);
common recipe for renormalization+factorization scale dependence;
PDF and $\alpha_s$ errors following PDF4LHC prescription;
all other parametric errors included;
three errors combined according to common recipe.
<table>
<thead>
<tr>
<th>Higgs process</th>
<th>$\sigma_{NLO, NNLO, NNLL, EW}$</th>
</tr>
</thead>
</table>
C.J.Glosser et al., JHEP (2002); V.Ravindran et al., NPB 634 (2002)  
D. de Florian et al., PRL 82 (1999)  
C.Anastasiou, K.Melnikov, NPB 646 (2002) (NNLO)  
V.Ravindran et al., NPB 665 (2003) (NNLO)  
S.Catani et al. JHEP 0307 (2003) (NNLL)  
G.Bozzi et al., PLB 564 (2003), NPB 737 (2006) (NNLL)  
| $q\bar{q} \rightarrow (W, Z)H$ | T.Han, S.Willenbrock, PLB 273 (1991)  
| $q\bar{q} \rightarrow q\bar{q}H$ | T.Han, G.Valencia, S.Willenbrock, PRL 69 (1992)  
| $q\bar{q}, gg \rightarrow t\bar{t}H$ | W Beenakker et al., PRL 87 (2001), NPB 653 (2003)  
Towards exclusive studies: including decays, cuts, jet vetos, backgrounds, . . .

- Obtain distributions from NLO/NNLO/NNLL calculations.
- Study the impact of higher order corrections in the presence of cuts, jet vetos, etc.
- If cuts imposed on decay products, need to include decays and estimate higher order corrections to the new process
  - high multiplicity of final state makes calculation more involved (very few NLO calculations exist)
- Interface with NLO Monte Carlo would be best:
  - MC@NLO: $gg \to H, W/ZH$
  - POWHEG: $gg \to H, q\bar{q}' H$
- Backgrounds need to be calculated with comparable accuracy.
**Ex. 1:** Exclusive NNLO results: $gg \rightarrow H$, $H \rightarrow \gamma\gamma,WW,ZZ$

Extension of (IR safe) subtraction method to NNLO

$\rightarrow$ HNNLO [Catani, Grazzini (05)]

$\rightarrow$ FEHiP [Anastasiou, Melnikov, Petriello (05)]

Essential tools to reliably implement experimental cuts/vetos.

Jet veto (to enhance $H \rightarrow WW$ signal with respect to $t\bar{t}$ background) seems to improve perturbative stability of $y$-distribution $\rightarrow$ jet veto is removing non-NNLO contributions.
Full fledged \((gg \rightarrow H \rightarrow W^+W^- \rightarrow l^+\nu l^-\bar{\nu})\)

The magnitude of higher order corrections varies significantly with the signal selection cuts.

[Anastasiou, Dissertori, Stöckli (07)]
$gg \rightarrow H$ implemented in MC@NLO and POWHEG

→ general good agreement with PYTHIA;
→ comparison MC@NLO vs POWHEG understood;
→ comparison with resummed NLL and NNLL results under control.

[Alioli, Nason, Oleari, Re, (08)]
### Recently completed NLO calculations: most are relevant backgrounds to Higgs-boson physics!

