Developments on SM Higgs-boson cross sections and branching ratios

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Outline

- Living through the most exciting time for Higgs physics: crucial to have access to the best theoretical predictions for SM Higgs-boson cross sections and branching ratios.
  - foundation of the Tevatron exclusion limits;

- State of the art of inclusive results for a SM Higgs boson (→ see Grazzini’s talk for in depth analysis of main channels).

- Towards exclusive results:
  - goals,
  - challenges,
  - highlights from existing studies.

- Results on branching ratios.
Motivation: with $\sqrt{s} = 7$ TeV and a few fb$^{-1}$ ...

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

- if no signal, the SM Higgs can be excluded up to 500 GeV;
- a 5$\sigma$ significance for a SM Higgs in the 140 – 170 GeV mass range.
- gain by adding new channels and optimizing cuts (→ see Metha’s talk).

Need adequate theoretical input and careful matching between th. and exp.
Inclusive SM Higgs-boson production cross sections

Implemented a coherent Higgs precision program:

→ 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 (→ see de Florian’s talk);
→ all other parametric errors included;
→ theory errors combined according to common recipe.
For $\sqrt{s} = 7$ TeV (from S. Dittmaier’s talk, BNL, May 2011)

<table>
<thead>
<tr>
<th>$M_H$</th>
<th>Uncertainties</th>
<th>NLO/NNLO/NNLO+</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$M_H$</td>
<td>scale</td>
</tr>
<tr>
<td>ggF</td>
<td>$&lt; 500$ GeV</td>
<td>6-10%</td>
</tr>
<tr>
<td>VBF</td>
<td>$&lt; 500$ GeV</td>
<td>1%</td>
</tr>
<tr>
<td>WH</td>
<td>$&lt; 300$ GeV</td>
<td>1%</td>
</tr>
<tr>
<td>ZH</td>
<td>$&lt; 300$ GeV</td>
<td>1-2%</td>
</tr>
<tr>
<td>t\bar{t}H</td>
<td>$&lt; 300$ GeV</td>
<td>10%</td>
</tr>
</tbody>
</table>

For $\sqrt{s} = 14$ TeV

<table>
<thead>
<tr>
<th>$M_H$</th>
<th>Uncertainties</th>
<th>NLO/NNLO/NNLO+</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$M_H$</td>
<td>scale</td>
</tr>
<tr>
<td>ggF</td>
<td>$&lt; 500$ GeV</td>
<td>6-14%</td>
</tr>
<tr>
<td>VBF</td>
<td>$&lt; 500$ GeV</td>
<td>1%</td>
</tr>
<tr>
<td>WH</td>
<td>$&lt; 300$ GeV</td>
<td>1%</td>
</tr>
<tr>
<td>ZH</td>
<td>$&lt; 300$ GeV</td>
<td>2-4%</td>
</tr>
<tr>
<td>t\bar{t}H</td>
<td>$&lt; 300$ GeV</td>
<td>10%</td>
</tr>
</tbody>
</table>
Based on several contributions:

<table>
<thead>
<tr>
<th>Higgs process</th>
<th>$\sigma_{\text{NLO,NNLO,NNLL,EW}}$</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)  
| $q\bar{q} \to (W, Z)H$ | T.Han, S.Willenbrock, PLB 273 (1991)  
| $q\bar{q} \to q\bar{q}H$ | T.Han, G.Valencia, S.Willenbrock, PRL 69 (1992)  
| $q\bar{q}, gg \to t\bar{t}H$ | W BEENAKKER ET AL., PRL 87 (2001), NPB 653 (2003)  
Towards exclusive studies: including decays, cuts, jet vetos, backgrounds, ... 

- Provide 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 (more and more NLO calculations coming on-line)
- Interface with NLO Monte Carlo programs should be implemented and results compared: MC@NLO, POWHEG.
- Backgrounds need to be calculated with comparable accuracy.
- Signal-background interference needs to be carefully addressed.
- More channel-specific issues ...
Magnitude of higher order corrections varies significantly with signal selection cuts and vetoes.

Ex.: $\,(gg \rightarrow) H \rightarrow W^+W^- \rightarrow l^+\nu l^-\bar{\nu}$

[$\text{Anastasiou, Dissertori, Stöckli (07)}$]

($\rightarrow$ see also Grazzini’s talk)
Main issues:

- Inclusive studies not indicative for exclusive predictions.
- Logarithmic dependence from extra scales (cuts/vetos) interferes with usual $\mu_R$ and $\mu_F$-dependence: difficult to estimate overall theoretical uncertainty (very cut/veto-dependent).
- Need to question stability of perturbative prediction
- Need dedicated studies, for all channels/analyses: availability of NLO (and NNLO if needed) codes becomes mandatory.

\[\downarrow\]

The exercise we are now completing for SM Higgs searches is a glorious application of the incredible progress in NLO calculations over the past few years.
NLO: challenges have largely been faced and enormous progress has been made (→ see also Maltoni’s talk)