<table>
<thead>
<tr>
<th>Process $(V \in {Z, W, \gamma})$</th>
<th>Calculated by</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp \to V+2 \text{ jets}(b)$</td>
<td>Campbell,Ellis,Maltoni,Willenbrock (06)</td>
</tr>
<tr>
<td>$pp \to V b\bar{b}$</td>
<td>Febres Cordero,Reina,Wackeroth (07-08)</td>
</tr>
<tr>
<td>$pp \to W b\bar{b}$</td>
<td>Campbell,Ellis (10)</td>
</tr>
<tr>
<td>$pp \to VV+\text{jet}$</td>
<td>Dittmaier,Kallweit,Uwer $(WW+\text{jet})$ (07)</td>
</tr>
<tr>
<td></td>
<td>Campbell,Ellis,Zanderighi $(WW+\text{jet+decay})$ (07)</td>
</tr>
<tr>
<td></td>
<td>Binoth,Karg,Kauer,Sanguinetti (09)</td>
</tr>
<tr>
<td>$pp \to VV+2 \text{ jets}$</td>
<td>Bozzi,Jäger,Oleari,Zeppenfeld (via WBF) (06-07)</td>
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<tr>
<td>$pp \to VVV$</td>
<td>Lazopoulos,Melnikov,Petriello $(ZZZ)$ (07)</td>
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<tr>
<td></td>
<td>Binoth,Ossola,Papadopoulos,Pittau $(WWZ, WZZ, WWW)$ (08)</td>
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<td></td>
<td>Hankele,Zeppenfeld $(WWZ \to 6 \text{ leptons, full spin correlation})$ (07)</td>
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<tr>
<td>$pp \to H+2 \text{ jets}$</td>
<td>Campbell,Ellis,Zanderighi (NLO QCD to $gg$ channel) (06)</td>
</tr>
<tr>
<td>$pp \to H+3 \text{ jets}$</td>
<td>Ciccolini,Denner,Dittmaier (NLO QCD+EW to WBF channel) (07)</td>
</tr>
<tr>
<td>$pp \to t\bar{t}+\text{jet}$</td>
<td>Figy,Hankele,Zeppenfeld (large $N_c$) (07)</td>
</tr>
<tr>
<td>$pp \to t\bar{t}Z$</td>
<td>Dittmaier,Uwer,Weinzierl (07), Ellis,Giele,Kunszt (08)</td>
</tr>
<tr>
<td>$pp \to t\bar{t}b\bar{b}$</td>
<td>Lazopoulos,Melnikov,Petriello (08)</td>
</tr>
<tr>
<td>$gg \to WW$</td>
<td>Binoth,Ciccolini,Kauer,Kramer (06)</td>
</tr>
<tr>
<td>$gg \to HH, HHH$</td>
<td>Binoth,Karg,Kauer,Rückl (06)</td>
</tr>
<tr>
<td>$pp \to t\bar{t}b\bar{b}$</td>
<td>Bredenstein et al., Bevilacqua et al. (09)</td>
</tr>
<tr>
<td>$pp \to V+3\text{jets}$</td>
<td>Berger et al., Ellis et al. (09)</td>
</tr>
<tr>
<td>$pp \to W+4\text{jets}$</td>
<td>Berger et al. (10)</td>
</tr>
</tbody>
</table>
**Ex. 2:** $W + 1 b$-jet: crucial background for $WH$ production

[Campbell, Ellis, Febres Cordero, Maltoni, L.R., Wackeroth, Willenbrock (09)]

Consistently combine 4FNS ($m_b \neq 0$) and 5FNS ($m_b = 0$) at NLO in QCD:

1. $q\bar{q}' \rightarrow Wb\bar{b}$ at tree level and one loop ($m_b \neq 0$)
2. $q\bar{q}' \rightarrow Wb\bar{b}g$ at tree level ($m_b \neq 0$)
3. $bq \rightarrow Wbq'$ at tree level and one loop ($m_b = 0$)
4. $bq \rightarrow Wbq'g$ and $bg \rightarrow Wbq'\bar{q}$ at tree level ($m_b = 0$)
5. $gg \rightarrow Wbbq'$ at tree level ($m_b \neq 0$) → avoiding double counting:

$\int_{x}^{1} dy \frac{1}{y} P_{qg} \left( \frac{x}{y} \right) g(y, \mu)$

$\rightarrow$ indeed: a fully consistent NLO 5FNS calculation (S-ACOT scheme).
Comparison with CDF measurement: a puzzle?

CDF Note 9321 (arXiv:0909.1505):

\[ \sigma_{b-\text{jet}}(W + b \text{jets}) \cdot Br(W \rightarrow l\nu) = 2.74 \pm 0.27(\text{stat}) \pm 0.42(\text{syst}) \text{ pb} \]

[Neu, Thomson, Heinrich]

From our \( W + 1b \) calculation:

[Campbell, Febres Cordero, L.R.]

\[ \sigma_{b-\text{jet}}(W + b \text{jets}) \cdot Br(W \rightarrow l\nu) = 1.22 \pm 0.14 \text{ pb} \]

(For comparison: ALPGEN gives 0.78 pb, PYTHIA 1.10 pb)

Outlook:

- need to compare more observables;
- need D0 measurement;
- need to compare with LHC measurements (coming soon);
- match \( W\bar{b}\bar{b} \) with NLO Monte Carlo (soon to be released in POWHEG).
Conclusions and Outlook

• We are living through a new era in Higgs boson physics: looking for direct evidence.

• SM Higgs boson precision physics has given a first coherent set of predictions for inclusive observables: Higgs boson production cross sections and branching ratios.

• Short term: study exclusive observables, including decays, background processes, and experimental cuts.

• Long term: the LHC can carry through a precision program that also include measurements of Higgs boson properties, to identify it.
  • high luminosity required;
  • strategies depend on intermediate discoveries;
  • more sophisticated techniques available by then.