- several independent codes based on traditional FD’s approach
- several NLO processes collected and viable in MFCM [Campbell, Ellis]
- Enormous progress towards automation:
  - Virtual corrections: new techniques based on unitarity methods and recursion relations
    ▶️ BlackHat [Berger, Bern, Dixon, Febres Cordero, Forde, Ita, Kosower, Maitre]
    ▶️ Rocket [Ellis, Giele, Kunszt, Melnikov, Zanderighi]
    ▶️ HELAC+CutTools, Samurai [Bevilacqua, Czakon, van Harmeren, Papadopoulos, Pittau, Worek; Mastrolia, Ossola, Reiter, Tramontano]
  - Real corrections: based on Catani-Seymour Dipole subtraction or FKS subtraction
    ▶️ Sherpa [Gleisberg, Krauss]
    ▶️ Madgraph (AutoDipole) [Hasegawa, Moch, Uwer]
    ▶️ Madgraph (MadDipole) [Frederix, Gehrmann, Greiner]
    ▶️ Madgraph (MadFKS) [Frederix, Frixione, Maltoni, Stelzer]
virtual+real:
  ▶️ MadLoop+MadFKS [Hirschi, Frederix, Frixione, Garzelli, Maltoni, Pittau]

interface to parton shower well advanced:
  ▶️ POWHEG [Nason, Oleari, Alioli, Re]
  ▶️ MC@NLO [Frixione, Webber, Nason, Frederix, Maltoni, Stelzer]
  ▶️ aMC@NLO [Frederix, Frixione, Hirschi, Maltoni, Pittau, Torrielli]

Tools that we can now use for signal and (high multiplicity) background.

A choice of examples to follow . . .
W+jets

\[ \int L dt = 35 \text{ pb}^{-1} \]

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

\[ m_{WW} \text{ [GeV/c}^2] \]

\[ \text{Entries / 20 GeV/c} \]

\[ L dt = 33 \text{ pb}^{-1} \]

\[ \int m_{WW} \text{ [GeV/c}^2] \]

\[ \text{Inclusive Jet Multiplicity, } N_{\text{jet}} \]

\[ \text{Theory/Data} \]

\[ \text{Blackhat+Sherpa: W+3j, W+4j at NLO} \]
$W + b$-jets: crucial background for $WH$ production

Two interesting signatures:

- $W + 2b$ jets ($m_b \neq 0$):
  - Badger, Campbell, Ellis, arXiv:1011.6647
  - Oleari, L. R., arXiv:1105.4488 $\rightarrow$ POWHEG
  - Frederix, Frixione, Hirschi, Maltoni, Pittau, Torrielli $\rightarrow$ aMC@NLO

- $W + 2$ jets with at least one $b$ jet:
  - Campbell, Ellis, Febres Cordero, Maltoni, L. R., Wackeroth, Willenbrock, arXiv:0809.3003
  - the ATLAS collaboration, A. Messina’s talk at EPS 2011, Caola, Campbell, Febres Cordero, L. R., Wackeroth, arXiv:1107.3714
In a nutshell:

One or two LO processes, depending on choice of 4FNS vs 5FNS:

\[ q \bar{q} \rightarrow W b \bar{b} \quad \text{at tree level and one loop} \quad (m_b \neq 0) \]
\[ q \bar{q} \rightarrow W b \bar{b} g \quad \text{at tree level} \quad (m_b \neq 0) \]
\[ b q \rightarrow W b q' \quad \text{at tree level and one loop} \quad (m_b = 0) \]
\[ b q \rightarrow W b q' g \quad \text{and} \quad b g \rightarrow W b q' \bar{q} \quad \text{at tree level} \quad (m_b = 0) \]
\[ g q \rightarrow W b \bar{b} q' \quad \text{at tree level} \quad (m_b \neq 0) \rightarrow \text{avoiding double counting:} \]

\[ b(x, \mu) = \frac{\alpha_s}{2\pi} \ln \frac{\mu^2}{m_b^2} \int_x^1 \frac{dy}{y} P_{qg} \left( \frac{x}{y} \right) g(y, \mu) \]

\[ \triangleright \] \( W + 2b \) jets: processes 1 + 2 + 5
\[ \triangleright \] \( W + 2 \) jets with at least one \( b \) jet: processes 1 + \( \cdots \) + 5.
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 prediction: 0.78 pb
PYTHIA prediction: 1.10 pb
Comparison with ATLAS

[ATLAS Preliminary]

Electron Channel
Combined Electron and Muon
Muon Channel
NLO 5FNS
ALPGEN + JIMMY (b-jet from ME and PS)
ALPGEN + JIMMY (b-jet only from ME)
PYTHIA

Data 2010, $\sqrt{s}=7$ TeV

$\int Ldt = 35$ pb$^{-1}$

[1 jet] [2 jet] [1+2 jet]

$\sigma(W \rightarrow l + \geq 1$ b-jet) [pb]

[Golling, Messina, et al.]
Further development: $Wb\bar{b}$ implemented in POWHEG and MC@NLO, including $W \to l\nu_l$ decay.

Distribution sample:

- used to estimate showering and hadronization uncertainties;
- $bq \to bq'W$ process being implemented.
$t\bar{t}bb$ at NLO: background for $t\bar{t}H, H \to b\bar{b}$.


best central scale choice:

$$\mu_0^2 = m_t \sqrt{p_T^b p_T^{\bar{b}}}$$

hard $b$ jet often from initial state gluons

\[\downarrow\]

different from $t\bar{t}H$

(Bredenstein, et al.)
Important to observe that:

- **effect of jet veto on extra light jet:**

  \[ \sigma \text{[fb]} \quad pp \to t\bar{t}b\bar{b} + X \]

  ![Graph showing the effect of jet veto on extra light jet](image)

  - \( m_{b\bar{b}} > 100 \text{ GeV} \)

- **regime of boosted Higgs:**

  \[ \frac{d\sigma}{d\Delta R_{b\bar{b}}} \text{[fb]} \quad pp \to t\bar{t}b\bar{b} + X \]

  ![Graph showing the regime of boosted Higgs](image)

  - \( m_{b\bar{b}} > 100 \text{ GeV} \)

  - \( p_{T,b\bar{b}} > 200 \text{ GeV} \)
$t\bar{t}b\bar{b}$ distributions: signal vs background, at NLO

(Bevilacqua, Czakon, Garzelli, van Hameren, Papadopoulos, Pittau, Worek, arXiv:1003.1241, Les Houches 09)

- $t\bar{t}b\bar{b}$ background: LO and NLO;
- $t\bar{t}H$ with $H \rightarrow b\bar{b}$: LO and NLO, calculated in NWA (valid for small $M_H$);
- to be revisited within the Higgs Cross Section WG (exclusive studies);
- signal now available in aMC@NLO ($\rightarrow$ see also Maltoni’s talk)
SM Branching Ratios

uncertainties:

- theoretical (QCD, EW)
- parametric ($m_c$, $m_b$, \ldots )

linearly combined.

Tools:

- HDECAV [Djouadi, Kalinowski, Müllheitner, Spira]
- Prophecy4f [Bredenstein, Denner, Dittmaier, Mück, Weber]
- EW-NLO corrections to $H \to \gamma\gamma$ and $H \to gg$ [Actis, Passarino, Sturm, Uccirati]
Strategy (from D. Rebuzzi’s talk, BNL, May 2011)

↩ Calculate decay partial width as accurate as possible for each decay mode.
↩ Calculate branching ratio from full set of partial width.
↩ Define Higgs total width as

\[
\Gamma_H = \Gamma_{H\text{DECAY}} - \Gamma_{ZZ} - \Gamma_{WW} + \Gamma_{4f}^{\text{Profecy4f}}
\]

where

\[
\Gamma_{4f}^{\text{Profecy4f}} = \Gamma_{H \rightarrow WW^* \rightarrow 4f} + \Gamma_{H \rightarrow ZZ^* \rightarrow 4f} + \Gamma_{WW/ZZ - \text{int}}
\]

Results (preliminary, to be compared with [Baglio, Djouadi, arXiv:1012.0530])

<table>
<thead>
<tr>
<th>Process</th>
<th>QCD</th>
<th>EW</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>(H \rightarrow b\bar{b})</td>
<td>(\sim 0.1 - 0.2%)</td>
<td>1 - 2% ((M_H \leq 135 \text{ GeV}))</td>
<td>(\sim 3 - 4%)</td>
</tr>
<tr>
<td>(H \rightarrow c\bar{c})</td>
<td>(\sim 0.1 - 0.2%)</td>
<td>1 - 2% ((M_H \leq 135 \text{ GeV}))</td>
<td>(\sim 10 - 13%)</td>
</tr>
<tr>
<td>(H \rightarrow \tau\bar{\tau})</td>
<td>(\sim 5%)</td>
<td>1 - 2% ((M_H \leq 135 \text{ GeV}))</td>
<td>(\sim 3 - 6%)</td>
</tr>
<tr>
<td>(H \rightarrow t\bar{t})</td>
<td>(\sim 5%)</td>
<td>2 - 5% ((M_H \leq 500 \text{ GeV}))</td>
<td>(\sim 5 - 10%)</td>
</tr>
<tr>
<td>(H \rightarrow WW/ZZ \rightarrow 4f)</td>
<td>(&lt; 1%)</td>
<td>0.5% ((M_H \leq 500 \text{ GeV}))</td>
<td>(\leq 2%)</td>
</tr>
<tr>
<td>(H \rightarrow gg)</td>
<td>(\sim 10%)</td>
<td>(\sim 1%)</td>
<td>(\sim 15 - 17%)</td>
</tr>
<tr>
<td>(H \rightarrow \gamma\gamma)</td>
<td>(&lt; 0.5%)</td>
<td>(&lt; 1%)</td>
<td>(\sim 1%)</td>
</tr>
</tbody>
</table>
Conclusions and Outlook

- We are living through a new era in Higgs-boson physics: looking for direct evidence.
- 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**: carry through a precision program that also include measurements of Higgs-boson properties, to identify possible candidates:
  - the LHC will play an important role but need very high luminosity;
  - LHC measurements will be important indications but are intrinsically model dependent;
  - a high energy Linear Collider could be the best if not the only environment to complete and conclude the investigation of EWSB.